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DIAGNOSIS OF AIR POLLUTANT AND NATURAL STRESS SYMPTOMS ON FOREST VEGETATION IN WESTERN CANADA

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ABSTRACT

Industrial operations in Alberta, Saskatchewan, Manitoba, and the Northwest Territories release airborne emissions that can injure surrounding forest vegetation. This report describes symptoms of these pollutants and of natural stresses that may appear similar. The industries discussed include natural gas processing plants, oil wells and refineries, oil sands plants, metal mines and smelters, cement plants, potash industry, pulp and paper mills, and agricultural chemical production and application. Nineteen pages of color photographs provide examples of these symptoms on forest vegetation.

RESUME

Les opérations industrielles dans l'Alberta, la Saskatchewan, le Manitoba et les Territoires du Nord-Ouest émettent des effluents aéroportés susceptibles d'endommager la végétation environnante. Le présent rapport décrit les symptômes de ces polluants ainsi que les stress naturels qui peuvent y ressembler. Les industries considérées comprennent les usines de traitement du gaz naturel, les puits et raffineries d'huiles, les usines de transformation des sables bitumineux, les mines et fonderies de métaux, les usines de ciment, l'industrie de la potasse, les usines de pâtes et papiers ainsi que la production et l'application de produits chimiques à des fins agricoles. Dix-neuf pages de photographies en couleurs donnent des exemples de ces symptômes sur la végétation forestière.

PREFACE

A wide variety of industrial operations in Alberta, Saskatchewan, Manitoba, and the Northwest Territories release considerable quantities of airborne emissions that can have a deleterious effect on surrounding forest vegetation. Such industries include natural gas processing plants, oil wells and refineries, oil sands plants, metal mines and smelters, cement plants, potash industry, pulp and paper mills, and agricultural chemical production and application. Some of the major pollutants from these operations are sulfur dioxide; oxides of nitrogen; hydrocarbons; heavy metals and particulates; dusts containing calcium, potassium, and sodium oxides; and salt water.

Visual symptoms of emission toxicity on vegetation are often the only basis for identifying an air pollution problem and assessing its magnitude. Under field conditions, symptom development on vegetation generally results from exposure to total emissions from an industry rather than to an individual pollutant. An attempt is made in this handbook to utilize the visual symptoms of air pollution toxicity to diagnose and assess the impact on forest vegetation of the total airborne emissions from a given industry.

The symptoms of air pollutant toxicity are not highly specific and can be confused with those caused by nonpollutant stresses such as abnormal climatic conditions, nutrient deficiencies, and insect and disease disorders. The main purpose of this handbook is to assist field personnel who lack formal training and experience in air pollution biology to become familiar with visible symptoms of airborne pollutants on forest vegetation and to acquaint them with certain similarities in symptom development by pollutant and nonpollutant stresses.

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PREFACE

Une grande variété d'opérations industrielles dans l'Alberta, la Saskatchewan, le Manitoba et les Territoires du Nord-Ouest, rejettent des quantités considérables d'effluents aéroportés qui peuvent avoir un effet délétère sur la végétation forestière environnante. Ces industries comprennent les usines de traitement du gaz naturel, les puits et raffineries d'huiles, les usines de transformation des sables bitumineux, les mines et fonderies de métaux, les usines de ciment, l'industrie de la potasse, les usines de pâtes et papiers ainsi que la production et l'application de produits chimiques à des fins agricoles. Au nombre des principaux polluants résultant de ces opérations se trouvent l'anhydride sulfureux; les oxydes d'azote; les hydrocarbures, les métaux et particules lourds; les poussières contenant des oxydes de calcium, de potassium et de sodium ainsi que l'eau salée.

Les symptômes visuels de la toxicité des effluents sur la végétation constituent souvent la seule base d'identification d'un problème de pollution atmosphérique et d'évaluation de son ampleur. Dans la nature, l'apparition de symptômes sur la végétation procède généralement de l'exposition aux effluents intégraux d'une industrie plutôt que d'un polluant déterminé. Dans le présent manuel une tentative est faite en vue d'utiliser les symptômes visuels de la toxicité de la pollution atmosphérique pour diagnostiquer et évaluer l'impact sur la végétation forestière des effluents intégraux aéroportés d'une industrie donnée.

Les symptômes de la toxicité des polluants atmosphériques ne sont pas très spécifiques, d'où la possibilité de les confondre avec ceux provoqués par des stress non polluants tels que conditions climatiques anormales, carences d'éléments nutritifs et troubles causés par les insectes et les maladies. Le but principal de ce manuel est d'aider le personnel oeuvrant sur le terrain, dépourvu de formation classique et d'expérience relativement à la biologie de la pollution atmosphérique, à se familiariser avec les symptômes visuels des polluants aéroportés sur la végétation forestière et à se renseigner sur certaines similitudes des symptômes provoqués par les polluants et par les stress non polluants.

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INTRODUCTION

Scattered throughout Alberta, Saskatchewan, Manitoba, and the Northwest Territories are industrial operations extracting and processing the varied natural resources of this vast area. These operations include natural gas processing plants, oil wells and refineries, oil sands plants, metal mines and smelters, cement plants, potash industry, pulp and paper mills, and agricultural chemical production and application (Fig. 1). All of these industries release airborne pollutants such as sulfur dioxide (SO_2), oxides of nitrogen (NO_x), ozone (O_3), hydrocarbons, and heavy metals—emissions that can damage surrounding forest vegetation.

The visible symptoms that such air pollutants cause on vegetation are often not highly specific; that is, they can be very similar to the symptoms caused by natural stresses in the forest. Consequently, when vegetation in an area declines, it is difficult to determine whether it is air pollutant toxicity that is affecting the vegetation.

Because many field personnel do not have formal training and experience in air pollution biology, this handbook has been written to assist in identifying the visible symptoms of airborne pollutants on forest vegetation and in separating them from often very similar symptoms caused by natural factors such as nutrient deficiency, climate, diseases, and insects. It is hoped that the information provided here will be sufficient to enable a keen observer to sort out the possible cause(s) of environmental degradation. If there is doubt, assistance should be obtained from scientific experts at universities, government agencies, or private consulting companies.

HOW TO USE THIS HANDBOOK

Because this handbook is intended for use in the field, it differs from other guides to air pollution symptomology in that it describes the effects of the **total aerial emissions** from each type of industry in the region. Vegetation in the field develops symptoms in response to the total emissions from any industrial operation, not to individual pollutants in isolation. Pollutant symptoms on spruce around a metal smelter, for example, differ from symptoms on the same species around a natural gas processing plant, even though SO_2 is the main pollutant in each case. Smelters also emit heavy metal particulates, and the combination of SO_2 and heavy metals causes different effects on vegetation than SO_2 alone does. Almost all of the photographs illustrating air pollutant symptoms were taken of actual vegetation in the field. Only the nutrient deficiency, nitrogen oxide, and ammonia vapor symptoms were developed under controlled conditions in the laboratory.

The description of pollutant symptoms is organized according to industry. The major industries dealt with and their emissions are

natural gas and oil processing—SO_2, hydrocarbons, salt water, nitrogen dioxide, hydrogen sulfide, and small amounts of heavy metals and other particulates,

metal mining and smelting—SO_2, heavy metals (copper, zinc, nickel, cadmium, lead) and other particulates,

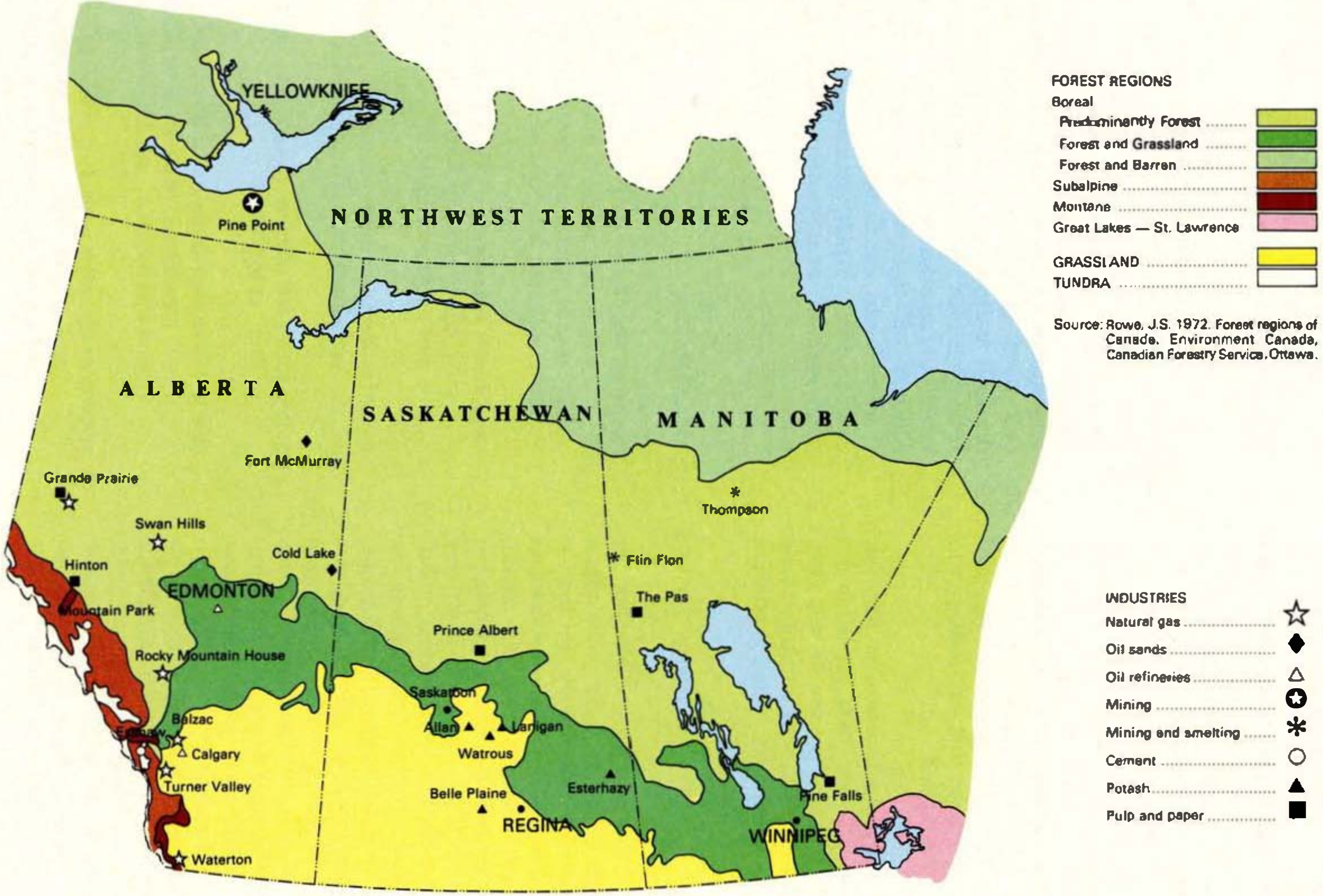
cement production—dust containing calcium, potassium, and sodium oxides,

potash mining and refining—potassium and sodium chlorides,

pulp and paper manufacturing—sulfur gases, methyl mercaptan, dimethyl sulfide, sodium hydroxide, and ammonia,

stationary combustion engines—oxides of nitrogen, ozone, PAN, hydrocarbons, sulfur gases, and carbon monoxide, and

agricultural chemical production and application (fertilizers, herbicides, soil sterilants, and pesticides)—ammonia vapor, 2,4-D, 2,4,5-T, picloram, bromacil, sodium chlorate, amitrole, and dimethoate.



Source: Rowe, J.S. 1972. Forest regions of Canada. Environment Canada, Canadian Forestry Service, Ottawa.

Figure 1. Map of the major air pollution sources in Alberta, Saskatchewan, Manitoba, and the Northwest Territories.

If air pollutants are suspected as the cause of vegetation injury, the investigator should determine if there is a source of emissions in the affected area and refer to the section on that industry in this handbook. Symptoms are described on both coniferous and deciduous species and, where applicable, on lichens and ground-cover species. For quick reference, a summary of symptoms appears in table form on pages 59-65. Also included are a glossary of technical terms, lists of common and scientific names of plants, diseases, and insects, a list of abbreviations and chemical nomenclature, and a pollutant and vegetation index.

HOW TO DIAGNOSE AIR POLLUTION INJURY

Air pollutant symptoms can be difficult to distinguish from symptoms caused by natural stresses. A good knowledge of the affected area is required, and considerable caution should be exercised in attributing nonspecific visible injuries and other abnormalities to air pollutants.

1. The first step is to establish the base-line condition of unaffected vegetation near the general area of concern. Affected vegetation can be compared with this.

2. If air pollutants are suspected as the cause of vegetation injury, verify the existence of an air pollution source in the problem area. Obtain information on the types of pollutants, the quantities released into the atmosphere, and the sources. Also determine the height of the stack and whether there has been a malfunction of the pollutant extracting devices.

3. If possible, obtain air quality, meteorological, and topographical information to determine the distribution pattern of air pollutants in the area.

4. Examine the visible injury symptoms on different species of vegetation and compare them with characteristic symptoms produced by individual pollutants or by total emissions from a similar industry, as documented and illustrated in this handbook. It is preferable to use the same indicator plant species throughout the affected areas.

5. Because symptoms of pollution can often be confused with those caused by natural stresses, it is important to consider factors such as soil nutrient deficiency, adverse climatic conditions, and disease and insect disorders. Insect infestations can ususally be identified by the presence of the insect in one of its life forms, and diseases can be confirmed by microscopic examination.

6. In many cases, air pollution injury to vegetation can be verified by chemical analysis of the affected vegetation for the presence of pollutants such as sulfur, fluoride, and heavy metals. There is generally a good relationship between the pollutant content and physical injury symptoms on vegetation. Changes in soil chemistry and pollutant content of the soil can also provide a good indication of pollutant impact on vegetation.

HELPFUL HINTS

1. Lichens are much more sensitive to air pollution than are vascular plants. Their extreme sensitivity to SO_2 and trace elements makes them a valuable biological tool for early warning and monitoring of air pollution injury to vegetation. The feather moss communities, lichen species inhabiting the branches and trunks of trees, and lichens growing on rock surfaces are all important bioindicators. When exposed to emissions from such industries as pulp mills, metal smelters, and oil and natural gas processing plants, most tree lichens start to show symptoms of degradation similar to those caused by natural deterioration. In areas affected by air pollutants, lichens become depleted, leaving only remnants, and the species distribution changes. Analysis of the remaining lichens to determine the presence of pollutant (emission) elements is often useful in diagnosing the cause of injury.

   Where the lichens are still intact, they can serve as indicators of smelter pollution and help in delineating the impingement zones. Furthermore, branch lichens from a homogeneous population in an unaffected area can be transplanted at increasing distances from the air pollution source and can be monitored for vigor, density, diversity, and emission element content over time. The relationship between changes in such parameters and distance from the source provides another effective means for assessing air pollution injury to vegetation and determining the impingement zones. Photographs taken when sample plots are first established and at different time intervals can be used for comparing the health of lichens in a gradient from the pollution source.

2. In general, symptom development is more prominent on the side of branches facing the emission source.

3. Deciduous species generally develop air pollutant symptoms much more rapidly than conifers. Conifers, because of their long foliar retention time, can accumulate pollutants to toxic levels and therefore are often more susceptible to lethal injury than deciduous species, which lose their leaves annually.

4. The response of vegetation to pollutants is mediated by many factors such as stage of plant development, time of year (dormancy vs. active growth), possible synergistic, additive, or antagonistic effects, atmospheric conditions (temperature, humidity, and wind speed and direction), soil moisture and nutrient status, time of day (gas exchange capability or open vs. closed stomata), type of vegetation (sensitive vs. resistant), pollutant concentration, and length of exposure time.

HEALTHY VEGETATION

In order to detect symptoms produced by any stress, whether natural or air pollutant, it is necessary first of all to know what healthy forest vegetation looks like. Not all healthy vegetation will look exactly like the common tree, shrub, and lichen species shown here, because foliar age, climate, and edaphic factors influence the color and form of leaves. Immature foliage, for example, is generally smaller, and its normal color and form are often different from those of mature foliage. Under normal conditions, leaf color of any species at a given site should be fairly uniform. The investigator should establish a base line for normal vegetation at each site.

CONIFEROUS SPECIES

Jack pine, lodgepole pine, white spruce, black spruce, balsam fir, and tamarack are the most common coniferous species in the boreal forest. **Jack pine** and **lodgepole pine** hybridize in a zone within the boreal forest in central and northwestern Alberta. Because pollutant and natural stress symptoms on jack pine, lodgepole pine, and their hybrids are usually very similar, these species have been treated as one. Mature needles of healthy pine foliage occur in pairs, are 2.5-7.5 cm long, uniformly dark green in color, straight or curved, and sometimes slightly twisted (Figs. 2 and 3). Healthy needles are normally retained on the tree for 3-5 years.

White spruce, black spruce, and **balsam fir** all have similar foliage. The branches bear needles singly along much of their entire length, and needles are normally retained from 5 to 8 years (Fig. 4). Mature needles are uniformly dark green and are normally straight to slightly curved with a prominent midvein (Fig. 5). Spruce needles are 1.2-2.5 cm long, four-sided in cross section, and easily rolled between the fingers, while balsam fir needles are 2.0-3.0 cm long, flat, and not easily rolled. The best diagnostic feature for differentiating black spruce from white spruce is the cone. Black spruce cones are egg-shaped (2.5 cm long) and are retained on the tree, while white spruce cones are cylindrical (2.5-7.5 cm long) and remain on the tree from only midsummer to midwinter. Except in the far north, black spruce is commonly found in wetlands and white spruce is found on the uplands.

Tamarack, or **eastern larch,** is also a common conifer in the lowlands. Its needles, which occur in clusters of 10-20, are quite small (about 2.5 cm long), slender, soft, and pale green; they turn yellow in autumn and drop off.

DECIDUOUS SPECIES

The most common deciduous species are balsam poplar, trembling aspen, and white birch. **Balsam poplar** leaves are oval, approximately 7.5-12.5 cm long, fine-toothed, and shiny green on the upper surface; on the lower surface they are whitish green and mainly hairless. They have a slightly less rounded base than trembling aspen leaves and gradually taper to a sharp tip (Fig. 6).

Mature foliage of **trembling aspen** is bright green on the upper surface, pale green on the lower, and always hairless. Leaf blades are circular in shape, approximately 4.0-5.0 cm in diameter, and fine-toothed with a short, pointed tip. The leaf stalk (petiole) is flat in cross section (Fig. 7).

White birch leaves are 7.5 cm long, more or less oval, sometimes triangular in shape, and often sharply double-toothed (Fig. 8). Mature leaves have uniformly bright green upper surfaces and slightly pale and hairy undersides. Mature bark is characteristically white with prominent lenticels (horizontal markings).

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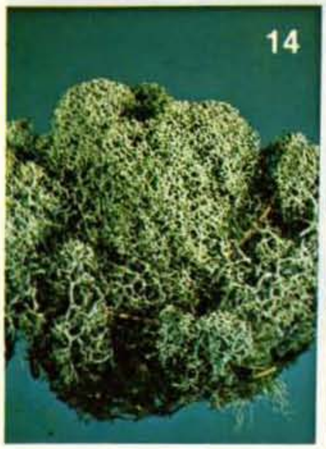

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UNDERSTORY SPECIES

Common woody and herbaceous understory species are numerous and diverse. **Willow** leaves are 7.5-10.0 cm long, relatively narrow (2.5 cm), usually fine-toothed, and tapered at both ends. Leaves have dark green upper and pale green lower surfaces (Fig. 9). **Green alder** leaves, which closely resemble white birch leaves, are somewhat sharp-toothed and broadly oval. They have dull green upper surfaces (Fig. 10) and hoary undersurfaces. **Chokecherry** has oval leaves (7.5-10.0 cm long) that are broadest in the middle. They are abruptly tapered at both ends, dull green on top, and finely toothed, each tooth ending in a straight, hairless point.

