Pattern of Damage Produced on Vegetation by Smog

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A new expression of injury to vegetation caused by air pollutants in the Los Angeles area has been observed in the field following smog. A type of banding, not hitherto described, occurs in the same location on leaves of the same age, the location appearing to be related to cellular maturity. A distinct pattern of banding was observed in some form on all but one of 50 species studied following a single exposure to smog. The area damaged was that in which cellular differentiation had most recently occurred. Fumigations with gasoline mixed with ozone and with car exhaust fumes mixed with ozone have produced these bands. Familiarity with this pattern makes it possible to determine by visual inspection whether damage has been caused by smog or by some other agent, and to establish the fact that smog has been present, even though no other measurements have been made. It has also assisted in establishing the fact that gasoline vapors and car exhaust gases are potential sources of crop damage. Because the location of the injury seems to depend on the stage of development of the leaf cells, plant fumigation could be of use to the botanist for studying growth and development rates of plants.

Gas damage to vegetation has been studied for many years. The effect of sulfur dioxide on plants has received the most attention, as it has been observed in many areas throughout the world, and heavy losses to crops have been reported. Fluorine is receiving much attention at the present time. The general subject of gas damage to plants has been well summarized by Thomas (*14*).

In the Los Angeles area, these two gases are now being controlled, but a new type of pollutant has appeared—smog. Losses in Los Angeles County, to vegetable crops alone, were estimated by one observer at $480,000 for one year (*13*). This was probably very conservative, as such effects as the reduction in size of many plants had not been reported at that time (*7*). Damage to vegetation caused by a single smog period has been observed from Ventura, Calif., to the Mexican border, a distance of approximately 200 miles.

Smog is defined by Webster as smoke and fog, but at the present time the term is used to indicate many types of air pollutants. The only one known to cause typical damage to vegetation, as observed in the Los Angeles area and considered in this paper, is that produced by the oxidation products of unsaturated hydrocarbons mixed with ozone (*5*). The chief sources of these vapors are the manufacture, storage, marketing, and daily use of gasoline (*11*). Injury to vegetation can be expected where any of these vapors are present, the extent of the damage depending on the quantity of the vapors and meteorological conditions.

Although a number of methods have been suggested for measuring the concentration of smog (*9*), one cannot be certain of the validity of these measurements because the substances that cause injury to vegetation and eye and throat irritation have not been completely identified (*8*). Plants themselves thus become a most useful tool in determining what substances form smog (*5*), detecting phytotoxic constituents in the atmosphere, tracing the occurrence of smog, and estimating its severity. Studies in this field by the Los Angeles County Air Pollution Control District have been in progress for more than 5 years and considerable information has been accumulated (*1, 2, 5, 7, 8, 10, 11*).

Five test plants were originally adopted: spinach, endive, oats, alfalfa, and sugar beets (*5*). Recently, two more plants have been added: annual blue grass, because of its extreme sensitivity and universality, and petunia, because it remains sensitive over a considerable period of time.

It is believed that the injury caused by smog is best diagnosed by means of a syndrome based upon three general types of observations: macroscopic, microscopic, and the location of the damage on the leaf.

Macroscopically, silvering, glazing, streaking, or speckling occurs on leaves of plants. The formation of anthocyanin is also observed. These symptoms vary, depending on the type of vegetation and the anatomical structure of the leaf. Variations in the color of the damaged leaves range from white through tan and bronze to brown-black, depending on the species of the plant and the severity of the injury. No complete description of the injury has been published, although reports have been made by Middleton (*13*), Thomas (*14*), and the Air Pollution Control District (*10, 11*). A considerable reduction in the size of plants exposed to smog has been observed (*7, 11*). Endive in filtered air has grown to twice the size of that grown in ordinary air during a smog period.

