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Chapter 9

The Use of Plants to Assess the Quality of Indoor Air

Walter W. Heck

Introduction

Plants have been used as initial indicators, or monitors, of air pollutants around industrial sources for a long time (Heck, 1966). Sulfur dioxide (SO_2) was early identified as causing injury to field-grown plants (Thomas, 1951; Zimmerman & Hitchcock, 1956). Ethylene has long been associated with plant damage found in greenhouses using artificial illuminating gas (Crocker, 1948; Heck & Pires, 1962) ethylene associated with auto exhaust caused severe orchid losses in greenhouses in the San Francisco area (James, 1963). Gaseous fluorides (i.e., HF) from aluminum smelting, super phosphate production and other processes have been monitored by a variety of plant species/cultivars (Zimmerman & Hitchcock, 1956; Hitchcock, Weinstein, McCune & Jacobson, 1964; Weinstein, 1961). The photochemical complex [principally ozone (O_3)] has been extensively studied and several plant systems have been used to monitor this complex (Middleton, 1961; Darley, Dugger Jr., Mudd, Ordin, Taylor & Stephens, 1963).

Early work utilized native plants as indicators of pollutants and characterized injury symptoms under natural conditions. The field survey includes visual symptomology and may include chemical analysis of plant tissues. Plant physiologists have used plants under controlled conditions to estimate concentrations of certain chemicals. This bioassay method has been used to monitor air pollutants both as a supplement to the field survey method and to monitor in studies involving various mixtures of chemicals (to distinguish specific toxicants or classes of toxicants).

This paper summarizes several ambient monitoring programs used to assess air pollutant effects on biological systems. It also develops a rationale for use of these techniques to assess the possible biological impact on indoor air quality.

Plants as Monitors of Air Pollutants

This section is divided into a brief discussion of field surveys, bioassays for field monitoring, bioassays of controlled exposures and selected monitoring programs in European countries.

Field Surveys

Visual inspection of a pollutant area or one that is suspected of being polluted is a field survey that can help assess pollution problems. Such surveys were common, and are still used, in areas of high pollution or high pollution potential as a means of identifying the presence of various pollutants.

Difficulties are inherent in field surveys. It is often difficult for the untrained observer to separate the effects of pollutants from environmental factors such as frost, drought, soil types, fertility level, insects, pesticides, plant diseases and old age. Foliar symptoms associated with different pollutants may resemble symptoms caused by an unfavorable environment. Thus, even a trained observer must be cautious in evaluating the parameters utilized to identify a given pollutant.

Field surveys for SO_2 injury started in the 19th century (Thomas, 1951). Major field surveys were conducted around the Trail, British Columbia, smelter (Katz, 1949; Scheffer & Hedgcock, 1955). These comprehensive surveys interrelated several meteorological parameters with topography, species susceptibility, and SO_2 concentrations. Plant injury from other factors was compared with injury from SO_2. Sensitive conifer and deciduous trees, as well as shrub and herb species, were listed. Cole (1959) reviewed the TVA vegetation surveillance program around their power stations. This program identified SO_2 injury patterns and severity of damage. Five criteria were proposed as a basis for selecting natural indicator species: SO_2 sensitivity, distribution, characterisitc markings, plant longevity, and a seasonal growth habit.

Bieberdorf, Shrewsbury, McKee and Krough (1958) and McKee (1961) analysed vegetation in Harris County, Texas, to relate total pollution load to the load of SO_2 released from heavy industry along the Houston ship channel. The SO_2 load was determined by measuring the levels of accumulated sulfate in native elm, Arizona ash and loblolly pine. None of the species showed visible symptoms of SO_2 injury. They found a positive correlation between levels of foliar sulfate in leaves of the indicator plants and proximity to the ship channel; this may not be an adequate index of total pollution.