The normal, healthy conditions of **Labrador tea, prickly rose,** and **wild sarsaparilla** are shown in Figs. 11, 12, and 13, respectively.

GROUND COVER AND TREE LICHENS

Lichens and bryophyte species make up most of the ground cover. The predominant ground **lichens** are the reindeer (*Cladonia-Cladina* species) lichens. *Cladina alpestris*, a ubiquitous lichen in the boreal forest, is shown in Fig. 14, and a large thallus of *Peltigera aphthosa* is shown in Fig. 15. Lichen species are also commonly found inhabiting the branches and trunks of trees (corticolous lichens) (Fig. 17) and rock surfaces (saxicolous lichens). **Bryophytes,** which include feather mosses (Fig. 16), other mosses, and liverworts, are very conspicuous and normally constitute a considerable portion of the vegetative mat.

Suggested Reading

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HEALTHY VEGETATION (Figs. 2-17).

Fig. 2. Pine branch. **Fig. 3.** Close-up of pine needles. **Fig. 4.** White spruce branch. **Fig. 5.** Close-up of white spruce needles. **Fig. 6.** Upper leaf surface of balsam poplar. **Fig. 7.** Upper leaf surface of trembling aspen. **Fig. 8.** Upper leaf surface of white birch. **Fig. 9.** Upper leaf surface of willow. **Fig. 10.** Upper leaf surface of green alder. **Fig. 11.** Current and 1-year-old foliage of Labrador tea. **Fig. 12.** Prickly rose. **Fig. 13.** Wild sarsaparilla. **Fig. 14.** Ground-cover lichen—*Cladina alpestris.* **Fig. 15.** Ground-cover lichen—*Peltigera aphthosa.* **Fig. 16.** Ground-cover feather moss—mostly *Pleurozium schreberi.* **Fig. 17.** Tree lichens—*Bryoria* sp., *Hypogymnia physodes, Parmelia sulcata,* and *Usnea* sp.


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FOREST VEGETATION AND NATURAL STRESSES

Trees and herbaceous species are subject to many infectious and noninfectious stresses that are an integral part of the natural ecosystem. Many of these stresses cause symptoms that are similar to those produced by air pollutants. In diagnosing pollutant impact on a forest it is therefore imperative to recognize and identify the influence of natural stresses. Presented here are a few of the most common natural stresses that may cause visible symptoms similar to those produced by airborne pollutants. Just as the symptoms caused by pollutants can be similar to those caused by natural stresses, so can the symptoms produced by different natural stresses be similar. An attempt is made here, however, to provide enough information for the user to make a credible judgment on the cause of injury to forest vegetation, whether pollutants or natural stresses.

CLIMATE

Water availability, hail, temperature, and light are frequent causes of vegetation injury or mortality in the forest. Meteorological records or reports of special weather phenomena may help to accurately assess a climate-related incident. Because topography can modify the effects of climatic patterns, it must be taken into account in such assessments.

DROUGHT

Periods of little or no precipitation can result in severe drought conditions. Young plants display drought symptoms first because their root systems are not developed enough to supply water from deeper reserves or because their transpiration greatly exceeds their water absorption capacity. In coniferous seedlings the first symptom is wilting of foliage and new shoots. Severe wilting can be followed by general yellowing (chlorosis), then browning and necrosis (tissue death), and eventually death of the seedling (Fig. 18). Deciduous species respond similarly to water deficit (Fig. 19).

Drought injury can result in winter from excessive transpiration during brief periods of high temperatures when there is an inadequate supply of water from the frozen stem and root system. This can severely injure buds and generally results in lack of foliage the next growing season (Fig. 20). **Red belt** areas of native conifers (Fig. 21) are examples of winter drying by chinook winds in mountainous areas, especially on the eastern slopes of the Rocky Mountains. Red belt is caused by rapid extreme changes in temperature from below 0°C to 20°C. Most conifers are susceptible to red belt injury, which is signified by reddish brown foliage that tends to remain on the tree due to the lack of abscis-

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NATURAL STRESSES—CLIMATE. Drought, winter drying, flooding, natural senescence, frost, and temperature symptoms on forest vegetation (Figs. 18-33).

Drought: Fig. 18. Reddish brown discoloration of needles on a white spruce seedling. **Fig. 19.** Leaf necrosis of poplar. **Winter drying: Fig. 20.** Bud damage to aspen. The patchy foliage that occurs the following year can also be frost induced. **Fig. 21.** Red belt of lodgepole pine. **Flooding: Fig. 22.** Premature aging (senescence) of aspen foliage caused by flooding of a stand adjoining a black spruce wetland. **Natural senescence: Fig. 23.** Fall discoloration of aspen leaves prior to leaf drop. **Hail: Fig. 24.** Unidirectional damage to pine branches. **Frost: Fig. 25.** New foliar flush of pine showing first droop symptoms. **Fig. 26.** Needle injury on a new foliar flush of pine. **Fig. 27.** Partial necrosis of pine needles. **Fig. 28.** Injury on a new foliar flush of white spruce (young needles in final necrotic stage). **Fig. 29.** Desiccation and necrosis of an aspen leaf. **Temperature: Fig. 30.** Winter flecking on a pine branch, caused by reflected sunlight. **Fig. 31.** Close-up of winter flecking on pine needles. **Fig. 32.** Browning of white spruce foliage, caused by heat from a nearby forest fire. **Fig. 33.** Bleaching and brown discoloration of white spruce foliage caused by severe heat from a forest fire.


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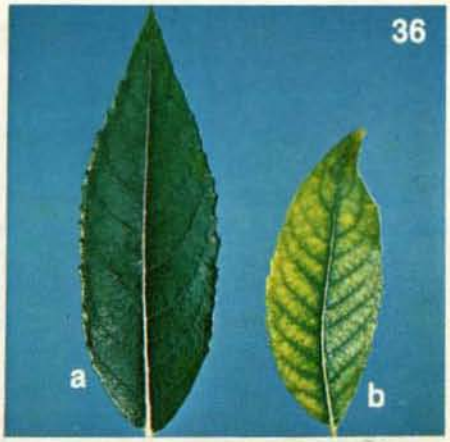
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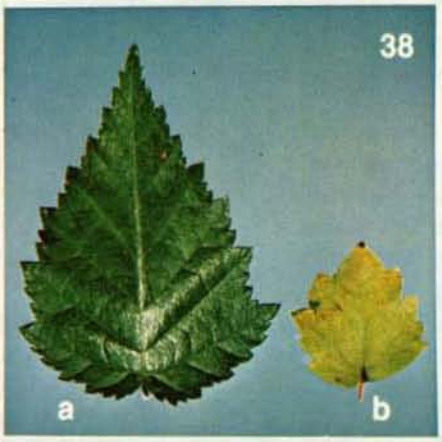
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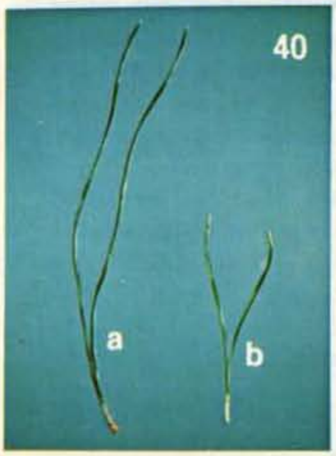
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sion layer formation. The cambium and buds are often killed during this process, and only partial foliar development occurs the next growing season. Repeated red belt injury has been known to kill trees.

EXCESSIVE MOISTURE

Much of the boreal forest is poorly drained. Excessive moisture can cause severe injury (foliar discoloration) to many forest species, mainly because of a lack of oxygen for the root system. Species such as black spruce and tamarack, however, can withstand excessive moisture for a considerable part of the year. Deciduous species on sites close to wetlands can develop flood tolerance but tend to have early foliar senescence when high water persists throughout the summer (Fig. 22). Foliar symptoms produced as a result of flooding are similar to those produced during fall senescence (Fig. 23). If flooding persists for several seasons, tree death occurs.

HAIL

Hail can damage forests by causing stem lesions, breaking crowns and branches, and defoliating trees (Fig. 24). Hail damage can usually be diagnosed because it is often unidirectional on stems or branches and its pathway can be easily discerned from the air. The injured foliage and branches may provide favorable conditions for diseases to infect the tree. Severe hailstorms can kill trees.

TEMPERATURE AND LIGHT

Extreme or rapidly fluctuating temperatures are common causes of forest injuries. Late spring and late summer frosts are the most common causes of frost damage to foliage, buds, and shoots. In conifers, wilting of young foliage is the first symptom of frost injury (Fig. 25) following a late spring frost. Wilting is generally followed by tissue discoloration and necrosis (Figs. 26-28). Clumping of aspen foliage can be caused by winter drying (Fig. 20) but may also result from frost damage, especially along the foothills. Low temperatures in winter may result in frost cracks in main stems.

In deciduous species, frost symptoms develop first on the leaf margin and progress toward the central portion of the leaf. Tissue necrosis caused by frost spreads rapidly, without any prolonged chlorosis (Fig. 29).

High temperatures combined with exposure of vegetation to bright sun can result in defoliation, leaf burn, or bark scorch. This kind of injury occurs where stand openings were made recently along roads or cut lines. Reflected sunlight is considered responsible for winter flecking of conifer foliage (Figs. 30 and 31).

Browning and bleaching of leaves from high temperatures associated with forest fires (Figs. 32 and 33) are sometimes similar to symptoms caused by air pollutants. Signs of fire or charred wood near the affected vegetation should identify fire as the cause.

NATURAL STRESSES—NUTRIENT DEFICIENCY. Nitrogen, potassium, phosphorus, iron, and sulfur deficiency symptoms on forest vegetation (Figs. 34-47). Note: With the exception of Fig. 45, all foliar symptoms shown here were produced on plants grown in greenhouse facilities under controlled conditions.

Nitrogen deficiency: Fig. 34. White spruce seedlings showing **(a)** normal growth and coloration and **(b)** a nitrogen deficiency. **Fig. 35.** Chlorosis of white spruce. **Fig. 36.** Willow leaves showing **(a)** normal growth and coloration and **(b)** a nitrogen deficiency. **Fig. 37.** Close-up of Fig. 36(b) showing chlorosis of willow. **Fig. 38.** Birch leaves showing **(a)** normal growth and coloration and **(b)** a nitrogen deficiency. **Fig. 39.** Close-up of Fig. 38(b) showing discoloration of a birch leaf. **Potassium deficiency: Fig. 40.** Pine needles showing **(a)** normal growth and coloration and **(b)** a potassium deficiency. **Fig. 41.** Stunted growth, distortion, and chlorosis of a new foliar flush of poplar. **Fig. 42.** Bleaching of birch. **Phosphorus deficiency: Fig. 43.** Uneven growth and discoloration of birch. **Iron deficiency: Fig. 44.** Yellowing of a new needle flush of pine. **Fig. 45.** Stunted growth and foliage discoloration of a pine seedling caused by a combination of nitrogen, potassium, and phosphorus deficiences. **Sulfur deficiency: Fig. 46.** Chlorosis of willow. **Fig. 47.** Light chlorosis of birch.


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NUTRIENT DEFICIENCY

A nutrient deficiency is a common natural stress in forest vegetation. The uptake and utilization of nutrients by plants can be affected by (1) absence of nutrients in an available form, (2) lack of soil aeration, (3) changes in soil pH that cause a change in nutrient solubility, (4) lack of soil moisture, and (5) lack of microbial activity needed for nutrient cycling.

Generally, nutrient deficiencies are difficult to detect because their symptoms are nonspecific; deficiency symptoms such as reduced growth rate and slight discoloration of foliage are not easily discerned. If a nutrient problem is suspected as the cause of forest injury, the foliage and soil should be chemically analyzed to confirm the diagnosis.

A **nitrogen deficiency** in conifers can cause stunted growth and chlorosis of the needles (Figs. 34 and 35). A nitrogen deficiency in deciduous species such as willow and birch also results in reduced leaf growth and chlorosis (Figs. 36-39).

Potassium deficiency symptoms in conifers appear first in young foliage. New growth is stunted and appears to lack normal chlorophyll development (Fig. 40). Similarly, in deciduous species a potassium deficiency results in stunted growth, distortion of foliage, and mild chlorosis or bleaching (Figs. 41 and 42).

A **phosphorus deficiency** also leads to stunting of foliage and retarded leaf development. Variegated leaves are often produced on deciduous plants as a result of phosphorus (Fig. 43) or other nutrient deficiencies. The intensity of color change is usually difficult to detect, however.

An **iron deficiency** is generally uncommon in the boreal forest but can produce chlorotic symptoms on young foliage (Fig. 44).

It is not uncommon for boreal forest species to show symptoms of combined nitrogen, phosphorus, and potassium deficiencies (Fig. 45). Such symptoms, which may be similar to individual nutrient deficiency symp-

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NATURAL STRESSES—DISEASES. Disease symptoms on forest vegetation (Figs. 48-62).

Fig. 48. Discoloration and needle cast on black spruce caused by snow blight. Injury is limited to branches covered by winter snow. **Fig. 49.** Spruce needle cast infection on older white spruce foliage. **Fig. 50.** Discoloration of current-year white spruce foliage caused by spruce needle rust. **Fig. 51.** Close-up of spruce needle rust pustules on white spruce. **Fig. 52.** Examples of (a) normal vs. (b) *Elytroderma* needle-cast-infected pine seedlings. **Fig. 53.** *Elytroderma* needle cast affecting only 1-year-old pine needles. **Fig. 54.** Black fruiting structures of *Elytroderma* needle cast on pine needles. **Fig. 55.** Yellow witches'-broom on white spruce, caused by dwarf mistletoe. **Fig. 56.** Injury to birch caused by birch leaf rust. **Fig. 57.** Willow leaf rust pustules on the undersurface of a willow leaf. **Fig. 58.** Leaf spot on poplar. **Fig. 59.** Shoot blight injury on aspen showing leaf discoloration, blackening, and typical hook formation. **Fig. 60.** Chlorotic pine foliage due to *Armillaria* root rot. **Fig. 61.** *Armillaria* root rot of a pine root system showing white mycelial felt that prevents normal transport of nutrients to the foliage. **Fig. 62.** Top dieback of a birch stand caused by an unknown root disease.


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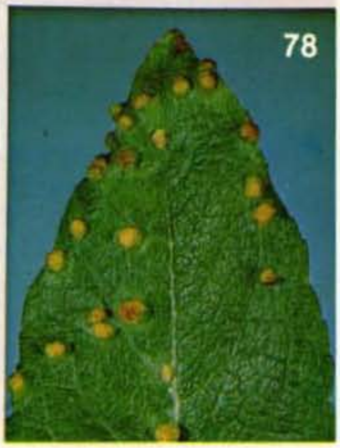
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toms, are most prevalent in young seedlings or actively growing tissues.

A **sulfur deficiency** in conifers results in reduced needle growth and intense chlorosis. In deciduous species it causes stunted growth and marginal and interveinal chlorosis (Figs. 46 and 47).

Other micronutrients such as copper, manganese, molybdenum, zinc, and boron are usually available in adequate amounts. **Boron** is perhaps worthy of note; its deficiency in forest tree species can be responsible for the rosetting of buds and injury to stem tips.

Suggested Reading

Hacskaylo, J., R.F. Finn, and J.P. Vimmerstedt. 1969. Deficiency symptoms of some forest trees. Ohio Agricultural Research and Development Centre. Wooster, Ohio. Research Bulletin 101.

Treshow, M. 1970. Environment and plant response. McGraw-Hill Book Co. Toronto, Ontario.

DISEASES

Many diseases induce physical symptoms similar to those produced by air pollutants. In the forest, most infectious plant diseases are caused by fungal pathogens. Infectious agents of lesser importance are nematodes, bacteria, viruses, and higher plant species such as mistletoe. Only brief coverage of tree and shrub diseases is given here, sufficient to indicate the variety of causal organisms and symptoms. Other texts, such as those listed as suggested reading, should be consulted for more detail. The diagnosis of most diseases involves recognizing the disease symptoms developing on leaves and verifying the presence of pathogens through microscopic examination.

In conifers, **snow blight** (Fig. 48), **needle cast** (Fig. 49), and **needle rust** (Fig. 50) cause foliar lesions and discoloration similar to those produced by heavy metals; these symptoms are followed by premature needle drop. The fungi responsible for these diseases are present in the needle tissues as fungal hyphae and sometimes as pustules (Fig. 51).

Some foliar diseases are systemic, invading cambium and apical tissues and causing severe injury to actively growing trees. The major systemic infections in the boreal forest are **Elytroderma** and **dwarf mistletoe.** *Elytroderma* of pine is caused by a fungal infection that ultimately results in stem deformation and needle mortality (Figs. 52-54). Dwarf mistletoe is a parasite that invades pine (and sometimes spruce) through the needles and moves into the bark and cambium. Many infected trees develop bushy or broomlike structures from which the mistle-

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NATURAL STRESSES—INSECTS. Insect symptoms on forest vegetation (Figs. 63-78).

Fig. 63. Needle defoliation of white spruce caused by the spruce budworm. **Fig. 64.** Aerial view of jack pine budworm injury to pine. **Fig. 65.** Close-up of jack pine budworm injury to pine. **Fig. 66.** Northern lodgepole pine needle miner entrance holes and injury on pine. **Fig. 67.** Spruce needle miner injury on white spruce. **Fig. 68.** White spruce needles wilting as a result of white pine weevil attack. **Fig. 69.** Pine needles dying as a result of lodgepole terminal weevil attack. **Fig. 70.** Spruce spider mite webbing and injury on white spruce. **Fig. 71.** Unknown defoliator insect injury on birch. **Fig. 72.** Injury to birch caused by the ambermarked birch leaf miner. **Fig. 73.** Injury to aspen caused by the cottonwood leaf-mining beetle. **Fig. 74.** Leaf miner injury on willow. **Fig. 75.** Injury on willow due to insect feeding or egg laying. **Fig. 76.** Injury on birch caused by a leaf-mining insect. **Fig. 77.** Leaf-rolling symptoms and skeletonized feeding injury on aspen caused by the early aspen leaf curler. **Fig. 78.** Injury on willow most likely caused by an *Eriophyes* gall mite.

toe plants obtain support, water, and most other nutrient requirements (Fig. 55).

Infectious diseases in deciduous trees also produce symptoms that can be mistaken for those caused by pollutants. **Rust**-infected leaves generally show a yellowish discoloration that leads to early senescence (Figs. 56 and 57).

A wide variety of other diseases such as **leaf spot, shoot blight,** and **powdery mildew** also invade tree leaves (Figs. 58 and 59). Symptoms range from irregularly shaped, discolored spots to complete necrosis. Shoot blight may be common following a wet spring; the symptoms are shriveling and blackening of the tender new growth (Fig. 59).

Root diseases may produce foliar symptoms somewhat similar to those produced by airborne pollutants. In conifers, foliar discoloration is generally the first obvious symptom of **Armillaria** root rot (Fig. 60) and is followed by wilting, drying, and necrosis from the reduction of water and nutrient transfer from the root system to the crown. Examination of the root collar often reveals resinosis and decay (Fig. 61). In deciduous species, root disease symptoms often begin with a gradual dieback of the uppermost foliage and branches that progresses downward until the entire tree dies (Fig. 62).