Microscopically (*1,11*), the cells become enlarged and usually turgid. This phase is followed by plasmolysis. The chloroplasts concentrate in the middle of the cell and disintegrate. Dehydration then occurs and the cells collapse without rupturing the walls or breaking contacts between cells. Further dehydration of the damaged area results in enlargement of the intercellular spaces between the collapsed cells, causing most of the macroscopic effects described. Except in severe cases, damage is limited to the cells surrounding the substomatal chamber. An excellent description of the microscopic appearance of the damaged cell has been given by Bobrov, research botanist for the district, in her paper on the anatomy of oat leaves (*2*).

In addition to the macroscopic and microscopic appearance, distribution of damage on the leaf produces a pattern related to the differential maturity of the leaf. This pattern, not heretofore described, was first observed by the author in the field and is always found when smog damage occurs. In addition to the Los Angeles area, it has been observed in San Diego and on plants shipped to the district from San Francisco and New York. Earlier terminology mentioned it only as damage to newly matured leaves.

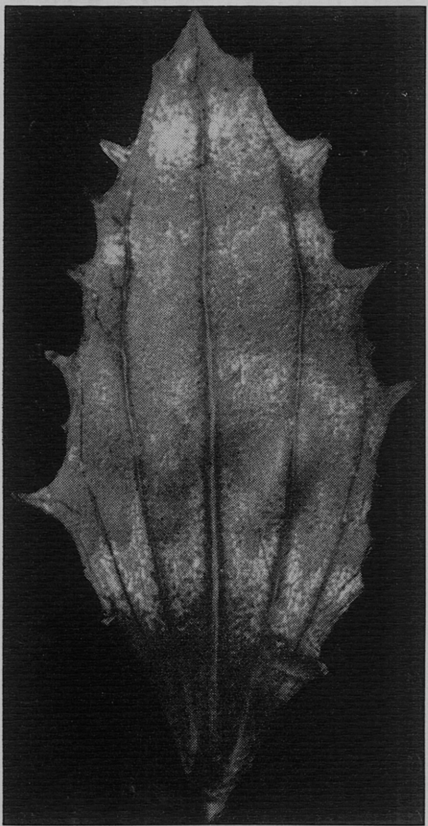

Figure 1. Four light bands of injury to mimulus caused by 4 successive days of smog

In 1952 it became apparent that the location of damage was related to the progressive development of the leaf. On many plants, damage from a single exposure was frequently found on only three leaves of any one stalk. The immature and senescent leaves showed no injury. Of the three which were damaged, the youngest would be injured at the tip, the next older about a third of the way down from the tip, and the next near the base. These locations correspond to the known progression of maturation of leaves. The tip of most leaves matures first and the age of the cells decreases progressively from the tip to the base. It is known that in monocotyledonous plants the base of the leaf remains meristematic for a long time and growth continues in that region. This may result in a series of bands, one for each successive day of exposure.

During a period when smog in the San Fernando Valley occurred repeatedly for several consecutive days, six successive diagonally transverse purple-brown bands of injury were found on single blades of rye grass. The intermediate areas remained undamaged, as smog injury does not occur at night. This is not because plants are insensitive at night, as fumigations with synthetic smog have produced damage at night, in darkness, but it is probably due to the fact that all the effects of smog in the atmosphere disappear shortly after sunset. This indicates that smog requires light for its formation, or possibly that light forces a reversible reaction in one direction.

Three factors have been observed to affect the size of the area damaged. Rapid growth or etiolation causes an increase in the width of the band on some plants. A high concentration of pollutants causes injury to the more resistant cells, so that larger areas will be affected. Extended periods of exposure, repeated daily, may cause an overlapping of bands in some plants which normally have wide bands of damage. Broad-leaved plants, such as spinach, show the largest area of sensitivity at about one third of the distance from the apex to the base of the leaf.