Because increased concentrations of fluoride in forage crops may injure livestock, vegetation analyses have been used to survey fluoride pollution. Compton, Remmert, and Mellenthin (1963) collected tissue from seven crop species, plus pine, growing in the vicinity of an aluminum factory in Oregon. Increases in leaf fluoride were found after the factory began operation. Fluoride increases were correlated with wind direction and distance from the factory.

Middleton and Paulus (1956) designed a crop survey for air pollution damage in California, using a special survey card for entry of information from various areas. Four types of crops were used and several pollutant damage characteristics were included. Toxicants responsible for plant damage included "smog", ethylene, and fluorides.

Field Monitoring–Bioassay

After field surveys have identified the presence of a pollutant, or a group of pollutants, field monitoring with selected plants may be used to better identify the problem. In these field bioassays, a sensitive species is grown under specific conditions before and after exposure in the field for a specified period of time. The results are used to estimate the pollutant load in the field.

An early field bioassay was done in Los Angeles (Noble & Wright, 1958) using annual bluegrass as the monitoring species. The study was intended to determine the feasibility of replacing automatic instrumentation with bioindicators to determine the relative concentrations of phytotoxic oxidants. The authors believed that the bioindicators were a good indicator of the response of biological systems and that responses should correlate with oxidant concentrations. The plants were grown and transported under controlled conditions (Juhren, Noble & Went, 1957). They were transported to holding chambers in various locations throughout Los Angeles County, exposed for a 24-hr period, then returned to a charcoal filtered chamber during symptom development. Annual bluegrass was used because it was sensitive to oxidants and showed characteristic markings on given aged tissue of specific leaves (Bobrov,1955). The area injured was determined and compared with the severity of the pollution episodes. Since the results showed poor correlation between oxidant concentrations and plant injury, and the procedures were time consuming, the program was not continued.

Middleton, Kendrick, Jr., and Darley (1955) also tried to use a bioassay to monitor oxidant pollution in the Los Angeles area. They removed the epicotyl of pinto bean just above the primary leaves and used the primary leaves for the bioassay; the plants were grown under greenhouse conditions. Five stations were established and operated for 4 months in the fall of 1954. Maximum and mean oxidant values were recorded at all stations and fresh plants were set out each day. The percent of days showing plant damage and the average injury index for each station were recorded. The correlation of injury with oxidant values was significant at two stations; when all values were combined, no significance was found.

Berry and Hepting (1964) identified a white pine disease in eastern Tennessee that they related to air pollution. Although sensitivity varied within the species, individual tree response was highly uniform. They used grafted clones (Young stems cut from same trees and attached to a young root stock) from individual trees of both the resistant and sensitive types as indicators of the air pollution condition. When both sensitive and resistant trees were exposed in the polluted area only the sensitive plants showed symptoms; in a pollution-free area they were unmarked. From this early work, white pine clones were developed as sensitive indicators of O_3, SO_2 or HF air pollution problems; they proved useful in mapping the extent of the polluted area.

Gladiolus cultivars have been used as bioindicators of low atmospheric concentrations of fluoride. Tip burn in leaves develops after a few weeks of exposure to less than 1 ppb of fluoride. Leaf area, or length, burned has been used to indicate the relative atmospheric concentrations of fluoride (Hichcock, Zimmerman & Coe, 1962). Hitchcock, Zimmerman, and Coe (1963) monitored field and greenhouse exposures of sorghum tp HF using the cultivar Snow Princess gladioulus as the monitor. They were interested in studying growth and yield of sorghum exposed over time to < 1 ppb of flouride.

Glater, Solberg and Scott (1962) related cellular differentiation and growth in tobacco to the patterns of damage associated with leaf injury due to oxidant pollution. The damage pattern was specific for photochemical oxidants and was used to identify the presence of oxidants in ambient air. Heck, Fox, Brandt and Dunning (1969) and Heck and Heagle (1970) utilized tobacco Bel W3 (Heggestad & Menser, 1962) in developing a field bioassay technique for O_3. This system has been widely used in the U.S. and other countries and is described in greater detail later in this paper.