Suggested Reading

Bega, R.V. 1978. Diseases of Pacific coast conifers. United States Department of Agriculture, Forest Service. Agriculture Handbook 521.

Boyce, J.S. 1961. Forest pathology. McGraw-Hill Book Co. Toronto, Ontario.

Peterson, G.W. and R.S. Smith, Jr. 1975. Forest nursery diseases in the United States. United States Department of Agriculture, Forest Service. Agriculture Handbook 470.

Ziller, W.C. 1974. The tree rusts of western Canada. Environment Canada, Canadian Forestry Service. Ottawa, Ontario. Publication 1329.

INSECTS

Insect injury to vegetation may be distinguished from pollutant injury by the presence of the insect in one of its various life forms. The only problem is that some life forms might not be easily detected. In general, insects are restricted to the known range of hosts they attack, and some are confined to one specific host or group of hosts.

CONIFEROUS SPECIES

Defoliation of conifers is typical of the feeding damage caused by such insects as the **spruce budworm** (Fig. 63), **jack pine budworm** (Figs. 64 and 65), and various **sawfly species** attacking pine, spruce, tamarack, and balsam fir. Partially eaten needles left by these insects provide diagnostic clues. Pine and spruce foliage are frequently attacked by **needle-mining insects** (Figs. 66 and 67) that enter the needle and feed on the succulent inner tissues. Entrance and exit holes made by larvae, mined-out needles, and the presence of larvae are characteristic identifying features.

Leader shoots of spruce and pine are girdled and killed by **weevil larvae** (Figs. 68 and 69) that bore into them. **Gall midges** and **shoot-boring sawflies** may also cause damage to buds and shoots.

The **spruce spider mite,** barely visible to the naked eye, may cause severe injury to the foliage of spruce by sucking juices from the needle tissues. When the insect is abundant, symptoms of damage include silken webbing and yellowing of needles (Fig. 70).

DECIDUOUS SPECIES

On deciduous trees a wide variety of insect species may cause injury that ranges from partly chewed leaves (Fig. 71) to total defoliation by such notorious insects as the

forest tent caterpillar. Various **leaf-mining** and **leaf-skeletonizing species** are also common (Figs. 72-77).

Some **leaf-mining species** may cause green to brown blotches on leaves (Figs. 72, 74, and 75), while others may leave a narrow trail as they feed through the leaf (Fig. 76). Certain **leaf-roller species** curl the leaf and tie it with silk so as to provide a protective sheath in which to feed and rest (Fig. 77). Another common sign of insect and mite damage on foliage, buds, and shoots is **galls** These abnormal growths appear in various shapes, sizes, and colors. Because gall-forming insect and mite species are highly specialized, each produces a characteristic gall (Fig. 78) as a result of feeding behavior and secretions.

Some **bark beetle** and **wood-boring species** confine their attack to the bark, cambium, and outer sapwood layer, whereas others may penetrate deep into the wood. While doing so, some species act as carriers for disease-causing fungi, bacteria, or viruses. The **mountain pine beetle** and its blue-stain fungal associates are an example of a complex insect-fungus relationship that kills the host pine tree (Safranyik *et al.* 1974). **Dutch elm disease** is caused by a fungus whose spores are usually carried to healthy American elms by two bark beetles common in North America. Symptoms of the disease are wilting followed by yellowing, death of branches, and ultimately death of the tree.

Suggested Reading

Furniss, R.L. and V.M. Carolin. 1977. Western forest insects. United States Department of Agriculture, Forest Service. Miscellaneous Publication 1339.

Johnson, W.T. and H.H. Lyon. 1976. Insects that feed on trees and shrubs. An illustrated practical guide. Cornell University Press. Ithaca, New York.

Rose, A.H. and O.H. Lindquist. 1973. Insects of eastern pines. Environment Canada, Canadian Forestry Service. Ottawa, Ontario. Publication 1313.

Rose, A.H. and O.H. Lindquist. 1977. Insects of eastern spruce, fir and hemlock. Environment Canada, Canadian Forestry Service. Ottawa, Ontario. Forestry Technical Report 23.

Safranyik, L., D.M. Shrimpton, and H.S. Whitney. 1974. Management of lodgepole pine to reduce losses from the mountain pine beetle. Environment Canada, Canadian Forestry Service. Ottawa, Ontario. Forestry Technical Report 1.

FOREST VEGETATION AND POLLUTANT STRESSES

When any air pollutant impinges upon the forest, a number of factors come into play to determine what effect the pollutant will have on the vegetation. A wide range of effects is possible, depending upon the interaction of the biological characteristics of the vegetation species, the nature of the pollutant, and the environmental conditions.

BIOLOGICAL CHARACTERISTICS OF VEGETATION

The tolerance or sensitivity of vegetation to pollutants is dependent upon (1) genetic makeup; (2) age, health, vigor, and state of metabolic conditions; and (3) rate of pollutant uptake and accumulation as determined by species morphology and anatomy. The varying sensitivities of individual plants to pollutant injury may be due to differences in genetic constitution, which controls the biochemical and physiological tolerance for the pollutant. Foliage at different stages of development also may exhibit different degrees of sensitivity to the same pollutant. Old jack pine needles, for example, are more sensitive to chronic levels of SO_2 than are young but fully developed needles. An immature (tender) new flush, however, is more sensitive to SO_2 than older needles. Because of their high rate of metabolic activity, young but fully developed needles can assimilate more SO_2 than old and metabolically less active needles. A pollutant becomes toxic within the tissues once it accumulates beyond a certain level.

NATURE, CONCENTRATION, AND EXPOSURE TIME OF POLLUTANTS

The nature of a pollutant is defined by its chemical characteristics, its persistence, and the phytotoxicity of possible chemical transformations. The response of vegetation to air pollution depends upon the concentration of the pollutant and length of exposure time.

High concentrations of pollutants often produce an immediate and acute impact with some easily recognizable symptoms. Low concentrations, however, produce more-subtle or chronic effects that develop gradually and are not always readily identifiable. Vegetation can respond to pollutant emissions at individual or population levels. The impact at the individual level is generally caused by low levels of pollutants, whereas that at the population level is brought about by toxic levels. If the plants are exposed to a pollutant mixture, as is the case under field conditions, the total effect may be synergistic, additive, or antagonistic.

ENVIRONMENTAL CONDITIONS

Plant response to air pollutants is partially governed by a number of environmental factors such as ambient temperature, light, relative humidity, soil moisture, nutrient status, and time of year. In general, the environmental conditions that are most conducive to plant growth also produce the maximum air pollution response; in winter, when plants are dormant, air pollution injury is minimal. Other factors such as wind direction, wind speed, and temperature inversions are also important, for these ambient conditions determine the dispersal and dilution of the pollutants and the ability of the forest to act as a receptor.

Vegetation weakened by stresses such as adverse climatic conditions, a nutrient deficiency, or disease and insect disorders responds to air pollution much more readily and severely than healthy vegetation. Vegetation under stress prior to even mild air pollution episodes may not possess an adequate defense mechanism to protect itself against pollutant injury.

NATURAL GAS AND OIL INDUSTRY

Because fossil fuel deposits often contain large quantities of sulfur, their processing and refining to produce natural gas and petroleum products result in emissions containing considerable amounts of potentially harmful compounds. Emissions from oil sands plants and other petroleum industries consist mainly of sulfur dioxide and nitrogen oxides and small quantities of organic compounds, heavy metals, and particulate matter. Sulfur dioxide is also the major air pollutant in emissions from natural gas processing plants; small amounts of hydrocarbons, nitrogen oxides, and hydrogen sulfide are released as well.

Natural gas processing plants generally convert sulfur compounds into elemental sulfur or sulfuric acid, with varying degrees of efficiency. Depending upon the original levels of sulfur compounds and the efficiency of the sulfur extraction process, varying amounts of SO_2 are continually released into the environment. Intermittent release of large quantities of SO_2 can also occur as a result of various industrial activities or accidents such as emergency flaring, breakdown of sulfur extraction equipment, elemental sulfur fires, and gas and oil well blowouts that occasionally catch fire.

SULFUR DIOXIDE

Sulfur dioxide is the predominant air pollutant from the oil and gas industry and by itself produces a set of well-defined symptoms on forest species. Many of the photographs of SO_2 symptoms in this section come from vegetation affected by sulfur-block fire incidents in which SO_2 was the only emission involved.

Sulfur dioxide, as either a gas or one of its oxidized forms (sulfite and sulfate), is extremely soluble in water. It has been reported that SO_2 and its other forms are toxic to vegetation only when dissolved in aqueous solution. Recently it has been suggested that, given moist conditions, dissolved but undissociated SO_2 would likely be the most biologically active (phytotoxic) chemical form for plant injury. The concentration of this chemical form under normal conditions is about 1/1000 of the total SO_2 present in water.

PHYTOTOXICITY

Sulfur is an essential element for plant metabolism because it is an important component of amino acids, proteins, and some vitamins. In healthy vegetation, sulfur content varies from 500 to 14 000 ppm by dry weight, depending upon the species. Plant tissue sulfur levels below 250 ppm are considered critical, giving rise to deficiency symptoms and to the substitution of selenium (when available) for sulfur in amino acids and proteins. Part or all of the sulfur requirements of plants may be met by direct uptake of SO_2 from the atmosphere if it is present at a very low concentration; if the concentration of SO_2 increases beyond a certain critical level, photosynthesis, respiration, and other fundamental cellular processes are impaired. As the concentration of SO_2 and length of exposure time increase, the injury becomes irreversible and leads to death.

It is often assumed that there has been no injury to vegetation until visible symptoms of phytotoxicity develop. This can be misleading, however. In many greenhouse studies, for example, SO_2 was shown to have reduced the growth and yield before any visible symptoms appeared. It is now commonly believed that the initial injury takes place at the biochemical level (interference with photosynthesis, respiration, etc.) and progresses to the ultrastructural level (disorganization of cellular membranes responsible for controlling cellular and intracellular transport of nutrients and other metabolites) then cellular level (cell wall, mesophyll, and nuclei breakdown). Finally, visible symptoms develop (chlorosis and necrosis of foliar tissues). Because this handbook is intended to be a diagnostic tool for use in the field, the major emphasis here is on visible symptoms only.

The deposition of large quantities of SO_2 on soils can alter soil characteristics sufficiently to cause indirect injury to the vegetation growing there. Such plant injury or depressed growth results from (1) chemical acidification of soils, (2) soil nutrient impoverishment due to increased nutrient solubility and consequent leaching, (3) changes in soil microflora (responsible for nutrient cycling) due to increased acidity, and (4) release of phytotoxic elements under acidic conditions. For example, aluminum (normally present as aluminum silicate) and manganese become readily available to vegetation in acidic soil and are phytotoxic to many species.

The following table ranks the major boreal forest tree species by their sensitivity to SO_2 as indicated by visible symptoms.

Table 1. Ranking of boreal forest tree species by sensitivity to SO_2*

Highly sensitive	Moderately sensitive	Relatively tolerant
Alpine fir	Balsam poplar	Black spruce
Balsam fir	Jack pine	White spruce
Green alder	Lodgepole pine	
Tamarack	Trembling aspen	
White birch	Willow	

* Trees are listed alphabetically.

Depending upon its concentration and exposure time, SO_2 can cause a variety of visible symptoms on forest vegetation. These symptoms can be classified as acute, chronic, and transitory.

Acute injury occurs during the growing season at SO_2 levels of 0.25-0.30 ppm over varying lengths of time. On conifers, acute symptoms include the sudden and widespread chlorosis of older needles followed generally by brown discoloration, desiccation, and necrosis. In deciduous trees, SO_2 fumigation causes a wet appearance and light chlorosis of the undersurfaces of leaves, which is a result of leakage of cellular fluids through the cell walls. Upper surfaces do not show wetting because of their wax covering. Symptoms develop when the concentration of various ionic forms of SO_2 in the tissues reaches a level higher than that which can normally be assimilated by the plant metabolism. The initial chlorotic symptoms are similar to symptoms of natural senescence.

Chronic injury results from periodic fumigations of sensitive species with varying concentrations of SO_2 (0.10-0.25 ppm) over a period long enough to partially disrupt one or more metabolic processes. When such disruptions occur continuously over an extended period, chronic injury symptoms such as persistent chlorosis and stunted growth start to develop. In conifers, extensive chronic injury can result in premature needle drop. Similarly, in deciduous trees, such injury over the entire leaf surface can cause early foliar death.

Transitory symptoms are brought about by low levels of SO_2 (less than 0.30 ppm) over relatively short intervals. Such exposures cause temporary chlorosis. The foliage recovers fully within a matter of days in an SO_2-lean or SO_2-free environment. Transitory symptoms are a result of partial degradation of chlorophyll, but the metabolic processes responsible for chlorophyll production are not affected permanently.

SYMPTOMS ON CONIFEROUS SPECIES

In general, SO_2 produces similar symptoms on all conifers. For example, symptoms of acute SO_2 fumigations on white spruce (Fig. 94) and black spruce (Fig. 91) are similar to those produced on pine (Figs. 81 and 89).

Visible symptoms on forest species depend on the SO_2 impingement pattern and species sensitivity. In mixed stands, spruce trees, which are relatively tolerant to SO_2, will often remain unaffected even though pine and deciduous species show foliar discoloration (Fig. 79). Injury to older trees ranges from severe crown decline to complete tree mortality after recurrent attacks (Figs. 79 and 83).

Under acute SO_2 levels, current-year pine needles rapidly develop chlorosis (Fig. 80) followed by needle browning, desiccation, and necrosis (Fig. 81). Young seedlings can occasionally be killed by a single acute fumigation because of resulting drying and death of vital tissues (Fig. 82).

Acute SO_2 fumigation occurring immediately after spring flush can cause severe injury to new growth. The new tissue is very tender and growing rapidly (Fig. 84) and is thus extremely sensitive. If fumigation occurs before bud break, uninjured buds may break dormancy and unaffected new foliage will emerge (Figs. 88 and 89). In young mature needles, discoloration appears first at the tip and progresses toward the base (Figs. 85-87). All or part of the needle may be injured. Tissue chlorosis generally appears adjacent to the necrotic zone. Needles that are only partially affected by a single fumigation are subject to further injury by subsequent fumigations, and this results in the development of injury bands corresponding to different SO_2 episodes.

In trees with several years' foliage, the most sensitive tissue to an acute SO_2 fumigation is the new, tender foliage developing after spring flush. Next in sensitivity are the oldest needles, which are more susceptible than the younger but mature ones. The younger needles, because of their higher rate of metabolic activity, can assimilate more sulfur into their normal metabolism than the older needles with a much slower rate of metabolic activity. Because of these differing sensitivities, the oldest mature needles can drop prematurely, while the young ones remain nearly unaffected (Fig. 90). Conifers extensively affected by SO_2 exhibit both dead buds and premature needle drop (Fig. 91).

Occasionally conifer needles exhibit differential responses to chronic concentrations of SO_2 so that some needles are more stunted than the others. This is due to varying SO_2 concentrations and the diversion of nutrients from more affected tissues to less affected ones, which eventually results in uneven growth (Figs. 92 and 93). Another type of differential response is caused by exposure of a tree crown to SO_2 fumigations. That portion of the crown exposed to directional fumigation may develop more intense injury symptoms than the rest of the crown.

In chronic injury, visible symptoms are restricted to various degrees of persistent foliar chlorosis (Figs. 92 and 93). The foliage is not lost immediately, but normal growth and yield are reduced. Extensive chronic injury to conifers can cause a reduction in needle retention time. Vegetation exposed to nonpollutant stresses such as winter flecking (Figs. 30 and 31) can be predisposed to severe SO_2 injury.

SYMPTOMS ON DECIDUOUS SPECIES

After exposure of deciduous species to high concentrations of SO_2, symptoms of acute injury progress rapidly. Birch, one of the most SO_2-sensitive deciduous species, exhibits foliar symptoms ranging from light chlorosis to almost complete necrosis between veins (Figs. 95-98). The initial chlorotic symptoms of SO_2 exposure on poplar and willow leaves (Figs. 99 and 100) are similar to those on birch leaves in the initial stages of injury following acute or chronic fumigation.

The first visible symptoms of SO_2 exposure on deciduous species are wetting of the leaf undersurface and light chlorosis (Fig. 101). After prolonged fumigation with SO_2, the water-soaked appearance is followed by severe chlorosis and browning around the edges and between the veins (Figs. 102-106) and eventually by extensive discoloration (Fig. 107). Discoloration progresses rapidly and is accompanied by leaf curling and shriveling in response to the rapid drying of leaf tissues.

Well-formed buds rarely display SO_2 injury because of their protective scales. However, buds and young foliage can be injured if subjected to a severe fumigation a few days after the beginning of spring flush.

Visible symptoms of chronic SO_2 injury on deciduous foliage include chlorosis, which may be confined to a portion of the leaf (Fig. 102) or appears uniformly over the


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whole leaf surface (Figs. 99 and 100), and premature leaf drop.

Transitory SO_2 injury to deciduous species is exhibited by a very light flecking of leaf margins and the interveinal area. Such injury usually goes undetected unless base-line information on normal vegetation is well established. Vegetation can recover fully from transitory injury, provided that the ambient air is free of SO_2 after the initial fumigation.

Higher-plant species of ground cover exhibit symptoms of SO_2 injury (Figs. 108-110) that are similar to those produced on deciduous trees. These symptoms include chlorosis, wet appearance, curling, shriveling, browning, and total necrosis. Tree canopies often protect the understory from high concentrations of SO_2 originating from an emission source above canopy height. Depending upon the atmospheric conditions and stack height, SO_2 injury may show up only on the overhead tree species, only on the ground cover, or on both.

Suggested Reading

Hindawi, I.J. 1970. Air pollution injury to vegetation. United States Department of Health, Education, and Welfare. National Air Pollution Control Administration. Raleigh, North Carolina. Publication AP-71.

Jacobson, J.S. and A.C. Hill (eds.). 1970. Recognition of air pollution injury to vegetation: A pictorial atlas. Air Pollution Control Association. Pittsburgh, Pennsylvania. Informative Report 1.

Linzon, S.N. 1965. Sulphur dioxide injury to trees in the vicinity of petroleum refineries. Forestry Chronicle 41:245-247 and 250.

Linzon, S.N. 1978. Effects of airborne sulphur pollutants on plants. Pages 109-162 *in* Sulphur in the environment. Part II. Ecological impacts. J.O. Nriagu (ed.). J. Wiley and Sons Inc. New York.

Treshow, M. 1970. Environment and plant response. McGraw-Hill Book Co. Toronto, Ontario.

United States Department of Agriculture. 1973. Air pollution damages trees. Forest Service, Northeastern Area, State and Private Forestry. U.S. Government Printing Office. Washington, D.C.

HYDROCARBONS

Hydrocarbons are released from the natural gas and oil industry as liquid or gaseous aerial emissions or as accidental oil spills. Aerial emissions generally consist of uncom-

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POLLUTANT STRESSES—NATURAL GAS AND OIL INDUSTRY. Sulfur dioxide emission symptoms on coniferous vegetation (Figs. 79-94).