In addition to the monocotyledons, multiple bands have been noted on single leaves of spinach, beets, chard, petunia, mimulus, chickweed (*Stellaria media*), pigweed (*Chenopodium*), dock (*Rumex*), and other plants. On some plants, such as mallow, nearly all of the surface of the leaf may be affected by a single exposure, but only one or at most two leaves will be injured by a moderate dosage. In the latter case, the younger leaf will tend to be damaged toward the periphery and the older toward the base. Cotyledons, where observed, show a pitted injury over the entire upper surface.

On most plants, definite bands may be distinguished. The occurrence of as many as four bands on a single leaf of mimulus or petunia is not uncommon (Figure I). This is, of course, of great value in quickly differentiating smog damage from insect or frost injury, as insects are not so particular where they attack and frost does not band in this fashion.

As the effect appears to be related to the anatomy of the leaf, it is not improbable that other gases might affect the leaves in a similar manner. Crocker (*4*) reports that hydrogen sulfide produces a somewhat similar pattern; and Katz and coworkers (*6*) report banding on yellow pine from sulfur dioxide, but attribute it to high concentration and mild winter weather. No such precise pattern, however, has been produced by sulfur dioxide, ozone, hydrogen fluoride, carbon monoxide, fumes of formic acid, and fumes of formaldehyde.

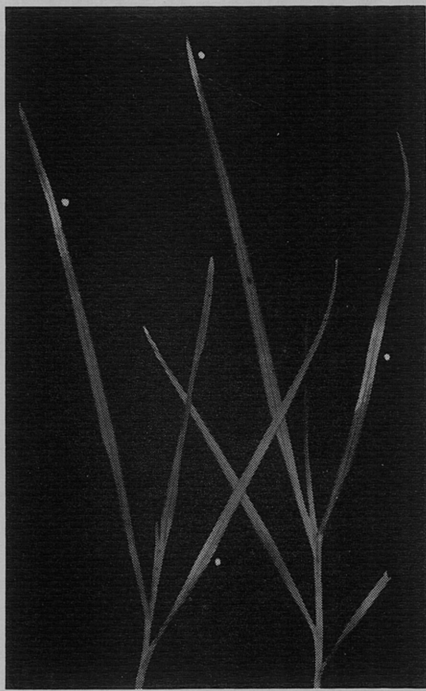

Figure 2. Two Poa annua exposed simultaneously to single day of natural smog

White dots indicate region of damage. Damage on corresponding blades appears nearer tip on younger plant and indicates age difference of approximately 1 day

Because cells are primarily sensitive at one stage of maturation, an interesting converse presents itself, in that the location of the damage might serve as a botanical tool in studying the growth and development of leaves (Figure 2). Simplified equipment could be developed by means of which plants could be gassed at various intervals and the progression of sensitivity observed under controlled conditions. Factors affecting the growth of plants could thus be studied in conjunction with a study of their anatomical structure.

An example of the use of the damage pattern is afforded in the studies of gasoline and automobile exhaust fumes as possible source materials in the production of smog.

The fumigation of plants by the Los Angeles County Air Pollution Control District began in June 1949. This work was carried on at the Earhart Plant Research Laboratory under the supervision of Went (*15*). This first attempt to determine the cause of crop damage was a cooperative venture of the California Institute of Technology, the University of California, and the Air