Bioassay of Controlled Exposures

The chemistry of photochemical oxidants is complex. In many of the early studies, there was a lack of chemical techniques to identify specific toxic components. Thus several plants, sensitive to the oxidant complex, were used to help elucidate the chemical nature of these phytotoxicants (Heck, 1966).

The research dealt with seven chemical reaction systems or specific pollutants. The foliar injury syndrome for specific plants was used to monitor the products from these systems. The pollutants (or reaction systems) important in the photochemical complex are: O_3, O_3 plus hydrocarbon, O_3 plus hydrocarbon (an irradiated mixture), nitrogen oxide plus hydrocarbon (an irradiated mixture), irradiated automobile exhaust, irradiated aldehydes, and ambient oxidant (Heggestad, Burleson, Middleton & Darley, 1964; Stephens, Darley, Taylor & Scott, 1961; Haagen-Smit, Darley, Zaitlin, Hull & Noble, 1952; Heck, 1964; Hindawi, Dunning & Brandt, 1965; Hull & Went,1952).

Analysis of the experimental results suggests seven specific phytotoxicants or classes of phytotoxicants. The seven are characterized on the basis of the response of sensitive plant tissues and the reaction systems used: (a) O_3 causes a white fleck or stipple on the leaves of sensitive plants, (b) an ozone-like injury occurs that is distinguished from O_3 injury by differential foliar response of mature tobacco plants, (c) PAN causes an undersurface glaze on young pinto bean primary leaves and on other sensitive plants, (d) a PAN-like injury affects similar plant tissue but occurs in responseto a nitrogen-free reaction system (O_3 plus hydrocarbon, irradiated), (e) a PAN-like injury on the undersurface of older pinto bean primary leaves but not on the undersurface of the young primary leaves from a nitrogen-free reaction system (O_3 plus hydrocarbon), (f) an upper surface glaze occurs on sensitive young leaf tissue exposed to irradiated auto exhaust, and (g) a nonoxidant that passes a reducing filter produced an oxidant type glaze on tomato. This research was not carried on to identify the specific chemicals responsible for the plant response observed, except of O_3 and PAN.

Plant Monitoring Systems

Extensive plant monitoring protocols have been developed for specific purposes. This section highlights several of these efforts but does not review those already covered in an earlier section. The use of tobacco as a monitor for photochemical oxidants was developed to determine time and space responses on a transect from a large urban area to a rural area. The tobacco program is covered in some depth becuase it has been extensively used.

Tobacco, A Sensitive Monitor for Photochemical Air Pollution

We have discussed several attempts to assess ambient oxidant levels and to identify specific oxidant components by exposing sensitive plant species to ambient air (i.e. annual bluegrass, petunia, pinto bean, tobacco). In these monitoring efforts, the monitoring plants were grown in carbon filtered air, exposed to ambient air for 24 hours, and returned to filtered air conditions for symptom development. The correlation of injury with oxidant levels was not very successful. Macdowall, Mukammal and Cole (1964) found a good correlation between tobacco injury and oxidant concentration when a coefficient of evaporation (an empirical factor calculated from the rate of evapotranspiration, wind speed and vertical water vapor gradient) was included in the function.

Tobacco (*Nicotiana tobacum*, L.) is an excellent monitor for O_3 because new leaves are produced continuously during the growing season, leaves vary in sensitivity by age, leaves are uniformly sensitive at a given age, and new

Table 1. Weekly and seasonal plant injury/oxidant ratios at oxidant-monitoring site. [From Heck & Heagle, 1970.]