Fig. 79. Foliar discoloration of pine and aspen. The pine (center) displays considerable necrosis, the aspen (left) shows extensive foliar discoloration, while the white spruce (right) is unaffected. **Fig. 80.** Needle chlorosis on a pine shoot 1 hour after an acute fumigation. **Fig. 81.** Needle browning and shoot desiccation of pine 2 days after an acute fumigation (same shoot as in Fig. 80). **Fig. 82.** Total necrosis of a pine terminal bud after an acute fumigation. **Fig. 83.** Complete foliar necrosis of balsam fir. Note premature needle drop. **Fig. 84.** Light brown discoloration of a new foliar flush of black spruce. **Fig. 85.** Typical pine needle necrosis progressing from the tip back. **Fig. 86.** Partial necrosis of white spruce needles. **Fig. 87.** Pine needle discoloration progressing from the tip back. **Fig. 88.** Uninjured black spruce bud that flushed after a single fumigation. **Fig. 89.** Flushing of a pine terminal bud after a single acute fumigation. **Fig. 90.** Loss of older white spruce needles. **Fig. 91.** Bud and needle necrosis and premature needle drop on black spruce. **Fig. 92.** Persistent chlorosis of pine resulting in partially stunted growth. **Fig. 93.** Stunted growth of pine as a result of highly variable fumigations. **Fig. 94.** Acute fumigation symptoms on white spruce foliage.


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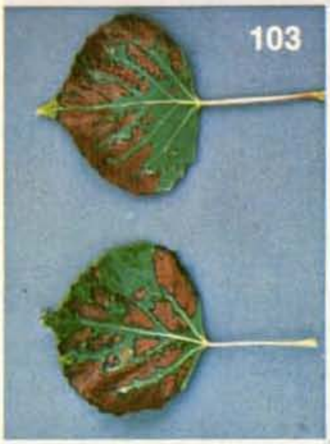
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busted hydrocarbons from processing and refining plants, cracking of fuels and condensates, line ruptures or pressure control valve malfunctions on high-pressure gas pipelines, and gas and oil well blowouts. Oil spills can result from pipeline breaks, valve failure, storage tank leaks, and other spills.

Coal-powered electric generators release not only SO_2, nitrogen oxides, and trace metals but also appreciable amounts of a variety of hydrocarbons.

LIQUID HYDROCARBONS

The phytotoxicity of most hydrocarbons released from the petroleum industry is related primarily to the carbon chain length. In general, light-weight hydrocarbons (13 carbons or less) are more phytotoxic than heavy-weight ones (more than 13 carbons) because of the relative ease with which the light-weight hydrocarbons can penetrate the waxy cuticle of leaves and buds. Emissions from the natural gas and oil industry contain different proportions of light and heavy hydrocarbons, depending upon the nature of the underground formation. Heavy-weight hydrocarbons are less volatile than the light-weight varieties, and their injury to vegetation is primarily due to the physical coating of plant surfaces, which inhibits stomatal gas exchange and transpiration processes.

The impact of aerial emissions of hydrocarbons on forest vegetation and soils depends on the time of year in which the emissions are released. During the growing season, from late spring to early fall, tree foliage (deciduous and coniferous) is the major receptor of hydrocarbons, protecting the main stems and ground-cover species. However, in late autumn before the snow falls and in early spring before leafing out, coniferous foliage, branches of deciduous trees, and ground cover (including bryophytes and lichens) are all affected. In the winter, heavy snow on the ground can protect the ground-cover plants and soils against relatively small quantities of aerial emissions of hydrocarbons, allowing time for some of the more toxic hydrocarbons to volatilize and an opportunity for clean-up operations.

Another major source of hydrocarbon injury to forest vegetation and soils is land spills of oil. In winter, large-volume oil spills usually penetrate the snow cover and seriously affect the ground-cover species. Sometimes the oil is even hot enough to melt the snow, which increases the potential for damage. Oil can be phytotoxic when it seeps into the root zone and penetrates vital cambial tissues. It disturbs the moisture regime, affects the microbial populations in the soil that are responsible for nutrient cycling, and causes changes in soil pH and aeration. In areas of heavy spills, the lack of aerobic conditions results in very slow breakdown of the hydrocarbons. The breakdown process can be accelerated by properly draining the oil puddles, cultivating the area to facilitate soil aeration for microbial activity, supplying additional mineral nutrients, and adjusting the soil pH by adding lime.

Symptoms on Coniferous Species: Hydrocarbon sprays from incomplete combustion or oil well blowouts cause the crowns of conifers to turn black (Fig. 111). Generally only the foli-

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POLLUTANT STRESSES—NATURAL GAS AND OIL INDUSTRY. Sulfur dioxide emission symptoms on deciduous vegetation (Figs. 95-110).

Figs. 95-98. Progressive injury to birch leaves. **Fig. 95.** Initial chlorotic symptoms. **Fig. 96.** Chlorosis advancing to water-soaked appearance. **Fig. 97.** Brown discoloration and necrotic symptoms. **Fig. 98.** Advanced necrotic symptoms. **Fig. 99.** Initial chlorotic symptoms on poplar. **Fig. 100.** Initial chlorotic symptoms on willow. **Fig. 101.** Wetting effect on the undersurface of an aspen leaf. **Fig. 102.** Marginal and interveinal leaf chlorosis on aspen. **Fig. 103.** Marginal and interveinal necrosis on aspen as a result of an acute fumigation. **Fig. 104.** Advanced marginal and interveinal injury on poplar **Fig. 105.** Acute necrosis symptoms on willow. **Fig. 106.** Varying degrees of necrosis on alder. **Fig. 107.** Nearly complete discoloration of poplar leaves—chlorosis followed by necrosis—as a result of an acute fumigation. Leaves had curled but were straightened to show the injury. **Fig. 108.** Acute symptoms on wild sarsaparilla. **Fig. 109.** Advanced acute symptoms on Labrador tea. **Fig. 110.** Symptoms on prickly rose.


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age directly exposed to the hydrocarbon spray gets coated (Fig. 112). Light-weight hydrocarbons cause rapid injury to vegetation, which results in defoliation within a few weeks (Fig. 113).

Light-weight hydrocarbons give an oily appearance to foliage (Fig. 114), whereas heavy-weight hydrocarbons leave a tarry coating (Figs. 115 and 116). Because heavy-weight hydrocarbons cannot easily penetrate into buds, new growth often results the following growing season (Fig. 115) and may be adequate for the tree's survival. Surface lesions and an oily sheen appear on coniferous needles (Fig. 117). Chlorotic symptoms start at the point of contact and are evident first on the younger needles (Figs. 118 and 119). If the vegetation is heavily coated by light-weight hydrocarbons, chlorosis is followed by general necrosis (Fig. 120) and eventually tree mortality. Dead tissues appear first at the needle tip and spread gradually to the needle base (Fig. 121). Such tissue necrosis is followed by premature needle drop and tree death (Fig. 122).

Hydrocarbons, especially the light-weight type, can severely curtail tree growth by penetrating the phloem conducting tissues and vital cambium tissues of the main stem (Fig. 123). Usually the side of the tree trunk facing the source receives the hydrocarbon deposit (Fig. 124a), and the side away from the source remains clean (Fig. 124b). Partial exposure of the tree trunk and foliage to hydrocarbons may result only in a temporary slowing of the growth rate.

Other Species in Coniferous Stands: When hydrocarbon deposits saturate the soil organic layer, they are able to move down to the roots of shallow-rooted ground vegetation. The infiltrated chemicals can be so toxic to the roots that the ground vegetation dies (Fig. 125). Tree lichens are also very sensitive to hydrocarbon sprays. Visible external symptoms are an oily coating and brown discoloration of the thallus (Fig. 126). Sometimes, because of penetration of the oil, the dead lichen thallus does not become dry and brittle.

Symptoms on Deciduous Species: Deciduous foliage is more sensitive to hydrocarbons than coniferous foliage, perhaps because conifers have a well-developed cuticle. The symptoms associated with hydrocarbon release onto deciduous foliage include curling, distortion, and discoloration and occur within a few hours of application (Figs. 127-130). Defolia-

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POLLUTANT STRESSES—NATURAL GAS AND OIL INDUSTRY. Light- and heavy-weight hydrocarbon emission symptoms on coniferous vegetation (Figs. 111-126).

Fig. 111. White spruce crown coated with heavy-weight hydrocarbon spray released from a flare stack. **Fig. 112.** White spruce branch heavily coated with heavy-weight hydrocarbons. **Fig. 113.** White spruce crowns coated with light-weight hydrocarbons released from a flare stack. Note chlorosis and partial foliar drop, especially of older needles, due to hydrocarbon phytotoxicity. **Fig. 114.** White spruce branch showing partial necrosis as a result of a light-weight hydrocarbon spray. Note the hydrocarbon spotting on the needle surfaces. **Fig. 115.** One-year-old pine foliage coated with heavy-weight hydrocarbons. Current-year flush is free of coating, indicating that the incident occurred before bud break. **Fig. 116.** White spruce branch coated with heavy-weight hydrocarbons. **Fig. 117.** Injury pattern and oily sheen on pine needles revealed after removal of a light-weight hydrocarbon film. **Fig. 118.** Chlorotic symptoms first appearing on younger needles and tips of white spruce after a light-weight hydrocarbon spray. **Fig. 119.** Chlorotic symptoms on a tamarack shoot in response to a light-weight hydrocarbon spray. **Fig. 120.** Advanced necrosis on white spruce as a result of a heavy coating with light-weight hydrocarbons. **Fig. 121.** Partial necrosis on balsam fir needles after exposure to a light-weight hydrocarbon spray. Note the hydrocarbon spotting on the needle surfaces. **Fig. 122.** Premature needle drop and bud death on white spruce as a result of a light-weight hydrocarbon spray. **Fig. 123.** Cambial, phloem, and outer sapwood tissues of a white spruce trunk destroyed by the penetration of light-weight hydrocarbons through the bark. **Fig. 124.** Light-weight hydrocarbon coating of a tree trunk **(a)** on the side facing the emission source and **(b)** on the side away from the emission source. **Fig. 125.** Ground-cover vegetation totally destroyed as a result of a heavy spray of light-weight hydrocarbons. Note needle drop on the ground. **Fig. 126.** Injury (brown discoloration) to a tree lichen thallus caused by a spray of light-weight hydrocarbons.


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tion occurs a few weeks later. Hydrocarbons cause localized injury to only the leaf area that is exposed (Fig. 131). Light-weight fractions spread evenly over the leaf surface to produce a distinct shiny appearance (Figs. 132-134). Symptom development often corresponds with the pattern of hydrocarbon deposition on the leaf surface. Hydrocarbons generally produce a curling and twisting response only in the foliar tissues (Figs. 135 and 136). Certain herbicides, on the other hand, can produce curling and twisting in all tissues, including twigs and branches.

Sprays of heavy-weight hydrocarbons, unless they are concentrated or have light-weight fractions, usually do not cause permanent injury to the buds, phloem, or cambium (Fig. 137). The buds produce new growth the next growing season. Mixtures of light- and heavy-weight hydrocarbons can permanently damage plant tissues by penetrating through the bud scales into the cambial layer (Fig. 138).

Other Species in Deciduous Stands: Ground vegetation is usually protected from hydrocarbon sprays by the tree canopy and is affected only if the spray is heavy enough to fall through the canopy or if the wind carries the spray near the ground. Most ground-cover species of higher plants respond to hydrocarbons much the same way as deciduous tree foliage. Light-weight hydrocarbons produce chlorosis and brown discoloration followed by marginal necrosis and leaf distortion (Figs. 139 and 140). Symptoms become more pronounced with time (Fig. 141). Eventually tissues above ground, including those of lichens and bryophytes, are severely affected (Fig. 142). If the hydrocarbons do not penetrate the root zones, new growth of higher plants may reappear after some time. The phytotoxic effects of an oil spill are persistent, and the vegetation will not reestablish until the hydrocarbons have been broken down by microbial action or removed by other means.

GASEOUS HYDROCARBONS

Ethylene, acetylene, propylene, and other related hydrocarbon compounds are secondary products of the incomplete combustion of natural gas, oil, coal, and other hydrocarbon resources. They may be present in variable amounts in gaseous emissions from natural resource extraction industries. Because the phytotoxicity of these gases is similar and because ethylene is the most common to occur around industrial areas (polyethylene manufacturing, coal- and gas-powered electric generators, etc.), ethylene will be discussed as typical of all of these gaseous hydrocarbons.

Ethylene is a normal product of plant metabolism, and at low concentrations it plays an important role in fruit ripening and

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POLLUTANT STRESSES—NATURAL GAS AND OIL INDUSTRY. **Light- and heavy-weight hydrocarbon emission symptoms on deciduous vegetation (Figs. 127-142).**

Fig. 127. Darkened and curled willow foliage as a result of a light-weight hydrocarbon spray. **Fig. 128.** Close-up of darkened and curled willow foliage shown in Fig. 127. **Fig. 129.** Acute foliar injury on willow following a light-weight hydrocarbon spray. **Fig. 130.** Acute curling and browning on birch after a light-weight hydrocarbon spray. **Fig. 131.** Dark necrotic tissues on aspen at the points of major contact following a light-weight hydrocarbon spray. **Fig. 132.** Oily sheen and injury on aspen from a light-weight hydrocarbon spray. **Fig. 133.** Progressively more severe injury symptoms on aspen from the light-weight hydrocarbon incident mentioned in Fig. 132. **Fig. 134.** Injury symptoms beginning to develop on poplar 1 hour after a light-weight hydrocarbon spray. **Fig. 135.** Curling, darkening, and oily sheen on alder as a result of a light-weight hydrocarbon spray. **Fig. 136.** Willow foliage after a light spray of heavy-weight hydrocarbons. **Fig. 137.** Aspen trunk lightly coated with heavy-weight hydrocarbons. Note the unaffected green cambium in the abraded area. **Fig. 138.** Aspen bark coated with a mixture of light- and heavy-weight hydrocarbon spray. Note the penetration into the cambium. **Fig. 139.** Discoloration of prickly rose foliage 1 week after a light-weight hydrocarbon spray. **Fig. 140.** Chlorotic and necrotic response of wild sarsaparilla 1 week after a light-weight hydrocarbon spray. **Fig. 141.** Chlorotic and curling symptoms on ground-cover vegetation (mainly grasses and woody shrubs) 1 week after a heavy spray of light-weight hydrocarbons. **Fig. 142.** Dead ground-cover vegetation 1 year after the spraying mentioned in Fig. 141.

aging. However, at concentrations above 25 ppb for 48 hours it can have a deleterious effect on the growth of many agricultural species and is considered an air pollutant. Although ethylene is often present in the atmosphere near large urban areas at levels exceeding 100 ppb, acute injury from ethylene is not very common. Some symptoms have been induced under laboratory conditions, but very little is known about ethylene's effects on vegetation in the field. If natural resource-extraction industries are located in the immediate vicinity of forested areas, ethylene and its analogs may have a marked effect on vegetation growth. Ethylene is known to accelerate the process of aging by reducing growth and by causing chlorosis, necrosis, and possibly abscission of foliage. Symptoms usually appear on the older growth first and develop slowly.

COAL EMISSIONS

The large deposits of coal in western Canada are another important hydrocarbon resource. Even though most of the coal is exported, a considerable amount is burned in the prairie region to power electric generators. The airborne emissions include hydrocarbons, SO_2, fly ash, nitrogen oxides, and trace metals such as arsenic, cadmium, lead, nickel, vanadium, and mercury. Coal dust in the vicinity of mining operations can cause physical injury to foliage by plugging stomata and thereby reducing the gas exchange capacity. The impact on forest vegetation of emission elements such as SO_2 and trace elements is discussed on pages 19-23.

Suggested Reading

Alberta Environment and University of Calgary. 1975. Conference on the environmental effects of oil and salt water spills on land. Banff, Alberta. Nov. 6-7, 1975.

Hindawi, I.J. 1970. Air pollution injury to vegetation. United States Department of Health, Education, and Welfare. National Air Pollution Control Administration. Raleigh, North Carolina. Publication AP-71. Pages 32-33.

SALTWATER SPILLS

Saline water is one of the major byproducts of the oil and gas industry in western Canada. Millions of barrels of salt water are produced annually by conventional extraction techniques for natural gas and oil, and production is gradually increasing as the older wells are partially depleted of oil and the oil formations are infiltrated by saline water.

The extracted salt water is routinely returned through saltwater disposal wells to the formations from which it was produced, but because of the size and nature of such operations, accidental saltwater and oil spills are unavoidable. Spills occur through pipeline ruptures caused by corrosion, excess pressure, or disturbance and through leakage of pressure control valves.

PHYTOTOXICITY

Sodium chloride (NaCl) is the major component of the oil- and gas-field brine that can cause severe damage to vegetation and soils. The phytotoxicity of NaCl results mainly from elevated levels of chloride in plant tissues. Foliar tissues are such effective accumulators of chloride that the chloride concentration in the leaves may be several times higher than that of the surrounding soil.

Problems associated with saltwater spills on land generally persist much longer than those from oil spills, probably because soil microorganisms can attack and degrade oil, but the salt cannot be broken down.

SYMPTOMS ON CONIFEROUS SPECIES

Unlike sulfur, salts accumulated in plant tissues cannot be adequately assimilated by normal metabolism and therefore result in rapid injury. Discoloration due to salt toxicity develops first on the current and 1-year-old needles. The degree of foliar discoloration (light pink to deep magenta) is related to the aging. However, at concentrations above 25 ppb for 48 hours it can have a deleterious effect on the growth of many agricultural species and is considered an air pollutant. Although ethylene is often present in the atmosphere near large urban areas at levels exceeding 100 ppb, acute injury from ethylene is not very common. Some symptoms have been induced under laboratory conditions, but very little is known about ethylene's effects on vegetation in the field. If natural resource-extraction industries are located in the immediate vicinity of forested areas, ethylene and its analogs may have a marked effect on vegetation growth. Ethylene is known to accelerate the process of aging by reducing growth and by causing chlorosis, necrosis, and possibly abscission of foliage. Symptoms usually appear on the older growth first and develop slowly.

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Coniferous trees affected by saltwater spills eventually display reddish brown or magenta crowns (Figs. 143 and 144). These symptoms initially appear near the top of the tree and gradually move downward. The current and 1-year-old spruce needles first become chlorotic, then turn brown (Fig. 145), intensifying to a reddish brown or magenta color (Figs. 144 and 146). If salt levels in the soil become very high, even the older needles that accumulate salts much more slowly become affected.

Salt phytotoxicity symptoms on pine needles are similar to those on spruce (Figs. 147 and 148). If the uptake of chloride is low, the buds may remain unaffected and flush during the next growing season. If high salt levels persist in the soil, however, new foliage will show injury symptoms starting at needle tips (Fig. 149).

Some injury to branch and stem cambium is common after saltwater spills (Fig. 150). Chloride seems to accumulate in the cambium and adjacent tissues, causing disruption in water conduction and eventual tree mortality.

SYMPTOMS ON DECIDUOUS SPECIES

In general, deciduous species respond to salt injury faster than conifers. The first external symptom that develops on birch after salt injury is leaf tip and marginal chlorosis that advances rapidly inward to the central axis (Fig. 151). If the salt toxicity is severe, chlorosis intensifies until the leaves become necrotic (Figs. 152 and 153). In aspen, leaf tips and margins first become slightly chlorotic then turn a dark green color, which produces a water-soaked appearance (Fig. 154). As the toxicity advances, the affected areas become bright yellow (reflecting the zone of salt accumulation) and eventually develop necrosis (Fig. 155) and curling (Fig. 156). Such symptom development is often followed by premature leaf drop. High salt concentrations can also kill buds and cambium, preventing any new growth the following year. Tree mortality from salt toxicity is common in areas of saltwater spills.