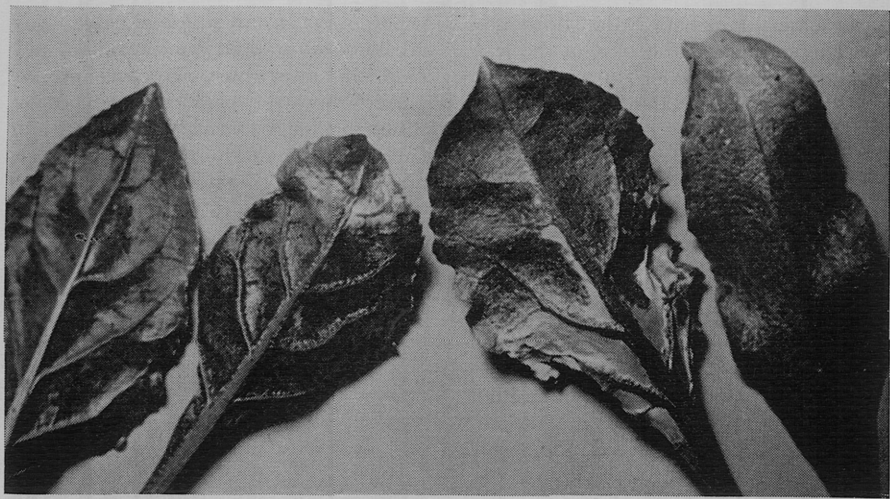

Figure 3. Sugar beet leaves from single plant fumigated with gasoline, ozone, and oxides of nitrogen

Youngest, on left, shows no injury. Next older, injury at tip. Next, injury at base. Oldest, on right, no injury

Pollution Control District. From these experiments (*5*) it was concluded that unsaturated hydrocarbons combined with ozone, in both the presence and absence of oxides of nitrogen, caused typical damage to vegetation. In this work, gases were allowed to react at high concentrations and were subsequently diluted. No observations were made concerning the pattern of damage, as it had not been noted, up to that time.

This method of mixing and diluting was subject to criticism, because reactions at high concentrations of pure substances might differ from those which occur at great dilution in the atmosphere. After many unsuccessful attempts, typical damage was produced on the five test plants—spinach, endive, alfalfa, oats, and sugar beets—by admitting the hydrocarbons and ozone into an 11,000-liter Plexiglas chamber through separate inlets placed at right angles in a horizontal plane with orifices 6 inches apart. A powerful electric fan was placed beneath the outlets and directed vertically upward to secure immediate and complete dispersion of the fumigants. The rate of air admitted to the chamber through an activated carbon filter was sufficient to produce, approximately, a 20-minute turnover. The temperature and humidity were held within reasonable limits by means of an evaporative cooler.

It is not intended to infer that these are the optimum conditions for fumigation. Further work is being carried on in this respect. They were, however, the first under which satisfactory results were obtained at reaction concentrations approaching those found in the atmosphere.

The results of these experiments have been reported in a recent paper (*3*) and in the Third Technical Report of the district (*12*). Typical damage on all five test plants was observed at 0.05 mg. per liter of hydrocarbons from gasoline vapor and at 0.04 mg. per liter of hydrocarbons from automobile exhaust gases in the presence of about 0.4 p.p.m. of ozone. This is less than the concentration of ozone recorded during heavy smog but several times the highest hydrocarbon concentrations measured. An excess of ozone, which could itself cause damage, is thus avoided.

In determining whether or not the damage was typical, the plants were examined macroscopically for general appearance, microscopically for anatomical effects, and for the location of the injury according to the cellular age and development as here described (Figure 3).

Because of important similarities between plant and animal cells, and because plant material is readily obtainable, the district plans to expand the present work on vegetation. Single cells will be isolated and the effects of various pollutants on them will be studied in an attempt to determine why certain cells are most sensitive.

Summary

A new method of diagnosis, based on the sensitivity of certain aged cells, has been added to the previously known macroscopic and microscopic diagnoses of damage to vegetation. This pattern of damage enables one to ascertain readily whether or not the injury was caused by smog. This pattern has been employed by the Los Angeles County Air Pollution Control District both in the field and in the laboratory, and by other workers in the field, to assay plant damage. It has aided in determining that gasoline and ozone, and automobile exhaust fumes and ozone, are capable of producing the same injury on plants as that which is observed in the field as a result of smog.

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Correction

In the article on "Reduction of Dental Caries and Goiter by Crops Fertilized with Fluorine and Iodine" [McClendon, J. F., and Gershon-Cohen, Jacob, J. Agr. Food Chem., 3, 72 (1955)] on page 73, Figures 1 and 2 were interchanged. The first figure on page 73 shows extensive caries and the second shows healthy molars.