Period	Weekly[a] 1966	1967	Ratios[b] 1968
1	0.06	0.03	0.04
2	0.74	0.30	1.21
3	0.74	0.56	0.29
4	1.52	5.70	0.33
5	1.38	0.77	0.47
6	1.77	5.80	0.61
7	1.16	1.19	0.78
8	0.34	1.29	0.86
9	0.97	1.71	1.33
10	2.04	1.33	0.60
11	1.89	0.70	1.39
12	0.66	2.10	0.98
13	1.04	1.59	1.52
Season Average	1.03	1.13	0.80'

a) Monitoring began on 6/10, 6/6,and 6/4 in 1966, 1967, and 1968, respectively.
b) Ratios are derived from values shown in Table 1 of Heck and Heagle (1970).

injury is easily separated from old injury. The tobacco variety Bel W3 is very susceptible (Heggestad & Menser, 1962) and shows characteristic and easily identifiable symptoms of O_3 injury.The response of Bel-W3 was used to determine the distribution, frequency of occurrence, and levels of photochemical oxidant (O_3) in rural areas near a large urban complex (Heck et al., 1969; Heck & Heagle, 1970).

Bel W3 tobacco, as a monitor for O_3, has received such widespread use that it seems worthwhile to give a brief discussion of the system and the first program (Heck et al. 1969). Four to 8 week old tobacco seedlings, grown in charcoal-filtered air, were transplanted into bushel baskets in a peat-perlite-soil mixture and exposed to ambient air at each of five sites located from 5 to 75 miles East of Cincinnati, Ohio (1966, 1967). Two of the plants were replaced with fresh 7 to 8 week old plants every 3 to 4 weeks. The total injury per plant, obtained by adding the percentage injury to each leaf, was determined three times per week and recorded as a weekly plant injury index for each location as an average of the four test plants. Oxidant (O_3) levels were continuously recorded at the main laboratory; hourly values above 0.03 ppm were

Table 2. Weekly oxidant indices and plant injury indices for the 1967 monitoring program.[From Heck & Heagle (1970)[a]]

Distance & Direction[c]	Weekly Period[b] 1	2	3	4	5	6	7	8	9	10	11	12	13	Total
5-E (lab)	310	200	90	35	110	40	80	210	170	135	150	95	110	1735
5-E (lab)	10	60	50	200	85	230	95	270	290	180	110	200	175	1955
7-NE	40	125	200	185	110	120	75	255	2609	240	160	801	35	1985
25-E	15	65	130	215	340	80	80	265	225	205	140	115	280	2155
50-E	10	65	240	230	255	115	65	20	255	75	75	120	140	1850
75-E	0	25	85	285	125	260	225	140	270	205	205	120	230	2025

a) Definitions for weekly oxidant and plant injury indices are given in the text.
b) Monitoring began on June 6, 1967.
c) Distance in miles and direction from City (NE=Northeast; E=East).

summed for the period from 6 am to 10 pm each day, and then for the 7-day period.The seven-day totals were arbitrarily divided by 2 to determine the weekly oxidant (ozone) indices. The ratios of weekly injury indices to oxidant indices at the main laboratory revealed no consistent relationship between injury and oxidant indices (Table 1). However, the seasonal ratios for three years (a third year of monitoring was carried out at the 7-mile site) were similar, suggesting that the seasonal phytotoxic potential of the oxidant complex was similar over years.The weekly site-to-site variations in plant responses (Table 2, 1967 only) indicate variations in phytotoxicant potential at the five monitoring sites, but the accumulated seasonal total indices across the five sites are similar. The weekly variations suggest that Cincinnati was not the source of the oxidant at the various sites. The results of this monitoring program were the first to show that all of Southwestern Ohio is affected by phytotoxic concentrations of oxidant and that oxidant (primarily O_3) is not just an urban problem but affects both rural and urban America. The authors (Heck & Heagle, 1970) suggested that all areas East of the Mississippi River had sufficient photochemical pollution to injure sensitive plants. Since that publication, the ubiquitous nature of ozone has been confirmed.

The monitoring system described above has provided communities with estimates of the frequency of occurrence of phytotoxic levels of oxidants (O_3), of the relative severity of each episode, and of the regional distribution of O_3. This has formed the basis for law suits throughout the U.S. and Canada, and in a number of European countries.