Normal fall discoloration of deciduous foliage may be similar to that caused by salt injury. Salt-killed foliage of some deciduous species may remain attached to the branches over the winter period, whereas after normal autumn senescence, leaves form an abscission layer and drop.

OTHER SPECIES

Ground-cover species of higher plants, ground lichens, and bryophytes are also subject to saltwater toxicity and show symptoms similar to those described for deciduous tree species. Severe spills result in brown or reddish brown discoloration of almost all ground-cover species (Figs. 157 and 158).

Because of their location, lichens on tree trunks and branches escape direct salinity effects and thrive quite normally on dead trees. The ground lichens and bryophytes, however, can be severely affected. In fact, the pathway of saltwater movement in a forest can often be delineated by the pattern of affected ground-cover foliage. This is mainly because spills follow downslope movement, and once the chloride ions penetrate the soil they do not disperse laterally to any great extent. This is especially true in clay soils.

Suggested Reading

Alberta Environment and University of Calgary. 1975. Conference on the environmental effects of oil and salt water spills on land. Banff, Alberta. Nov. 6-7, 1975.

Foster, A.C., M.A. Maun, and D.P. Webb. 1978. Effects of road salt on eastern white cedar. Environment Canada, Canadian Forestry Service, Great Lakes Forest Research Centre. Sault Ste. Marie, Ontario. Information Report O-X-277.


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OTHER EMISSIONS

ELEMENTAL SULFUR

In western Canada, sulfur is often present in appreciable quantities in hydrocarbon and mineral resources such as natural gas (except arctic deposits), conventional and oil sands petroleum deposits, coal, and various ore bodies. Western coal is lower in sulfur than the eastern deposits. During the extraction and refining processes sulfur is normally recovered in a molten form that is solidified as elemental sulfur and stored in large blocks.

Drift of sulfur particles from solidifed blocks and sulfur dust produced during the process of loading elemental sulfur into rail cars can adversely affect surrounding vegetation and soils. The sulfur blocks are not subject to dissolution by rain, because elemental sulfur is highly insoluble in water. Sulfur oxidation by bacterial action on the surface of the blocks can yield water-soluble compounds, which are transported to the adjacent areas in runoff water. The pH of such runoff and of nearby water bodies can be highly acidic (pH 2-3) and can have a detrimental effect on vegetation and soil chemistry. The acidic material in transit through the soil may solubilize various elements such as aluminum and magnesium, which in themselves can be phytotoxic.

Normally, vegetation occupying low-lying areas is affected most by acidic runoff. In the boreal forest, this involves black spruce and tamarack stands. Conifers subjected to either elemental sulfur drift or highly acidic water display symptoms of chlorosis (Figs. 159 and 160) and premature defoliation (Fig. 160). These symptoms are similar to those produced by SO_2, as discussed earlier.

Ground-cover species with shallow roots are very susceptible to injury from excess sulfur and high acidity and often show toxicity symptoms first. A yellow layer of elemental sulfur is often seen in low-lying areas around sulfur piles and can cause severe injury to the ground cover (Fig. 161). Entrapment of elemental sulfur dust and impoundment and treatment of precipitation runoff from sulfur piles may be an effective way to minimize plant injury.

FLARE PITS AND WELL BLOWOUTS

Other important sources of airborne emissions from the oil and gas industry are flare pits and natural gas and oil well blowouts. These emissions may contain a mixture of phytotoxic compounds, usually sulfur gases, hydrocarbons, and saline water. Emissions from well blowouts are released under considerable pressure and can occasionally catch fire, converting hydrogen sulfide to SO_2.

Vegetation injury can range from light (reversible) to severe (irreversible). Light injury may be due to light coating of foliage with hydrocarbons, blowouts without fire, or incidents during the winter when the vegeta-

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POLLUTANT STRESSES—NATURAL GAS AND OIL INDUSTRY. Saltwater spill symptoms on forest vegetation (Figs. 143-158).

Fig. 143. Reddish brown discoloration of a white spruce crown. **Fig. 144.** Magenta discoloration of dead or dying pine crowns. **Fig. 145.** Brown discoloration of a black spruce branch. **Fig. 146.** Magenta discoloration of current-year black spruce foliage. **Fig. 147.** Magenta discoloration on pine. **Fig. 148.** Close-up of magenta discoloration on pine needles. **Fig. 149.** Magenta discoloration of previous year's black spruce foliage. Current-year growth is starting to show injury symptoms at the needle tips. **Fig. 150.** Death of cambium and sapwood tissues of a pine stem. Note the absence of green cambium under the bark. **Fig. 151.** Initial discoloration pattern on birch. **Fig. 152.** Advanced symptoms on birch. **Fig. 153.** Necrosis on willow. **Fig. 154.** Initial stage of injury on aspen. Note tip and marginal water-soaked appearance. **Fig. 155.** More advanced toxicity symptoms on aspen. Note chlorosis and necrosis that progress toward the central portion of the leaf. **Fig. 156.** Chlorosis followed by necrosis and leaf curling on poplar. **Fig. 157.** Discoloration of Labrador tea. Symptoms move toward the leaf base, indicating the zone of salt accumulation. **Fig. 158.** Dead ground-cover vegetation (mainly grasses and woody shrubs).


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tion is mostly in the dormant stage. Severe injury takes place when emissions occur on a large scale during the active growing season and when blowouts catch fire, converting the less phytotoxic hydrogen sulfide to the more phytotoxic SO_2.

Continuous emissions (SO_2 and incomplete combustion products of hydrocarbons) from flare pits near large oil batteries can cause severe injury to adjacent forest vegetation (Fig. 162). The pattern of such injury is influenced by the direction and speed of prevailing winds. Tree saplings and ground cover are deleteriously affected in areas of heavy impingement by emissions at ground level. The symptoms produced on vegetation (Figs. 163 and 164) are similar to those described earlier for SO_2 (pages 19-23). Branch lichens, the most sensitive indicators of SO_2 pollution, must be examined in these areas because they usually will be the first species to display injury symptoms.

ACID MISTS

Occasionally, sulfur dioxide and nitrogen oxides in the emissions from the oil and gas industry can react with moisture to form acid mist. Hydrochloric acid is also used in oil and gas wells to dissolve some of the limestone formation and sometimes to clean wells. As a result of accidental well blowbacks, hydrochloric acid may be released into the atmosphere as a mist that can injure vegetation and soils. Acids can cause physical injury on the leaf surface or can enter the foliage through the cuticle and stomata, causing dissolution of vital mesophyll and other tissues.

On conifers one of the earliest symptoms developed from exposure to acid mist is chlorotic mottling at the points of contact (Fig. 165). These areas can rapidly turn into brown necrotic tissues (Fig. 166). On deciduous species, mild sulfuric acid mist can cause slight discoloration of the foliar tissues (Figs. 167 and 168). Droplets containing strong acids cause the rapid formation of necrotic spots at points of contact (Figs. 169 and 170). Young foliage appears to be highly sensitive to strong acid mists and becomes desiccated, necrotic, and often distorted (Figs. 171 and 172).

Suggested Reading

Jacobson, J.S. and A.C. Hill (eds.). 1970. Recognition of air pollution injury to vegetation: A pictorial atlas. Air Pollution Control Association. Pittsburgh, Pennsylvania. Informative Report 1.

United States Department of Agriculture. 1973. Air pollution damages trees. Forest Service, Northeastern Area, State and Private Forestry. U.S. Government Printing Office. Washington, D.C.

POLLUTANT STRESSES—NATURAL GAS AND OIL INDUSTRY. Other emission (elemental sulfur, flare pit, well blowout, and acid mist) symptoms on forest vegetation (Figs. 159-172).

Elemental sulfur: Fig. 159. Chlorotic symptoms on black spruce as a result of highly acidic runoff water from sulfur piles. **Fig. 160.** Severe yellowing of young white spruce foliage and initiation of premature defoliation. **Fig. 161.** Ground-cover vegetation (mainly grasses and woody shrubs) killed by highly acidic runoff water from sulfur piles. **Flare pit and well blowout: Fig. 162.** Conifers killed by sulfur and other gases emitted from the flare pit in the foreground. **Fig. 163.** White spruce seedling foliar injury caused by emissions from a well blowout that caught fire. **Fig. 164.** Pine seedling killed by emissions from a well blowout that caught fire. **Acid mist: Fig. 165.** Discoloration of pine needles caused by hydrochloric acid droplets. Note localized injury at the point of contact. **Fig. 166.** Hydrochloric acid mist symptoms on white spruce. **Fig. 167.** Light bleaching of aspen caused by a mild sulfuric acid mist. **Fig. 168.** Light discoloration on aspen showing the sulfuric acid spray pattern. **Fig. 169.** Hydrochloric acid injury on poplar at the point of contact. **Fig. 170.** Close-up of hydrochloric acid injury on poplar at the point of contact. **Fig. 171.** Curling of new birch foliage as a result of exposure to a mild hydrochloric acid spray. **Fig. 172.** Close-up of hydrochloric acid discoloration on birch. The leaf had curled but was straightened to show the injury.

METAL MINING AND SMELTING INDUSTRY

The continued expansion of the base metal mining and smelting industry carries considerable potential for emissions that can damage northern forest ecosystems. Because the nickel-copper-zinc ore bodies in western Canada occur naturally as sulfides, the smelting and other metallurgical processes employed release into the environment considerable quantities of SO_2, trace elements such as zinc, copper, nickel, lead, arsenic, mercury, and cadmium, and other particulate matter.

Heavy-metal particulates can cause injury to vegetation by forming a film of particulate matter on foliar surfaces or by becoming embedded in the cuticle and stomata. This embedded material, which is difficult to remove by washing, can interfere with gas exchange processes, light availability, rate of photosynthesis, and transpiration. Additionally, heavy metals in aerosol form can be absorbed by the foliage.

Smelter emission injury to vegetation is generally quite different from injury attributed to SO_2 alone. In areas close to the source, metal pollutants produce lesions or mottling on needle surfaces. The injury is more prominent on the side facing the emission source.

The combined effects of some heavy metals and SO_2 on vegetation and soil chemistry may be additive or synergistic. In soils the acidity contributed by SO_2 can solubilize many heavy metals that are normally chelated in the soil surface organic matter and thus make them more readily available to uptake by vegetation and the subsequent blockage of key metabolic processes.

Sulfur is normally cycled within the forest ecosystem, and incoming pollutant sulfur can also be cycled. Heavy metals, however, are cumulative because they are nonbiodegradable. Although some metals are essential in trace amounts, small excesses can be poisonous.

Soil made sterile through the addition of excess sulfur can be rendered productive with reasonable economy by chemical treatment such as liming. Areas exposed to uncontrolled smelter emissions for any length of time soon become devoid of vegetation and difficult to reclaim. Liming can decrease heavy metal toxicity of soils by reducing metal availability to plants.

PHYTOTOXICITY

The effects on forest vegetation of emissions containing SO_2 and heavy metals from smelters may be immediate and acute or long term and chronic, depending on the concentration and kind of pollutant. Forest species can respond to SO_2, heavy metals, and other emissions at the individual or population levels. Effects at the individual level, the more common, result from comparatively low concentrations, and effects at the population level are brought about by highly toxic levels of emissions.

Species respond differently to increased levels of smelter emissions and in their ability to develop a tolerance. Revegetation of areas contaminated by heavy metals generally depends upon the evolution of tolerant species. Tolerance may be due to the ability of species to avoid metals in the environment or to true resistance in their metabolic processes.

SYMPTOMS ON VEGETATION WITHIN A SPRUCE COMMUNITY

In general, low concentrations of smelter emissions reduce growth and yield without producing any visible symptoms of injury for several years. High concentrations of smelter emissions, even on an intermittent basis, can cause visible injury to vegetation

(Fig. 173). At first the injury is spotty and may not be readily identifiable from the air. Crowns of conifer trees in an area showing partial forest decline display chlorosis (Fig. 174), then premature needle drop. If an area is frequently fumigated by high concentrations of smelter emissions, symptoms of acute injury such as chlorosis, necrosis, and premature needle drop may result throughout the impingement zone (Fig. 175). When exposed to toxic levels of smelter emissions over many years, an area may become completely denuded (Fig. 176). Toxic levels of heavy metals and SO_2-caused acidity in the soils have rendered impossible or uneconomical the reestablishment of forest species around Sudbury, Ontario.

In spruce, the older foliage is always the first to show symptoms of smelter emission toxicity. However, if the lower branches are protected by snow cover during the winter, then the upper branches will bear more severe symptoms of toxicity (Fig. 177) because they are directly exposed to emissions throughout the year. On older needles, chlorosis and necrosis develop first at the tip, then gradually progress to the needle base (Figs. 178 and 179). Young needles, because of their higher rate of metabolic activity, can assimilate more SO_2 into their metabolism than the older ones before showing symptoms of toxicity. Where severe fumigations have occurred, young seedlings become as chlorotic as the older ones and eventually die (Fig. 180).

Black spruce is generally more resistant to smelter emissions than white spruce but displays general chlorosis and defoliation when exposed to toxic concentrations for an extended period (Fig. 181). The side of the tree exposed to the prevailing winds exhibits the maximum air pollutant injury (Fig. 182), with chlorotic symptoms appearing first on the older needles on the exposed side (Fig. 183). As these symptoms intensify, progressive necrosis starts at the needle tip (Figs. 185 and 186). Needles drop prematurely, and even younger needles display symptoms (Fig. 184). In areas where heavy metal contamination has moved into the mineral soil or root zones, premature needle drop and toxicity symptoms are common even on current-year growth (Fig. 187). The current-year growth becomes stunted and chlorotic before it drops.

Epiphytic lichens are capable of taking up sulfur from SO_2 and large amounts of trace elements. In areas subjected to frequent smelter emissions, these pollutants can virtually wipe out epiphytic lichen populations, leaving only remnants (Fig. 188).

SYMPTOMS ON VEGETATION WITHIN A PINE COMMUNITY

Lodgepole and jack pines are more sensitive to smelter fumigations than either white or black spruce. Crown deterioration in pine forests is quite common in areas frequently exposed to smelter emissions, although individual trees vary in sensitivity to smelter emissions (Fig. 189). If severe fumigations continue over a considerable length of time, pine will display acute injury symptoms (Fig. 190), with needle tips showing the first necrotic symptoms (Figs. 191 and 192). As on spruce, necrotic symptoms gradually spread to the base of the needle before it drops prematurely. Necrosis is mostly attributable to the extent of SO_2 fumigation.

If the fumigations are not severe enough to kill the buds, the trees will flush the following spring; but the older needles, because of high sensitivity to smelter emissions or because they have been fumigated for a longer time, may show severe discoloration and eventually drop off (Figs. 193 and 194). Some needles may show bands of irregular discoloration due to the combined effects of SO_2 and heavy metals (Fig. 195).

If the fumigations continue after spring bud break, new growth is stunted, chlorotic, and necrotic. Uneven growth of pine needles is frequently observed in the air pollution impingement areas around smelters and is caused by intense exposures at different stages of needle development. On vegetation close to the source, smelter emissions produce lesions or mottling on needles (Figs. 196-198).

Lichens inhabiting the branches and trunks of pine trees near smelter emissions are


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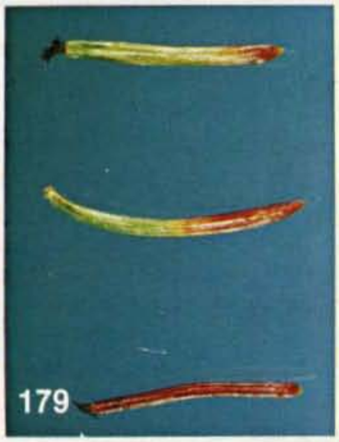
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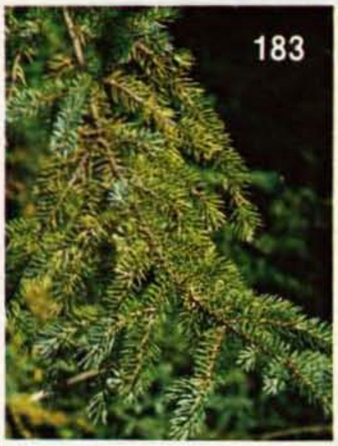
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subject to severe degradation (Fig. 201). Because of their direct exposure to aerial emissions, they are much more sensitive to air pollutants than are the ground lichens.

Soils heavily contaminated by smelter emissions also provide a hostile environment for plant growth. The fairly long root network of a healthy pine seedling is shown in Fig. 202. In contaminated soils, seedlings invariably have stunted root systems with few or no secondary roots (Figs. 203 and 204). This is especially true of shallow-rooted species that are in direct contact with emission elements in the upper layers of contaminated soil. Poor root development brought about by trace element toxicity in such soils prevents any regeneration of forest species.

FLUORIDE EMISSIONS

In forest areas exposed to high levels (acute concentrations) of fluoride emissions (from aluminum smelters and the phosphorus and fertilizer industry), pine needles may exhibit spectacular tip burn that rapidly extends toward the needle base (Figs. 199 and 200). This injury appears first on young tissues or current-year needles as chlorosis at the tip that later turns reddish brown. The older conifer needles are comparatively resistant to fluoride injury. Occasionally, bands of severe discoloration may appear at irregular intervals (Fig. 200). Low levels (chronic concentrations) of fluoride emissions, on the other hand, have been shown to cause a reduction in retention of 2-year-old needles on black and white spruce.

SYMPTOMS ON VEGETATION WITHIN A DECIDUOUS COMMUNITY

In general, the foliage of deciduous species such as birch, aspen, and poplar shows symptoms of smelter emission injury much more readily than coniferous species. Deciduous species are not as susceptible to severe injury, however, because the foliar retention, or exposure time, is only 4-6 months compared to 4-6 years for conifers.

Birch is generally the most sensitive deciduous species. Moderately high concentrations of smelter emissions invariably cause acute injury, which appears as severe foliar discoloration (Fig. 205). Advanced injury symptoms are generally preceded by interveinal and marginal wet appearance and mild chlorosis. After multiple fumigations, the foliage turns necrotic and then falls prematurely (Fig. 206). The necrotic symptoms on such foliage are shown in Fig. 207.

Aspen foliage responds to smelter emissions initially by developing interveinal chlorosis (Fig. 208). After repeated exposures this is followed by tissue necrosis (Figs. 209 and 210). Poplar behaves similarly to birch and aspen (Figs. 211 and 212). As a result of necrotic injury, leaves become very dry and

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POLLUTANT STRESSES—METAL MINING AND SMELTING INDUSTRY. **Nickel-copper-zinc smelter emission symptoms on vegetation within a spruce community (Figs. 173-188).**

Fig. 173. General forest decline. **Fig. 174.** Partial decline of a forest stand due to gaseous (SO_2) and heavy metal emissions. **Fig. 175.** Severe decline of a forest stand as a result of acute fumigations with SO_2 and exposure to heavy metal particulates. **Fig. 176.** Denuded forest and ground-cover vegetation in the immediate vicinity of a metal smelter. **Fig. 177.** Severe defoliation of the upper branches and discoloration of the lower branches of a white spruce. **Fig. 178.** Severe discoloration of white spruce needle tips. **Fig. 179.** White spruce needle injury. Symptoms start at the needle tip and progress toward the base. **Fig. 180.** Total necrosis of a white spruce seedling grown in a highly contaminated area. **Fig. 181.** Severe discoloration of a black spruce crown. **Fig. 182.** Severe injury on the side of a black spruce crown facing the smelter. **Fig. 183.** Discoloration of older foliage on black spruce indicates first injury symptoms. **Fig. 184.** Intensification of symptoms on older foliage of black spruce and premature needle drop. **Fig. 185.** Initiation of needle tip necrosis on black spruce as a result of acute concentrations of smelter emissions. **Fig. 186.** Intensification of necrotic symptoms on black spruce and premature drop of older needles. **Fig. 187.** Needle loss and severely injured current-year needles on black spruce indicate probable soil contamination. **Fig. 188.** Dead or severely degraded tree lichens in an area heavily impinged by smelter emissions.