Selected Other Monitoring Systems

Many plant species have been used to monitor chemical releases from industrial operations. Cotton, alfalfa and giant ragweed have been use to monitor acute doses of SO_2 from point sources (i.e. smelter and power plants). Cotton and grape are sensitive monitors for growth-hormone type herbicides (2,4-D). Gladiolus and other bulb type plants have been used to monitor fluoride exposure (Compton, Remmert & Mellenthin, 1963; Hitchcock at al., 1962; Hitchcock et al.,1963).The release of chemicals from a number of industrial sources is often first observed on sensitive species. These species are often used for monitoring future releases.

An example of a specific problem that we became involved with near Raleigh, N.C., was the apparent release of chemicals from one or two industrial plants. The problem was first identified based on injury and death of loblolly pine found within several miles of the industrial plants. Injury to needles was not always definitive, but was helpful in diagnosing the problem. There were no major chemical releases that might account for the pine response. A two year program was set up using clonal loblolly pine trees as test organisms from both a sensitive and resistant tree. Sensitive and resistant trees were planted at various locations around the industrial sites and at some distance from the sources. All sensitive trees were severely injured close to the industries, but the plants in the control areas were not affected. Trees were tested in opentop field chambers with and without charcoal filters and similar results were found with the sensitive pine trees. A number of chemicals (including aniline) were identified as being released from the industrial sources and were tested in controlled exposures. The sensitive trees showed similar symptoms to those found near the industrial sites when exposed to < 1 ppm of analine for relatively short periods of time. It was the first report of analine as an air pollutant. The sensitive pine trees served as an excellent monitoring test for this study and helped solve a pollution problem (Cheeseman, Lund, Doggett & Perry,1978; Cheeseman, Perry & Heck, 1980).

White pine, as a species, is differentially sensitive to the three gases: O_3, SO_2 and HF. Individual trees were identified that were selectively sensitive to only one of the three pollutants. Other tree species have been used as indicators of biologically harmful levels of pollutants (i.e., O_3 - sycamore, tulip, poplar; SO_2 - several pine, oak, maple; HF - grape, apricot, pine). Lichen and moss species have been used to define the overall biological health around large industrial complexes and industrial cities. Generally, the results show a slow deterioration and death of the sensitive species that correlates well with pollution indices.

Pollutant Uptake

Plants have also been used as accumulators of many known atmospheric pollutants. Those most studied have been SO_2 (S accumulation, Bieberdorf, Shrewsbury, McKee & Krough, 1958; McKee,1961), HF (F accumulation, Compton, Remmert & Mellenthin, 1963; Hitchcock, Zimmerman & Coe, 1963) and various heavy metals (i.e., Pb, Cu, Zn, Cd, Hg). Ozone does not accumulate and many organics have been deemed difficult to separate from naturally occurring organics. Results with S are mixed because of the high concentrations of S in soils and the role of S in plant metabolism; studies of chronic S levels need to be done with care.

A number of plants have been used to monitor pollutant uptake–with grasses and lower plants (lichens, mosses) being used most successfully. Grasses are valuable here because they can often accumulate fairly large concentrations of a given pollutant without showing adverse effects (i.e., visible injury or reductions in growth).

The Germans have made some effort to develop plants to monitor hydrocarbons/organics in the atmosphere. They have had some success in these efforts (i.e. binzoa pyrene uptake by Brassica was identified) and their results and techniques should be seriously reviewed (Steubing, Kirschbaum, Poof & Corneluis, 1983). The spider plant has been identified as an accumulator of formaldehyde in a recent study (Wolverton, McDonald & Watkins, Jr. 1984).

Plant Monitoring Programs

Several early programs in the U.S. have been overviewed in previous sections of this paper and will not be repeated. However, the most extensive and long term monitoring programs have been established in Europe and are worth comment. Although lichens have been used widely in many countries and around many industries (there are many hundreds of articles in the literature on lichens as monitors), they will not be further discussed in this paper. However, it should be recognized that lichen systems might be worth testing for indoor air pollution problems (i.e., the "sick" building syndrome).

The Program in the West German State of North Rhine-Westfallia

Staff at the Landesanstalt für Immissions und Bodennutzungsschütz des Landes Nordrheim-Westfalen in Essen initiated a biological monitoring program in the early 1970s (Prinz & Scholl, 1975) which, although changed, is continuing. The primary purpose was to cover the Rhein-Ruhr area with a network of sensitive biological indicators and to relate effects with pollution loading. They used two plants in these studies (Prinz & Scholl, 1975). The first was a lichen species (*Hypogymnia physodes*) which was grown on a board (10 samples per board) at each monitoring site. The boards were photographed periodically and the photographs were subjectively evaluated for percent of dead thallus tissues. There appeared to be a seasonable correlation with thallus death and population density in the study area. The second bioindicator was a standardized grass culture exposed for 14 days and then clipped. Concentrations of sulfur, fluorine, lead, zinc and cadmium were determined. Concentrations correlated well with housing and industrial density. This type of monitoring was a primary goal of the Landesanstalt for many years.

The Program in the Netherlands

Posthumus, 1976, 1981 reported on the use of higher plants as indicators of air pollution within the Netherlands.The biomonitoring program which they developed is probably the most intensive to date.The program was made part of the routine air pollution monitoring program for the Netherlands.The publications give some details on methods used to grow, expose and analyse the test plants. Methods have been made routine and repeatable. They use plants to monitor for peroxyacetyl nitrate, O_3, HF, SO_2, ethylene and nitrogen dioxide. Results are used to give them an idea of the severity of the effects and to estimate approximate levels of the pollutants.

The Program in Giessen West Germany

Steubing and Kirschbaum (1982) reported on a rather intensive bioindicator program around Frankfurt. They utilized lichen as a general indicator of pollution loading. They also used a number of plant species that are known to be sensitive to specific pollutants in their monitoring design. Results were closely related to expected pollution levels. Unlike other pollutants, oxidants were found at distances from the city. They did analyse for polycyclic aromatic hydrocarbons in plant tissues. This was apparently a successful monitoring effort.

The use of Plants to Monitor Indoor Air Pollution

It is clear that different plant species/cultivars have been successfully used to help identify toxic chemicals in the atmosphere. Likewise, some plants have made useful accumulators of selected phytotoxic chemicals in the identification of the presence of the phytotoxicant.Thus, it is reasonable to suggest that plants may develop identifiable symptoms associated with indoor air pollution or the "sick building" syndrome. Likewise, plants may serve as accumulators of specific chemicals and thus may be used to identify the presence of the chemical(s) in indoor pollution problems.This does not mean that plants will enable us to identify the component(s) toxic to humans, but the plants might identify a complex of chemicals associated with a given problem.

A case in point can be made using, as an example, a severe indoor air pollution problem associated with a greenhouse complex (unpublished). The greenhouse was built as a self-contained unit over an old petroleum refinery area and was set up to grow tomato and cucumber on a commercial basis. The company felt they had satisfactorily isolated the greenhouse from any soil contamination. After several months of growth, severe injury and growth abnormalities developed in both species, and yield was reduced. In time, they were not able to grow the plants to maturity. They identified many hydrocarbons in the greenhouse air (in the ppm range) but none had known phytotoxic effects. It was surmised that a complex of the hydrocarbons may have caused the injury. As of this writing, no specific chemical or group of chemicals has been specifically associated with the problem. It would take a major research effort to identify the specific active chemical(s). However, this example of an indoor air pollution problem suggests that plants might serve as a useful indicator of a general biological problem with indoor air quality.