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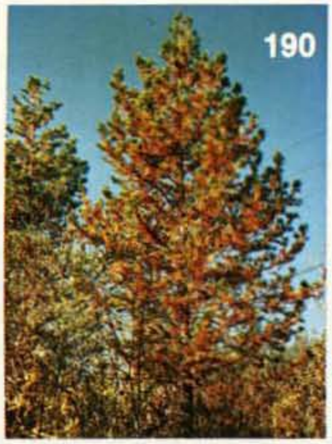
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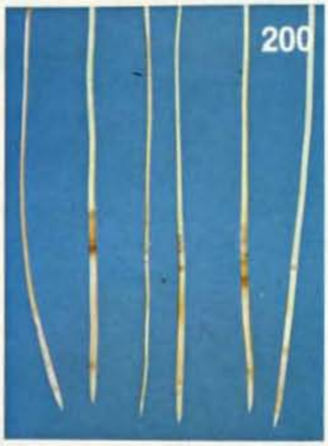
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brittle before being shed. Since air pollutants such as SO_2 and heavy metals do not initiate the formation of an abscission layer, even the dried, necrotic leaves remain attached to the branches for a considerable length of time before they drop. Because of their protective scales, buds remain unaffected by an occasional moderately severe fumigation incident or several mild ones and will flush during the next growing season. A single acute fumigation during the spring bud break will affect only the fully emerged leaves; there is no appreciable effect on the foliage that subsequently flushes (Fig. 211).

Symptoms of chlorosis and necrosis produced on willow leaves tend to be irregular in pattern (Fig. 213). Willow, however, is not as sensitive to smelter emissions as birch, aspen, poplar, and alder. Alder produces marginal and interveinal discoloration in response to smelter emissions (Fig. 214).

Because of their shallow roots and direct contact with accumulated toxic elements in the top organic layer, ground-cover species of higher plants are either killed or affected deleteriously by smelter emissions over extended periods of time. Labrador tea, one of the more sensitive ground-cover species, develops necrotic areas on the foliage tips in response to smelter emissions (Fig. 215). Necrosis eventually extends to the stem. The development of these symptoms on the current-year foliage is preceded by premature drop of the previous year's leaves (Fig. 216).

FLUORIDE EMISSIONS

Fluoride emissions from aluminum smelters and fertilizer plants cause a variety of symptoms on deciduous species. The most common pattern is a light green, water-soaked appearance followed by tip and marginal leaf necrosis that eventually spreads to the whole leaf. When fluoride concentration in plant tissues accumulates beyond a certain critical level, it can cause mottling or necrotic banding at the point of accumulation.

BRYOPHYTES AND LICHENS

Bryophytes and lichens are effective indicators of smelter pollution. In heavily impinged areas, rock outcrops that are normally inhabited by lichens become denuded (Fig. 217). Similarly, soils that were once rich with lichens and bryophytes become bare

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POLLUTANT STRESSES—METAL MINING AND SMELTING INDUSTRY. Nickel-copper-zinc smelter emission symptoms on vegetation within a pine community (Figs. 189-198 and 201-204). Figs. 199 and 200 show fluoride emission (aluminum smelter) symptoms. Seedlings in Figs. 202-204 were grown under greenhouse conditions using uncontaminated and heavy-metal-contaminated soil obtained from field locations.

Fig. 189. Pine crowns under stress. Note the differences in sensitivity of various trees. **Fig. 190.** Acute SO_2 fumigation injury on pine. **Fig. 191.** Acute SO_2 fumigation symptoms on pine needles showing necrosis developing from the tip back. **Fig. 192.** Close-up of acute SO_2 injury on pine needles. **Fig. 193.** Chlorotic injury on pine as a result of frequent exposures to smelter emissions. **Fig. 194.** Irregular pollutant symptoms on a pine seedling as reflected in uneven needle growth. **Fig. 195.** Close-up of pine needles showing bands of different degrees of discoloration. **Fig. 196.** Varying degrees of pine needle response. The pine branch with the least number of needles was from an area close to the smelter and the one with the most needles was from a more distant site. The lesions were caused by heavy metal injury. **Fig. 197.** Directional mottling response on pine needles facing (a) toward the stack and (b) away from the stack. **Fig. 198.** Close-up of mottled pine needles illustrated in Fig. 197(a). **Fig. 199.** Symptoms of fluoride (aluminum smelter) injury on pine foliage. Note severe discoloration of needle tips. **Fig. 200.** Symptoms of fluoride (aluminum smelter) injury on pine needles. Early stages of symptom development occurs on the needle tips (Fig. 199). The banding symptoms shown here indicate more severe injury. **Fig. 201.** Tree lichens on a pine tree showing degradation and depletion. **Fig. 202.** Healthy pine seedling with a full network of roots. **Fig. 203.** Injured pine seedling grown in heavy-metal-contaminated soil showing stunted roots and little lateral root development. **Fig. 204.** Dead pine seedling that had been grown in heavy-metal-contaminated soil. Note lack of root elongation and lateral root development.


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when subjected to long-term smelter emissions (Figs. 218 and 219). Such soils often become unfit to support most vegetation.

Sensitive lichen species inhabiting tree trunks and branches become severely degraded (Fig. 220) and depleted after long exposure to smelter emissions, even at low concentrations.

Suggested Reading

Foy, C.D., R.L. Chaney, and M.C. White. 1978. The physiology of metal toxicity in plants. Annual Review of Plant Physiology 29:511-566.

Hutchinson, T.C. (ed.). 1975. International conference on heavy metals in the environment—symposium proceedings. Volume II. Toronto, Ontario. Oct. 21-31, 1975. Institute for Environmental Studies, University of Toronto. Toronto, Ontario.

Jacobson, J.S. and A.C. Hill (eds.). 1970. Recognition of air pollution injury to vegetation: A pictorial atlas. Air Pollution Control Association. Pittsburgh, Pennsylvania. Informative Report 1.

Sidhu, S.S. 1978. Patterns of fluoride accumulation in forest species as related to symptoms and defoliation. Proceedings of the 71st annual meeting of the Air Pollution Control Association, Houston, Texas. Air Pollution Control Association. Pittsburgh, Pennsylvania. Paper 78-24.7

Treshow, M. 1971. Fluorides as air pollutants affecting plants. Annual Review of Phytopathology 9:21-44.

POLLUTANT STRESSES—METAL MINING AND SMELTING INDUSTRY. **Nickel-copper-zinc smelter emission symptoms on vegetation within a deciduous community (Figs. 205-220).**

Fig. 205. Acute symptoms on birch foliage. **Fig. 206.** Partial defoliation of birch due to successive emission exposures. **Fig. 207.** Interveinal and marginal leaf chlorosis and necrosis on birch. **Fig. 208.** Interveinal chlorosis on aspen leaves 1 day after exposure to smelter emissions. **Fig. 209.** Interveinal and marginal necrosis on aspen after exposure to high concentrations of smelter emissions. **Fig. 210.** Close-up of interveinal necrosis on aspen. **Fig. 211.** Symptoms on poplar foliage after a single acute exposure to emissions during bud break. Note the lack of symptoms on leaves that emerged after the incident. **Fig. 212.** Progression of symptoms on poplar. Note irregular pattern of symptom development. **Fig. 213.** General necrotic symptoms on willow. **Fig. 214.** Interveinal and marginal discoloration on alder. **Fig. 215.** Necrosis on Labrador tea leaf tips. **Fig. 216.** Current-year foliar injury and loss of 1-year-old leaves on Labrador tea. **Fig. 217.** Denuded rocks and completely depleted lichens. **Fig. 218.** Complete depletion of mosses in an area severely impinged by smelter emissions. **Fig. 219.** Lack of ground-cover vegetation as a result of severe contamination. Note dead needles fallen from affected trees. **Fig. 220.** Severely degraded tree lichens.


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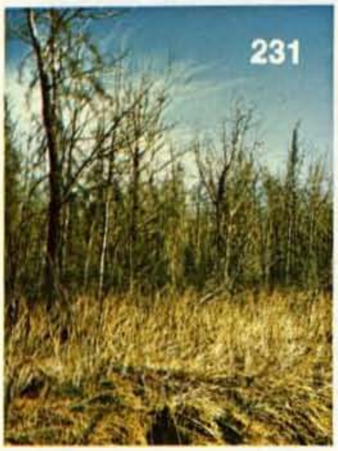
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OTHER MINERAL INDUSTRIES

Aerial emissions from cement production, potash mining and refining, and stockpiling of calcareous and siliceous materials contain particulates that can have a detrimental effect on vegetation and soils.

CEMENT INDUSTRY

Portland cement production involves quarrying of limestone, feldspar, shale, and clay. These materials are then crushed, screened, mixed with gypsum, and processed to form cement. The principal emission during processing is cement dust released from kilns; the dust contains calcium, potassium, and sodium oxides and smaller amounts of magnesium, manganese, and sulfur. Calcium oxide is the largest constituent. Because of the large volumes of parent materials used in the kilns, extremely efficient electrostatic precipitators are required to reduce particulate emissions.

Cement dust can affect vegetation directly, indirectly through soil contamination, or both ways. Very fine dust particles can coat foliar surfaces (Figs. 221-223), thereby plugging stomata and reducing transpiration and gas exchange capability. Growth is impaired, mainly because of the reduction in photosynthetic activity. Long exposures of foliage to cement dust can cause premature foliar drop. Frequent rains, however, reduce such direct effects by washing off at least some of the deposited dust (Fig. 223).

Cement dust may also injure the higher-plant understory and lichens and bryophytes. The reduced number of ground-cover species and depauperate ground and tree lichens in such areas are probably due to the effects of cement dust.

Cement dust indirectly affects vegetation by influencing soil chemistry. Because the dust is alkaline, it can shift soil pH toward the basic side. This encourages the growth of calciphile species and limits others, such as conifers, that grow better in acidic soils. Large trees, because of their deeper root systems, are not affected as severely as the young, shallow-rooted species. In calcareous soils, cement dust has little or no effect, and consequently there is no shift in the vegetation species that normally grow there.

Suggested Reading

Treshow, M. 1970. Environment and plant response. McGraw-Hill Book Co. Toronto, Ontario. Pages 369-373 (dusts).

POLLUTANT STRESSES—OTHER MINERAL INDUSTRIES. Cement dust, salts, and calcareous material emission symptoms on forest species (Figs. 221-234).

Cement dust: Fig. 221. Coating of white spruce needles. **Fig. 222.** Heavily coated willow leaf. **Fig. 223.** Coated aspen leaf with dust partially washed off by rains. **Salts from the potash industry: Fig. 224.** Deposition of sodium and potassium salts on soil surface. **Fig. 225.** Chlorotic and necrotic symptoms on willow. **Fig. 226.** Interveinal and marginal chlorosis of Manitoba maple foliage. **Fig. 227.** Marginal necrosis on aspen. **Fig. 228.** Close-up of marginal necrosis on aspen. **Fig. 229.** Branch tip dieback and proliferation of lateral buds on aspen. **Fig. 230.** Close-up of lateral bud proliferation on aspen caused by dieback of branch tips. **Drift from storage piles of calcareous materials: Fig. 231.** Forest stand mortality caused by a heavy coating of gypsum. **Fig. 232.** Death of a white spruce as a result of gypsum dust coating foliage and stems. **Fig. 233.** Main stem of a tree coated with calcareous material. **Fig. 234.** Dead white spruce needles resulting from the deposition of gypsum dust.

POTASH INDUSTRY

The potash mining and refining industry in Saskatchewan produces large quantities of aerial emissions containing mostly potassium and sodium chlorides in the ratio of 3:1. Aerial emissions take the form of salt particles that originate from the drying stacks during the refining process. A visible layer of white potassium and sodium salts sometimes accumulates on soil surfaces (Fig. 224) around processing plants. In general, such areas support little or no vegetation. Saltwater sprays are also quite common from such operations.

Phytotoxicity is believed to be due mainly to an excess of chloride, sodium, and potassium ions. Generally, deciduous species appear to be more sensitive to chloride salts than conifers, as pointed out on page 31. This is probably because deciduous species accumulate toxic levels of these salts in their tissues at a faster rate than conifers. The following table, based on field observations and elemental analyses on vegetation samples from central Saskatchewan, shows relative sensitivities to salt emissions of the predominant species.

Table 2. Species sensitivity to salt emissions from the potash industry

Species	Sensitivity
Manitoba maple	High
Poplar	High
Caragana	High
Willow	Medium
Elm (American)	Medium
Scots pine	Low
Colorado blue spruce	Low

Injury symptoms directly attributed to salt emissions include interveinal and marginal chlorosis (Figs. 225 and 226). At a high level of salt accumulation these symptoms are followed by the development of marginal necrotic tissues (Figs. 225, 227, and 228) and premature leaf drop (Fig. 229). The dieback of branch tips (Fig. 229) results in proliferation of lateral buds and formation of broom-like structures (Figs. 229 and 230).

STORAGE PILES OF CALCAREOUS MATERIALS

Certain industrial operations require storage piles of calcareous, siliceous, and other materials, generally in the form of particulate matter or powder. When blown or washed away into forested areas in large enough quantities, these materials can cause severe phytotoxicity. A common example is gypsum dust that has drifted from storage piles. The vegetation injury observed in such areas is mostly due to coating of leaf surfaces with gypsum or other such materials. Coating of leaf surfaces and plugging of stomata can retard growth and eventually kill vegetation (Figs. 231 and 232). Tree stems and foliage noticeably coated with calcareous or other such materials in the vicinity of storage piles (Figs. 233 and 234) leave no doubt as to the cause of vegetation decline.

PULP AND PAPER INDUSTRY

The chemical conversion of wood chips into cellulose fibers and the refining and drying required to make paper results in a wide range of aerial emissions, which vary according to the process used for pulping. Two wood digestion methods are normally employed: the acid sulfite process and the kraft, or alkaline, process. The major emission from the acid sulfite process is SO_2. The kraft process releases appreciable amounts of hydrogen sulfide (H_2S), methyl mercaptan, and dimethyl sulfide as well as limited amounts of SO_2, sodium hydroxide, and ammonia; it therefore can cause a more serious air pollution problem in the surrounding areas than the acid sulfite process. Emissions may contain some or all of these substances and various products of their interactions; for example, ammonium salts and sodium hydroxide can interact to form blue plume, or smoke. In western Canada, the kraft process is most commonly used for producing paper because of its suitability for coniferous trees of the boreal forest.

SYMPTOMS ON LICHENS

The vegetative response to pulp mill emissions varies according to the composition of emissions and the vegetation types. When tree lichens are exposed to pulp mill emissions they exhibit symptoms of degradation similar to those caused by natural deterioration. The three major types of tree lichens are foliose (leaflike) (Figs. 235 and 237), fruticose (branchlike) (Figs. 238 and 239), and crustose (crustlike). Because of their large surface area and consequently high pollutant uptake, fruticose lichens are more sensitive to industrial airborne emissions than foliose or crustose lichens.

An example of a healthy foliose lichen (*Hypogymnia* species) is shown in the upper part of Fig. 235. Partially and fully degraded lichens (*Parmelia* species) (Figs. 236 and 237) occur as a result of exposure to pulp mill emissions containing H_2S and SO_2. A pinkish discoloration (Fig. 237) occurs during the advanced stage of degradation.

After continuous exposure of fruticose lichens such as *Usnea* species to pulp mill emissions containing sulfur gases, the network of highly functional fine branches (Fig. 239a) becomes severely degraded (Fig. 239b). At this stage, the lichens become discolored and appear compacted (Figs. 238 and 239b); the green color in Figs. 238 and 239b is due to algae growth on air-pollutant-damaged tissues. When severely degraded, lichens lose their structural strength and ability to cling to trees; only a few remnants may be seen (Figs. 188 and 201).

Normal ground lichens such as the leaflike *Peltigera* species turn chlorotic when exposed to pulp mill emissions (Fig. 240). They become brown or necrotic and disintegrate (Fig. 241) after continuous exposure. In general, depauperate ground and tree lichens are found in heavily polluted areas.

SYMPTOMS ON CONIFEROUS SPECIES

Most pulp mills in the boreal region are located near spruce-pine forests; pine is used here to exemplify symptoms produced by all conifers in response to pulp mill emissions.

Pine trees subjected to pulp mill emissions over extended periods of time often display a sparse crown (Fig. 242). Foliage becomes chlorotic (Fig. 243), needle growth is stunted, and needles drop prematurely (Figs. 244 and 245). In heavily fumigated areas, acute injury symptoms (Fig. 245) appear on needles of all ages that remain on the trees and are more intense on older needles (Fig. 246). The most common symptom of consistent and moderately heavy exposures to emissions containing sulfur gases is the development of chlorosis that gradually progresses from the needle tip to the base


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(Fig. 246). Such foliar symptoms are more intense on older needles than on younger ones (Fig. 247). Since pulp mill emissions contain sulfur gases plus several other pollutants, chlorotic bands occasionally are produced (Fig. 248). Sometimes sprays of alkaline materials in the emissions are deposited as residues on the needle surfaces, resulting in some discoloration at the point of contact (Figs. 249 and 250). It is common for pulp mill emissions to kill trees, especially in areas often exposed to emissions during the active growing season.

Suggested Reading

Carlson, C.E. 1974. Sulphur damage to Douglas-fir near a pulp and paper mill in western Montana. United States Department of Agriculture. Forest Service, Northern Region. Division of State and Private Forestry. Missoula, Montana. Report 74-13.

POLLUTANT STRESSES—PULP AND PAPER INDUSTRY. Emission symptoms on forest vegetation (Figs. 235-250).

Fig. 235. Normal appearance of foliose tree lichens (mostly *Hypogymnia* sp.). **Fig. 236.** Partially degraded foliose tree lichens (mostly *Parmelia* sp.). **Fig. 237.** Fully degraded foliose tree lichens (mostly *Parmelia* sp.). Note the slightly pink coloration, an indication of lichen degradation. **Fig. 238.** Degraded fruticose tree lichens (*Usnea* sp.). **Fig. 239.** Examples of **(a)** normal and **(b)** degraded fruticose tree lichens (*Usnea* sp.). **Fig. 240.** *Peltigera aphthosa*, a leaf-like ground lichen, displaying chlorotic symptoms. **Fig. 241.** Shriveled, brown, necrotic remnants of the ground lichen *Peltigera aphthosa.* **Fig. 242.** Partially defoliated pine crowns. **Fig. 243.** Severe chlorosis and necrosis of pine needles. **Fig. 244.** Lack of pine needle growth and retention. **Fig. 245.** Acute injury on pine. Note specks of emission residue on needles. **Fig. 246.** Chlorosis and necrosis on pine progressing from needle tip to needle base. **Fig. 247.** Necrosis of 1-year-old pine needles, with current-year needles relatively unaffected. **Fig. 248.** One-year-old pine needles showing bands of green and chlorotic tissues. **Fig. 249.** Light chlorosis on pine needles caused by the accumulation of alkaline residues. **Fig. 250.** Close-up of pine needles in Fig. 249 showing light chlorosis caused by the accumulation of alkaline residues.