Another system that concerns many of us is the Closed Environmental Life Support System (CELSS) that William T. Knott discusses in this volume (Chapter 11). In this system there is concern for the quality of the atmosphere. Initially the concern is directed more at growing plants in closed systems than in the potential for health effects but for the total program the health affects will be a major concern. Research to date has identified numerous contaminants but it has not been carried far enough to know what, if any, phytotoxic problems will arise. This section is meant to address research needs in the development of plants to monitor indoor air pollution problems.

Characterize the Chemical Atmosphere

It is important that the indoor chemical atmosphere of "sick buildings" be well-monitored and as many chemicals identified as possible. From this information, the biologist can make some predictions as to possible phytotoxic effects. Alternatively if interest is high, the biologist may be able to use the information to experimentally identify the active component(s) of the indoor atmosphere that causes a phytotoxic response. This would certainly be true if there were a single phytotoxicant present or a combination of two or possibly three. If the complex was phytotoxic and no individual or small group of chemicals produced similar results, one could hypothesize that the mix of chemicals caused the effects seen (see Chapter 7). A characterization of the chemical atmosphere is also necessary to differentiate "sick" and healthy buildings. Assuming healthy buildings do not induce a phytotoxic response, or that the response is different, the differential chemistry of the two types of buildings can be used to help isolate or identify the phytotoxic component(s).

Preliminary Experimental Research

A survey of sick buildings for sick plants could be one approach to identifying sensitive test (monitoring) species. Alternatively, plants which are known to be sensitive to air contaminants, or other stresses, could be grown under similar growing conditions in both "sick" and healthy buildings. A detailed analysis of these plants could be used as an initial indication of differential sensitivity to the two atmospheres as a means of identifying possible monitor-'ing species. In instances where differences are found, the plants should be further tested in both atmospheres using filtered versus unfiltered chamber comparisons. If the filtered chamber is designed to remove all or most of the atmospheric pollution load, one would expect to see healthy plants in the filtered chamber and some identifiable unhealthy response in the unfiltered chamber in the "sick" building comparisons. A similar, but probably less pronounced, effect may occur in the healthy building comparisons. Differences should be well described and repeatable before a plant can be seriously considered for a monitoring program.

Growth of Plants Under Prescribed Conditions

Once one or more potential monitoring plants has been identified, tests should be run under controlled growth conditions to identify those conditions under which the best growth can be described for each species/cultivar. When these are determined, specially designed exposure chamber [using the continuous stirred tank reactor (CSTR) concept] should be used to maintain the growth conditions (Heck, Philbeck & Dunning, 1978). The chambers should be used as filtered vs non-filtered chambers in both sick and healthy buildings to better quantify the effects found.

Visual differences found between the filtered and non-filtered chambers in both sick and healthy buildings should be completely characterized. Assuming that identifiable responses are found, these should be described. Research could then be directed at identifying short-term or long-term physiological responses that could be used to further characterize the sick building syndrome. Assuming the approach is reasonable, the experimenter could broaden his/her interests and try to understand what is happening and to identify the toxic components in the sick building atmosphere.

Summary

Plants served as the first visual evidence of the presence of sulfur dioxide in the atmosphere around smelter operations in both Europe and North America. Since these early observations, plants have been used to assess air quality around many industrial sources. Plants have also been used to assess the biological importance of ozone as a widespread pollutant throughout the industrialized world. Since the 1950's, a number of programs have identified and utilized specific plants, grown under specified conditions, to assess air quality and to relate effects to concentrations of a given pollutant. Results have included the identification of specific foliar injury symptoms and the uptake of pollutants in plant foliage. The possibility of utilizing sensitive plants under specified growth conditions, to monitor the biological toxic potential of indoor air pollution, is discussed. A protocol for developing such systems is presented.

References

Berry, C.R., & Hepting, G.H. (1964). Injury to eastern white pine by unidentified atmospheric constituents. *Forest Science*, **10**, 2-13.

Bieberdorf, F.W., Shrewsbury, C. L., McKee, H. C., & Krough, L. H. (1958). Vegetation as a measure indicator of air pollution-I.: The pine (*Pinus taeda*). *Bulletin ofThe Torrey Botanical Club*, **85**, 197-200.