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STATIONARY COMBUSTION ENGINES

Stationary combustion engines are used mostly for compressing natural gas, pumping natural gas and oil through pipelines, and generating electricity. The hydrocarbons in the natural gas, oil, diesel oil, or coal used to power the high-temperature engines produce emissions containing nitrogen oxides, partially combusted hydrocarbons, sulfur gases, and small quantities of carbon monoxide (CO).

At combustion temperatures higher than 3500°C some of the nitrogen in the air is oxidized to form nitrogen oxide (NO). As much as 40% of the total NO is then further oxidized within 1.5 km of the source to form nitrogen dioxide (NO_2) by photochemical reactions involving sunlight and hydrocarbons. NO_2 interacts photochemically to generate ozone (O_3) and peroxyacetyl nitrate (PAN).

NITROGEN OXIDES

Nitrogen oxides are probably the major pollutants from stationary combustion engines and can have phytotoxic effects on forest areas. NO_2 is a fairly common nitrogen oxide that can cause considerable injury to forest vegetation.

Young conifers subjected to moderately high concentrations of nitrogen oxides develop necrotic lesions on the needles or needle tip burning. Sometimes the initial symptoms appear as a ring of white markings close to the base of the needles (Fig. 251). With further fumigation, general bleaching occurs, and the affected tissues gradually turn necrotic (Fig. 252). Acute concentrations of NO_2, on the other hand, cause rapid necrosis of older needles from the tip back and general chlorosis of younger needles (Figs. 253 and 254).

In deciduous species, NO_2 initially causes nonspecific chlorosis, browning, or bleaching between the leaf veins, especially near margins (Figs. 255-257 and 259). These symptoms are followed by more intense discoloration or necrosis that spreads through the leaves in the form of irregular spots or general tissue collapse (Figs. 258 and 260). Tissue collapse first appears as water-soaked, collapsed areas, which later dry out and turn brown. In alder, severe interveinal chlorosis precedes necrosis, which is exemplified by a reddish brown discoloration (Fig. 261). Normally, mature leaves are more sensitive to nitrogen oxides than younger ones. Moist conditions appear to enhance the symptoms. Upon reaction with water on or within the leaf surfaces, NO_2 is converted to toxic compounds such as nitrous and nitric acids, caus-

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POLLUTANT STRESSES—STATIONARY COMBUSTION ENGINES AND AGRICULTURAL CHEMICAL INDUSTRY (ANHYDROUS AMMONIA FERTILIZER). Symptoms of nitrogen oxides (from stationary combustion engines) and ammonia vapor (from anhydrous ammonia fertilizer) emissions on forest species (Figs. 251-266). All symptoms of nitrogen oxides were produced on plants grown in the laboratory under controlled conditions.

Nitrogen oxides: **Fig. 251.** Initial injury symptoms appear first at the base of young pine needles. **Fig. 252.** Advanced symptoms on pine resulting in general bleaching followed by brown coloration. **Fig. 253.** Chlorosis and needle tip necrosis on pine caused by an acute fumigation. **Fig. 254.** Close-up of chlorosis and needle tip necrosis on pine shown in Fig. 253. **Fig. 255.** Initial stage of chlorosis development on aspen. **Fig. 256.** Marginal and interveinal chlorosis and bleaching on poplar. **Fig. 257.** Early stage of marginal and interveinal necrosis on aspen. **Fig. 258.** Advanced interveinal and marginal necrosis on birch. **Fig. 259.** Initial symptoms of marginal and interveinal discoloration on willow. **Fig. 260.** Advanced necrotic symptoms on willow prior to total tissue collapse. **Fig. 261.** Symptoms of severe interveinal chlorosis and irregular necrosis on alder. **Ammonia vapor:** **Fig. 262.** Initiation of chlorosis on poplar. **Fig. 263.** Acute foliar injury on poplar, appearing first at the margins and then moving toward the middle. **Fig. 264.** Nonspecific leaf spotting on aspen. **Fig. 265.** Nonspecific leaf spotting and glazing on willow. **Fig. 266.** Discoloration of poplar as a result of a short exposure to ammonia vapor.

ing tissue injury when the concentrations exceed a certain threshold.

Chronic foliar injury as a result of continuous exposure to relatively low concentrations of nitrogen oxides appears as an enhancement of the green color followed by chlorosis and extensive leaf drop. Physiological injury can also occur at very low concentrations of nitrogen oxide, resulting in slower growth and lower yield without any visible symptoms of phytotoxicity. Such injury is probably brought about by inhibition of photosynthesis and other vital processes.

On deciduous species it may be difficult to accurately identify the symptoms of nitrogen oxide injury in the field. Several other pollutants such as SO_2, hydrogen chloride, and ozone as well as a magnesium deficiency produce chlorotic and necrotic symptoms that may be similar to those produced by NO_2. It is particularly important, therefore, to verify the existence of possible emission sources and to obtain air quality and meteorological information pertaining to the area.

OZONE AND PAN

An important product of NO_2 interaction with partially combusted hydrocarbons is photochemical smog containing O_3 and PAN. Photochemical smog generally originates from large urban areas as automobile exhaust and has the potential to cause injury to forest vegetation through long-range transport.

On deciduous species ozone causes chlorosis, necrosis, and flecking on the upper surface of leaves. Necrotic tissues can range from almost white to orange red in color, depending upon the species. Ozone can destroy small veins but leaves the large ones unaffected. In most deciduous plants, bleaching of the upper leaf surface is a common type of injury.

In conifers ozone produces mottled yellow and green patches of tissue on needle surfaces. In sensitive species the entire needle turns necrotic and drops prematurely. Necrosis begins at the needle tip, and the mottled symptoms occur in the zone below the necrotic tissues.

PAN generally causes glazing, bronzing, or silvering of the lower surface of deciduous leaves and may affect the upper surface in some species. Incipient chlorosis develops shortly after fumigation with high concentrations of PAN, and the injured area gradually becomes flaccid. Wilting may be followed by glazing and bronzing along the edge of the collapsed band. In severe injury the glazing and bronzing symptoms often do not develop. PAN symptoms on conifers have not been well described in the literature.

Suggested Reading

Hill, A.C., H.E. Heggestad, and S.N. Linzon. 1970. Ozone. Pages B1-B22 *in* Recognition of air pollution injury to vegetation: A pictorial atlas. Jacobson, J.S. and A.C. Hill (eds.). Air Pollution Control Association. Pittsburgh, Pennsylvania. Informative Report 1.

Taylor, O.C. and D.C. MacLean. 1970. Nitrogen oxides and peroxyacyl nitrates. Pages E1-E14 *in* Recognition of air pollution injury to vegetation: A pictorial atlas. Jacobson, J.S. and A.C. Hill (eds.). Air Pollution Control Association. Pittsburgh, Pennsylvania. Informative Report 1.

AGRICULTURAL CHEMICAL INDUSTRY

AMMONIA VAPOR

The major source of gaseous ammonia pollution is anhydrous ammonia, now commonly used as a fertilizer. If an accidental spill of anhydrous ammonia occurs during transport, the fumes can cause severe injury to vegetation. Injury can also be caused by leakage of ammonia from storage tanks; injured vegetation has been observed 3 km downwind from the site of an ammonia spill.

Ammonia injury is not always specific and may not be restricted to interveinal areas, which is the case with SO_2. In deciduous species, the foliage may or may not show chlorosis in response to low levels of ammonia. High concentrations of ammonia result in chlorosis of the whole leaf surface, which sometimes gives the foliage a cooked appearance (Fig. 262). Chlorotic symptoms are often followed by bronzing, which starts along the leaf margins and progresses toward the middle (Fig. 263). In many instances, ammonia causes scattered necrotic spotting and glazing of the upper surfaces of leaves (Figs. 264 and 265). Tree foliage that is moderately affected by ammonia vapor over a short period of time (Fig. 266) can recover rapidly after the fumigation incident.

There is little information on how ammonia affects conifers, because it is used mainly on agricultural areas in the parkland, where aspen and poplar predominate. Generally, old conifer needles turn dark and younger needles display a reddish yellow discoloration.

Suggested Reading

Heck, W.W., R.H. Daines, and I.J. Hindawi. 1970. Other phytotoxic pollutants. Pages F1-F24 *in* Recognition of air pollution injury to vegetation: A pictorial atlas. Jacobson, J.S. and A.C. Hill (eds.). Air Pollution Control Association. Pittsburgh, Pennsylvania. Informative Report 1.

Temple, P.J., D.S. Harper, R.G. Pearson, and S.N. Linzon. 1979. Toxic effects of ammonia on vegetation in Ontario. Environmental Pollution 20:297-302.

Treshow, M. 1970. Environment and plant response. McGraw-Hill Book Co. Toronto, Ontario. Pages 362-363 (ammonia).

HERBICIDES, SOIL STERILANTS, AND PESTICIDES

Herbicides, soil sterilants, and pesticides represent a serious threat to the environment because of their wide use in agriculture. One of the pioneer agricultural chemicals, 2,4-D, and its derivatives are probably the most widely used, among the most phytotoxic, and under certain conditions the most selective of herbicides. Severe injury to vegetation can occur as far as several kilometres from the point of application as a result of chemical drift and sometimes because of the volatility of certain compounds.

There are a number of herbicides, soil sterilants, and pesticides that can cause injury to vegetation; however, it is beyond the scope of this handbook to include them all.

HERBICIDES

Many different herbicides are currently being used near forests. Only the more commonly used chemicals, 2,4-D and 2,4,5-T, are discussed here. These compounds are widely distributed and fairly toxic; they can injure a wide variety of plant species at very low concentrations. In general, 2,4-D is most effective in killing broadleaf vegetation. Grasses, cereals, and other monocots are relatively resistant to it. Almost all types of vegetation can be treated effectively with 2,4,5-T, which is used for brush control along energy transmission corridors.


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Poplar, willow, and aspen leaves are extremely sensitive to 2,4,5-T and turn necrotic even at low to moderate concentrations (0.25-1.0 kg/ha) (Figs. 267-269). Severe necrosis is often followed by foliar drop and tree mortality.

Low concentrations of 2,4-D act as a growth hormone by stimulating cell division and elongation; however, excessive growth at the expense of metabolites that are also required for other cellular processes results in eventual tissue collapse. Some of the typical growth responses to 2,4-D are epinasty (hooking) of terminal shoots, twisting and curling of tissues, and foliar bleaching (Figs. 270 and 271). Hooking, twisting, and curling symptoms are generally produced within a matter of hours after 2,4-D application and can lead to foliar discoloration and severe necrosis (Fig. 272).

In conifers, young needles are more sensitive to 2,4-D injury than old ones (Figs. 273 and 274), but the amount of 2,4-D required to injure or kill conifers is much higher than for deciduous species. In spruce, after the initial bleaching symptoms the needles start to turn brown (Fig. 275); eventually all foliar tissues, regardless of age, become reddish brown or necrotic, and the tree dies (Fig. 276). Pine responds to 2,4-D by producing twisted and necrotic needles (Figs. 277 and 278).

Suggested Reading

Heck, W.W., R.H. Daines, and I.J. Hindawi. 1970. Other phytotoxic pollutants (herbicides). Pages F3-F4 *in* Recognition of air pollution injury to vegetation: A pictorial atlas. Jacobson, J.S. and A.C. Hill (eds.). Air Pollution Control Association. Pittsburgh, Pennsylvania. Informative Report 1.

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Turner, D.J. 1977. The safety of the herbicides 2,4-D and 2,4,5-T. Forestry Commission. Her Majesty's Stationery Office. London, England. Bulletin 57.

Yarish, W. 1980. Recognizing herbicide action and injury. Alberta Agriculture. Edmonton, Alberta. Agdex 641-7.

SOIL STERILANTS

Certain sterilants may be partially lost by vaporization when applied to soils. Vapors of picloram from treated soils, for example, can be toxic to sensitive vegetation nearby. The rate of air movement and the temperature above the treated soil determine the extent of vaporization.

Soil application of picloram initially causes current-year needles of conifers to turn

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POLLUTANT STRESSES—AGRICULTURAL CHEMICAL INDUSTRY (HERBICIDES). 2,4,5-T and 2,4-D symptoms on forest species (Figs. 267-278).

2,4,5-T: Fig. 267. Poplar leaf showing marginal necrosis. **Fig. 268.** Necrotic spotting on willow. **Fig. 269.** Tissue necrosis on aspen. **2,4-D: Fig. 270.** Poplar foliage showing bleaching, hooking, and curling symptoms on willow. **Fig. 271.** Bleaching, hooking, and curling symptoms on willow. **Fig. 272.** Curling, hooking, and severe foliar necrosis on birch. **Fig. 273.** Bleaching of new growth flushes on white spruce 1 week after a 2,4-D spray. **Fig. 274.** Close-up of bleached needles from the white spruce shown in Fig. 273. **Fig. 275.** Bleaching and subsequent brown discoloration of white spruce needles. **Fig. 276.** Advanced symptoms of almost total necrosis of white spruce. **Fig. 277.** Necrotic symptoms appearing first at the base of pine needles (young tissues). **Fig. 278.** Close-up of pine needles in Fig. 277 showing twisting and necrotic tissues.


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brown, which is followed by general necrosis of the entire foliage and eventual tree mortality (Fig. 279). Picloram is especially effective in killing broadleaf vegetation, even when applied to the soil at very low concentrations (Fig. 280).

Bromacil, or Hyvar, is another important weed and brush killer that is very effective as a soil sterilant. It is normally used in noncrop areas, but it can cause injury to forest vegetation if carried there as aerial drift. In spruce it can cause severe chlorosis of young current-year needles and tip browning of older needles (Fig. 281). Yellowing appears to begin at the needle tip and progress downward (Fig. 282). The green zone below the chlorotic area is generally interrupted by small yellow markings (Fig. 282). This is unlike the SO_2 injury pattern, in which there is a very sharp boundary between the chlorotic or necrotic zone and the solid green zone. Bromacil injury in pine foliage is similar to that produced in spruce (Fig. 283).

Sodium chlorate is also used as a soil sterilant, especially for killing deep-rooted perennials. It acts on vegetation as both a defoliant and a desiccant, or drying agent. When used at high concentrations as a desiccant, it stops plant growth and development within a few hours after application. In conifers, soil application of sodium chlorate causes bleaching of young needles (Figs. 284 and 285).

In leaves of deciduous species such as aspen, soil application of sodium chlorate produces bleaching around the leaf edge and irregular white markings on the remainder of the leaf (Fig. 286). At high concentrations it causes foliar desiccation, necrosis (Fig. 287), and premature leaf drop.

Amitrole, because of its high phytotoxicity and persistence, is often used as a soil sterilant. It causes injury to vegetation by destroying leaf pigments, reducing moisture, and initiating defoliation, especially at low concentrations. Leaf chlorosis and necrosis (Fig. 288) are the direct results of its interference with chlorophyll pigments. Amitrole injury starts at the leaf tips and margins and gradually spreads to the entire leaf surface.

PESTICIDES

A diverse array of insecticides and fungicides is also in wide use. Compounds considered potentially toxic are given restricted status, and labels specify the conditions and limitations of their application. There are a number of pesticides that can cause injury if used on plants other than those for which the chemical has been tested. Many of these chemicals can injure forest vegetation and produce visible symptoms that may be similar to those produced by some air pollutants.

Insecticides, in general, can be more phytotoxic than fungicides. A commonly used insecticide for controlling insects on shade and shelterbelt trees and in agricultural crops is dimethoate. At higher than recommended dosages dimethoate can produce toxicity symptoms on broadleaf species similar to those produced by SO_2. On chokecherry leaves it causes distinct interveinal and marginal chlorosis (Fig. 289). Unlike SO_2

POLLUTANT STRESSES—AGRICULTURAL CHEMICAL INDUSTRY (SOIL STERILANTS AND PESTICIDES). Picloram, bromacil, sodium chlorate, and amitrole soil sterilants and dimethoate pesticide symptoms on forest species (Figs. 279-290).

Picloram: Fig. 279. Symptoms on pine. **Fig. 280.** Leaf discoloration of poplar. **Bromacil: Fig. 281.** Pronounced yellowing of current-year growth and tip burning of older white spruce needles. **Fig. 282.** Close-up of injury to current-year white spruce needles shown in Fig. 281. **Fig. 283.** Partial chlorosis of the current-year pine foliage starting at the needle tips and browning of older foliage. **Sodium chlorate: Fig. 284.** Bleaching of the current-year white spruce foliage 2 days after application of sodium chlorate. **Fig. 285.** Bleaching of young pine foliage. **Fig. 286.** Marginal bleaching of aspen. **Fig. 287.** Desiccation and necrosis of birch. **Amitrole: Fig. 288.** Necrotic injury to aspen. **Dimethoate: Fig. 289.** Interveinal and marginal chlorosis on chokecherry. **Fig. 290.** Bleaching and necrotic symptoms of birch.

symptoms, dimethoate symptoms appear on leaves of all ages, young leaves being more sensitive than the older ones. Dimethoate is also known to cause interveinal bleaching and brown discoloration in birch leaves (Fig. 290).

Suggested Reading

Hindawi, I.J. 1970. Air pollution injury to vegetation. United States Department of Health, Education, and Welfare. Air Pollution Control Administration. Raleigh, North Carolina. Publication AP-71. Pages 36-39.

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SUMMARY OF MAJOR INDUSTRIAL EMISSIONS AND VISIBLE INJURY SYMPTOMS ON FOREST VEGETATION

The following table provides brief descriptions of the visual symptoms that characterize the damage to coniferous and deciduous tree species by each of the industrial pollutant emissions discussed in this handbook. As noted in the remarks column, the visual damage caused by one pollutant may in some instances be similar to, or confused with, symptoms caused by another pollutant or a nonpollutant stress. When making a diagnosis it is recommended that the reader examine the appropriate industry section in the main body of the text to ensure an accurate assessment of the pollutant(s) causing the damage observed.

Industry	Major emissions	Visual symptoms coniferous
Natural gas and oil	SO_2	Yellowing of older needles followed by brown discoloration and tissue death. Discoloration appears first at needle tip and progresses toward needle base (Fig. 87). Generally sharp boundary between the discolored and green zones.
	Liquid hydrocarbons	Light-weight fractions give an oily appearance to foliage; heavy-weight fractions leave a tarry coating. Chlorotic symptoms first appear on younger needles at the point of contact with light-weight fractions. When hydrocarbons are uniformly sprayed, injury begins at needle tip, gradually spreading to needle base (Fig. 121).
	Saltwater spills	Light pink to deep magenta or reddish brown discoloration of current and 1-year-old needles initially (Fig. 146). Symptoms appear first at needle tip and gradually progress to base. Unlike natural fall senescence, salt-killed foliage remains attached to the branches much longer.
Metal mining and smelting	SO_2, heavy metals, and particulates	Chlorosis and necrosis appear first at the tip of older needles and gradually progress to the needle base (Fig. 179). Because of heavy metal presence, smelter emissions often produce bands of irregular discoloration on the needle surfaces (Fig. 198).
	Fluorides	Pine needles exhibit spectacular tip burn that rapidly extends toward the needle base. Injury first appears on current-year needles; older needles are fairly resistant.
Other minerals		
Cement	Dust containing mainly calcium, potassium, and sodium oxides	Stunted growth and premature needle drop. Cement dust residue often visible on needle surfaces.
Potash	Potassium and sodium chlorides	——[1]
Storage piles of calcareous materials		Coating of needles or stems with gypsum or other such materials.

SUMMARY OF MAJOR INDUSTRIAL EMISSIONS AND VISIBLE INJURY SYMPTOMS ON FOREST VEGETATION

Visual symptoms deciduous	Remarks
Initial wet appearance of leaf undersurfaces followed by interveinal and marginal discoloration (Fig. 102). Fast drying of leaves can cause curling and shriveling.	Pesticides such as dimethoate can produce symptoms on deciduous species similar to those caused by SO_2 ; but unlike SO_2 , young leaves are more sensitive to dimethoate than are the old ones. SO_2 can sometimes produce symptoms on deciduous species similar to those caused by NO_2 and ammonia vapor.
Localized injury to the leaf area at the point of contact. Light-weight fractions produce curling and twisting of foliar tissues (Figs. 130 and 135) followed by defoliation.	Herbicides such as 2,4-D and picloram can also produce twisting and curling of deciduous leaves. Herbicides, however, produce this response in all tissues, including twigs and branches.
Leaf tip and marginal chlorosis and necrosis advance rapidly inward over the entire leaf surface (Figs. 154 and 155) and are followed by leaf curling (Fig. 156).	The pathway of saltwater movement in a forest can often be delineated by the pattern of affected ground-cover foliage.
Leaf interveinal and marginal wet appearance followed by chlorosis (Fig. 208), necrosis (Fig. 210), and premature defoliation (Fig. 206). Symptoms produced are often irregular in pattern (Fig. 212), especially close to the emission source.	
A light green, water-soaked appearance is followed by tip and marginal necrosis, which eventually spreads to the entire leaf. Fluoride can cause mottling or necrotic banding at the point of accumulation.	
Same as for conifers.	
Similar to those produced by saltwater spills.	
Coating of leaves or stems with gypsum or other such materials.	

Continued on next page

Industry	Major emissions	Visual symptoms coniferous
Pulp and paper	H_2S, methyl mercaptan, dimethyl sulfide, sodium hydroxide, and ammonia	Stunted needle growth and bands of chlorotic and necrotic tissues at the points of contact with aerially dispersed liquid emissions (Fig. 248) close to the source. At more distant sites, gaseous pollutants produce chlorotic symptoms at the needle tip that progress to needle base (Fig. 246). Specks of liquid emission residue often noticed on foliar surfaces near the emission source.
Stationary combustion engines	Nitrogen oxides	Lesions on needle surfaces (Fig. 252) and often needle tip burn (Figs. 253 and 254). Symptoms appear first on older needles.
	Ozone	Mottled yellow and green patches of tissue occur on needle surface. Necrosis (if it occurs) begins at the needle tip, and the mottled symptoms occur in the zone below the necrotic tissue.
	PAN	——
Agricultural chemicals		
Anhydrous ammonia fertilizer	Ammonia vapor	Old needles often turn black. Younger needles display reddish yellow discoloration.
Herbicides	2,4-D	Bleaching followed by brown discoloration appears first on young needles (Figs. 273 and 274). Needles become twisted (Fig. 278).
	2,4,5-T	——
Soil sterilants	Picloram	Current-year needles are first to turn brown. General necrosis (Fig. 279) follows.

SUMMARY OF MAJOR INDUSTRIAL EMISSIONS AND VISIBLE INJURY SYMPTOMS ON FOREST VEGETATION continued

Visual symptoms deciduous	Remarks
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Initial enhancement of green color followed by water-soaked appearance and development of irregularly shaped white, yellow, or brown spots on leaves (Figs. 256 and 257). Mature leaves more sensitive than younger ones.	Injury symptoms on deciduous species may be confused with those produced by SO_2, HCl, O_3, and magnesium deficiency.
Chlorosis, necrosis, and flecking occur on the upper leaf surface. Necrotic tissue can range from white to orange red in color, depending on species.	
Leaf wilting, which may be followed by glazing, bronzing, or silvering of the lower leaf surface. Upper leaf surfaces of some species may also be affected.	
Chlorosis develops over the entire leaf and foliage appears cooked (Fig. 262). Marginal bronzing follows, progressing toward the middle (Fig. 263). Glazed upper surfaces of leaves with necrotic spots are common (Figs. 264 and 265).	Ammonia injury on deciduous species is not always specific and may not be restricted to interveinal areas, as is the case with SO_2.
Hooking, twisting, curling, and bleaching of terminal shoots (Figs. 270 and 271).	Liquid hydrocarbons can also produce twisting and curling of deciduous leaves; however, liquid hydrocarbons do not affect twigs and branches.
Reddish brown discoloration of foliage even at low concentrations (Fig. 267).	
General necrosis of the entire leaf area even at low concentrations (Fig. 280).	

Continued on next page

Industry	Major emissions	Visual symptoms coniferous
Soil sterilants (continued)	Bromacil	Severe chlorosis of young current-year needles followed by tip burning of older needles (Fig. 281). Yellowing appears first at needle tip and progresses to base. Green zone below the chlorotic area often interrupted by small yellow markings.
	Sodium chlorate	Initial symptom is bleaching of young needles (Fig. 285). Necrosis follows.
	Amitrole	——
Pesticides	Dimethoate	——

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[1] Insufficient information available.

SUMMARY OF MAJOR INDUSTRIAL EMISSIONS AND VISIBLE INJURY SYMPTOMS ON FOREST VEGETATION continued

Visual symptoms deciduous	Remarks
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Marginal bleaching with irregular white markings in the remainder of the leaf (Fig. 286) followed by necrosis and premature leaf drop.	
Chlorosis and necrosis appear first on the leaf tips and margins. Symptoms gradually spread to the entire leaf surface.	
Interveinal and marginal discoloration (Figs. 289 and 290).	SO_2 can produce symptoms on deciduous species similar to those caused by dimethoate; but unlike SO_2, symptoms appear on leaves of all ages. Young leaves are more sensitive than old ones.

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GLOSSARY

Abscission layer: A special group of cells at the base of the leaf or fruit stalk, whose formation precedes leaf or fruit drop.

Acute symptom: Sudden and widespread necrosis of foliar tissues in response to high concentrations of air pollutants over a short period of time.

Additive effect: The combined effect of two or more factors is equal to the sum of the effects taken independently.

Aerosol: A suspension of ultramicroscopic particles of liquids or solids in air or gas.

Amino acids: Organic compounds that are building blocks for all proteins.

Analogs: One compound closely related to another.

Antagonistic effect: The combined effect of two or more factors is less than the sum of these effects taken independently.

Assimilation: The process whereby essential ingredients are utilized for the normal function of tissues.

Bioindicator: A biological species used as an indicator of air pollution impingement.

Blight: Disease or plant injury caused by fungi, bacteria, viruses, insects, or adverse climatic conditions; does not result in rotting.

Bryophytes: Nonflowering plants such as mosses and liverworts.

Calcareous: Materials containing calcium carbonate or other calcium salts.

Calciphile: A plant that grows mainly on alkaline soils rich in calcium.

Cambium: A layer of cells in higher plants that divide to form xylem on the inside and phloem on the outside of the stem.

Cellular metabolism: The process of formation and breakdown of organic compounds in living organisms.

Chelation: A process of binding a metal ion with one or more groups of another compound.

Chlorophyll: Green pigment of plants normally found in foliar tissues.

Chlorosis: Loss or reduction of green plant pigment or chlorophyll; generally, yellowing.

Chronic symptom: Chlorosis that may lead to necrosis after exposure of vegetation to variable concentrations of air pollutants over a long period of time.

Cladina: Ground lichens that are intricately branched and lacking cups.

Cladonia: Cup-shaped ground lichens that are not intricately branched.

Corticolous lichens: Growing on tree trunks or branches.

Crustose lichens: Crustlike lichen growing in close contact with the substratum.

Cuticle: A noncellular outer layer of waxy material secreted by epidermal and other inside cells; chief function is to prevent excessive water loss.

Depauperate: Falling short of the natural growth and development of its species.

Desiccation: Process of tissue dehydration, or loss of water.

Ecosystem: A single functional system that includes all living organisms and nonliving factors such as sunlight, temperature, moisture, soil, mineral elements, topography, and all their interactions.

Epidermis: The outermost layer of plant cells below the cuticle, normally one cell thick, that provides protection to the underlying parts.

Epinasty: An outward and downward growth of a plant part that is caused by more rapid growth of one side of the plant.

Epiphytic: Plant growing on the surface of other plants, not parasitically but for support.

Flaccid: Lacking firmness and stiffness.

Foliose lichens: Leaflike growth form.

Fruticose lichens: Shrubby or upright branched growth form.

Fruiting structure: An organ specialized for producing spores or seeds.

Fumigation: Exposure of vegetation to gas, vapor, or smoke, whether under laboratory or field conditions.

Fungal hyphae: Microscopic multicellular threads that make up the fungal thallus.

Herbicide: A chemical compound used to destroy or inhibit plant growth.

Hydrocarbons: A class of organic compounds containing hydrogen and carbon; includes those occurring in oil, tar sands, natural gas, and coal.

Hypogymnia: Leaflike lichens with hollow lobes, usually grey or greyish brown in color, that grow on trees.

Intercostal injury: See interveinal injury.

Interveinal injury: Chlorotic or necrotic symptoms between the veins of leaves.

Larva: The preadult feeding form of insects that develops through several stages before emerging as an adult.

Lichens: Complex lower plants composed of algal and fungal components.

Lichen thallus: The vegetative plant body of a crustose, foliose, or fruticose lichen.

Marginal leaf injury: Development of chlorotic or necrotic symptoms on the leaf margins.

Mesophyll: A layer of cells between epidermal layers of leaves that are capable of photosynthesis, respiration, and cell division.

Molecular weight: The sum of all the atomic weights in a chemical formula.

Monocot: A class of plant distinguished by the presence of an embryo that produces a single leaf.

Mottling: Mingling of other colored spots with normal green in the foliage.

Mycelium: A mass of interwoven hyphae that produce spores in fungi.

Necrosis: Death of living tissues, characterized by browning and drying.

Nucleus (pl. nuclei): Subcellular structure containing hereditary material and from which new cells may originate.

Nonbiodegradable: Not able to be destroyed or reduced to much simpler form by biological means.

Parmelia: Leaflike lichens with flattened thallus, found on tree trunks, rock surfaces, etc.

Particulate: Minute separate particles.

Peltigera: Large, succulent, leaflike lichens, greenish in color, that normally grow on soil or mosses.

pH: Negative logarithm of the hydrogen ion concentration in a solution, used as an indicator of the extent of acidity or alkalinity.

Phloem: Complex conducting tissues mainly responsible for translocation of foods from leaves to buds and roots.

Photosynthesis: The process by which green plants harness the energy of sunlight absorbed by chlorophyll to build organic compounds from carbon dioxide and water.

Phytotoxicity: Injury to plants in response to toxic compounds or other undesirable factors.

Predisposition: A condition or set of conditions enhancing susceptibility to other stress factors.

Red belt: Foliar damage resulting in reddish brown discoloration on conifers, caused by adverse weather conditions. Damage occurs mostly in the middle and upper foothills and in the eastern portions of major mountain passes of the Rocky Mountains.

Resinosis: Excessive leakage of resins from coniferous tissues, usually as a result of injury.

Respiration: Energy-yielding process by which high-energy foods are broken down into much simpler products.

Rosetting: Circular cluster of foliage.

Rust pustule: An elevated spot containing the fruiting structure of a parasitic fungus (rust).

Saxicolous lichens: Growing on rocks.

Senescence: Process of aging, leading to tissue death.

Siliceous: Relating to silica or silicates.

Stomata: Small openings in the epidermis of leaves facilitating gaseous exchange and transpiration.

Symptom: The visible evidence of an unhealthy condition.

Synergistic effect: The combined effect of more than one factor is greater than the sum of those effects taken independently.

Systemic: A compound absorbed by and translocated throughout the plant body.

Thallus: See lichen thallus.

Transitory symptom: Mild foliar chlorosis that develops after fumigation and from which full recovery is possible within a few days in an air-pollutant-free atmosphere.

Transpiration: The loss of water vapor from leaves, chiefly through stomata and other aerial parts of the plant.

Ultrastructure: The submicroscopic organization of the plant protoplasm.

Variegation: The irregular presence of different colors in plant leaf tissues due to suppression of normal pigment development.

Winter flecking: Formation of small irregular lesions on foliar surfaces, caused by winter injury.

Xylem: A complex tissue in higher plants, chiefly responsible for upward conduction of water and nutrients.

APPENDIXES

1. Common and scientific names of plants.
2. Common and scientific names of diseases.
3. Common and scientific names of insects.
4. Abbreviations and chemical nomenclature.

APPENDIX 1

COMMON AND SCIENTIFIC NAMES OF PLANTS[1]

Alder:	*Alnus crispa* (Ait.) Pursh
American elm:	*Ulmus americana* L.
Aspen:	*Populus tremuloides* Michx.
Alpine fir:	*Abies lasiocarpa* (Hook.) Nutt.
Balsam fir:	*Abies balsamea* (L.) Mill.
Balsam poplar:	*Populus balsamifera* L.
Birch:	*Betula papyrifera* Marsh.
Black spruce:	*Picea mariana* (Mill.) B.S.P.
Bryoria:	*Bryoria* sp.
Caragana:	*Caragana arborescens* Lam.
Chokecherry:	*Prunus virginiana* L.
Colorado blue spruce:	*Picea pungens* Engelm.
Eastern larch:	*Larix laricina* (Du Roi) K. Koch
Feather moss:	*Hylocomium splendens* (Hedw.) B.S.G. *Pleurozium schreberi* (Brid.) Mitt.
Green alder:	*Alnus crispa* (Ait.) Pursh
Ground-cover lichens[2]:	*Peltigera aphthosa* (L.) Willd. Most *Cladonia* sp.
Hypogymnia:	*Hypogymnia physodes* (L.) W. Wats.
Jack pine:	*Pinus banksiana* Lamb.
Labrador tea:	*Ledum groenlandicum* Oeder
Lodgepole pine:	*Pinus contorta* Loudon var. *latifolia* Engelm.
Manitoba maple:	*Acer negundo* L.
Parmelia:	*Parmelia sulcata* Tayl.
Peltigera:	*Peltigera aphthosa* (L.) Willd.
Pine:	*Pinus banksiana* Lamb. *Pinus contorta* Loudon var. *latifolia* Engelm.
Poplar:	*Populus balsamifera* L.
Reindeer lichens[2]:	*Cladina alpestris* (L.) Harm. *C. mitis* (Sandst.) Hale & W. Culb. *C. rangiferina* (L.) Harm. A few *Cladonia* sp.
Scots pine:	*Pinus sylvestris* L.
Tamarack:	*Larix laricina* (Du Roi) K. Koch
Tree lichens:	*Bryoria* sp. *Evernia mesomorpha* Nyl. *Hypogymnia physodes* (L.) W. Wats. *Parmelia sulcata* Tayl. *Usnea* sp.
Trembling aspen:	*Populus tremuloides* Michx.
Usnea:	*Usnea* sp.
White birch:	*Betula papyrifera* Marsh.

White spruce: *Picea glauca* (Moench) Voss
Wild sarsaparilla: *Aralia nudicaulis* L.
Willow: *Salix* sp.

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[1] Lichens: Hale, M.E., Jr. and W.L. Culberson. 1970. A fourth checklist of the lichens of the continental United States and Canada. The Bryologist 73(3):499-543.

Mosses: Crum, H.A., W.C. Steere, and L.E. Anderson. 1973. A new list of mosses of North America north of Mexico. The Bryologist 76(1):85-130.

Vascular plants: Moss, E.H. 1959. Flora of Alberta. University of Toronto Press. Toronto, Ontario.

[2] Reindeer lichens are also ground-cover lichens.

APPENDIX 2

COMMON AND SCIENTIFIC NAMES OF DISEASES[1]

Armillaria **root rot:**	*Armillaria mellea* (Vahl ex Fr.) Kumm.
Birch leaf rust:	*Melampsoridium betulinum* (Fr.) Kleb.
Dutch elm disease:	*Ceratocystis ulmi* (Buism.) C. Moreau
Dwarf mistletoe of lodgepole pine:	*Arceuthobium americanum* Nutt. ex Engelm.
Elytroderma **needle cast:**	*Elytroderma deformans* (Weir) Darker
Poplar leaf spot:	*Marssonina populi* (Lib.) Magn.
Shoot blight of aspen:	*Venturia macularis* (Fr.) E. Müll & Arx
Snow blight of spruce:	*Sarcotrochila* sp.
Spruce needle cast:	*Lophodermium* sp.
Spruce needle rust:	*Chrysomyxa ledicola* Lagh.
Willow leaf rust:	*Melampsora epitea* Thüm.
Yellow witches'-broom rust of spruce (dwarf mistletoe):	*Chrysomyxa arctostaphyli* Diet.

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[1] Agriculture Québec. 1975. Names of plant diseases in Canada. 2nd edition. Québec City, Québec. Publication QA38-R4-1.

APPENDIX 3

COMMON AND SCIENTIFIC NAMES OF INSECTS[1]

Ambermarked birch leaf miner:	*Profenusa thomsoni* (Konow)
Cottonwood leaf-mining beetle[2]:	*Zeugophoira scutellaris* Suffr.
Early aspen leaf curler:	*Pseudexentera oregonana* Wishm.
Eriophyes **gall mite:**	*Eriophyes* sp.
Forest tent caterpillar:	*Malacosoma disstria* Hbn.
Jack pine budworm:	*Choristoneura pinus pinus* Free.
Lodgepole terminal weevil:	*Pissodes terminalis* Hopping
Mountain pine beetle:	*Dendroctonus ponderosae* Hopk.
Northern lodgepole needle miner[3]:	*Colestechnites starki* (Free.)
Spruce budworm:	*Choristoneura fumiferana* (Clem.)
Spruce needle miner:	*Taniva albolineana* (Kft.)
Spruce spider mite:	*Oligonychus ununguis* (Kft.)
White pine weevil:	*Pissodes strobi* (Peck)
Willow leaf miner[4]:	*Lyonetia* sp.

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[1] Source unless otherwise noted:
Agriculture Québec. 1975. Noms francais d'insectes au Canada. (French names of insects in Canada with corresponding Latin and English names.) 4th edition. Québec City, Québec. Publication QA38-R4-30.

[2] MacAloney, H.J. and H.G. Ewan. 1964. Identification of hardwood insects by type of tree injury, north central region. United States Department of Agriculture, Forest Service. Lake States Forest Experiment Station and North Central Region. St. Paul, Minnesota. Research Paper LS-11.

[3] Furniss, R.L. and V.M. Carolin. 1977. Western forest insects. United States Department of Agriculture, Forest Service. Miscellaneous Publication 1339.

[4] Canadian Forestry Service. 1976. Forest insect and disease survey annual report, 1975. Fisheries and Environment Canada. Ottawa, Ontario.

APPENDIX 4

ABBREVIATIONS AND CHEMICAL NOMENCLATURE

Amitrole:	3-amino-1,2,4-triazole
Bromacil:	5-bromo-3-sec-butyl-6-methyluracil
CO:	Carbon monoxide
Dimethoate:	O, O-Dimethyl phosphorodithioate S-ester with 2-mercapto-N-methylacetamide
Gypsum:	Calcium sulfate
H_2S:	Hydrogen sulfide
Hyvar:	See Bromacil
NaCl:	Sodium chloride
NO:	Nitric oxide
NO_2:	Nitrogen dioxide
NO_x:	Nitrogen oxides
O_3:	Ozone
PAN:	Peroxyacetyl nitrate
Picloram:	4-amino-3,5,6-trichloropicolinic acid
ppb:	Parts per billion
ppm:	Parts per million
SO_2:	Sulfur dioxide
2,4-D:	2,4-dichlorophenoxyacetic acid
2,4,5-T:	2,4,5-trichlorophenoxyacetic acid

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