Bobrov, R.A. (1955). The leaf structure of Poa annua with observations on its smog sensitivity in Los Angeles County. *American Journal of Botany*, **42**, 467-474.

Cheeseman, J.M., Lund, S.C., Doggett, C.A., & Perry, T.O. (1978). The use of meterological modeling and biological indicators to identify sources of phytotoxic pollutants. *Journal Air Pollution Control Association*, **28**, 1213-1216.

Cheeseman, J.M., Perry, T.O., & Heck, W.W. (1980). Identification of anniline as an air pollutant through biological assay with lablolly pine. *Environmental Pollution* (Series A), **21**, 9-22.

Cole, G. A. (1959). Vegetation survey methods in air pollution studies. *Agronomy Journal*, **50**, 553-555.

Compton, O.C., Remmert, L.F., & Mellenthin, W.M. (1963). Flourine Levels in 1961 Crops of the Dallas Area. Oregon Agricultural Experiment Station, Special Report 153, Corvallis, Oregon.

Crocker, W. (1948). *Growth of Plants*, pp.139-203. New York: Reinhold.

Darley, E.F., Dugger Jr. W.M., Mudd, J.B., Ordin, L.O., Taylor, C., & Stephens, E. R. (1963). Plant damage by pollution derived from automobiles. *Archives of Environmental Health*, **6**, 761-770.

Glater, Ruth A., Solberg, R.A., & Scott, F.M. (1962). A developmental study of the leaves of Nicotiana glutinosa as related to their smog sensitivity. *American Journal of Botany*, **49**, 954-970.

Haagen-Smit, A.J., Darley, E.F., Zaitlin, M., Hull, H., & Noble, W. (1952). Investigations on injury to plants from air pollution in the Los Angeles area. *Plant Physiology Lancaster*, **27**, 18-34.

Heck, W.W. (1964). Plant injury induced by photochemical reaction products of propylene-nitrogen dioxide mixtures. *Journal of Air Pollution Control Association*, **14**, 255-261.

Heck, W.W. (1966). The use of plants as indicators of air pollution. *International Journal of Air and Water Pollution*,**10**, 99-111.

Heck, W.W., & Pires, E.G. (1962). Effect of ethylene on horticultural and agronomic plants.Texas Agricultural Experiment Station, MP613. College Station, Texas.

Heck, W.W., Philbeck, R. B., & Dunning, J. A.(1978). A continuous stirred tank reactor (CSTR) system for exposing plants to gaseous or vapor contaminants: Theory, specifications, construction, and operation. Agricultural Research Service, Series No. ARS-S-181. 32 pp. North Carolina State University, Raligh, NC.

Heck, W.W., Fox, F.L., Brandt, C.S., & Dunning, J.A. (1969). Tobacco, a sensitive monitor for photochemical air pollution. National Air Pollution Control Administration Publication Number, AP-55. North Carolina State University, Raligh, NC.

Heck, W.W. & Heagle, A.S. (1970). Measurement of photochemical air pollution with a sensitive monitoring plant. *Journal of Air Pollution Control Association*, **20**, 97-99.

Heggestad, H.E., & Menser, H.A. (1962). Leaf spot-sensitive tobacco strain Bel-W3, a biological indicator of the air pollutant ozone. *Phytopathology*, **52**, 735.

Heggestad, H.E., Burleson, F.R., Middleton, J.T., & Darley, E.F. (1964). Leaf injury on tobacco varieties resulting from ozone, ozonated hexene-1, and ambient air of metropolitan areas. *Air and Water Pollution International Journal*, **8**, 1-10.

Hindawi, I.J., Dunning, J.A., & Brandt, C.S. (1965). Morphological and microscopical changes in tobacco, pinto bean and petunia leaves exposed to irradiated auto exhaust. *Phytopathology*, **55**, 27-30.

Hitchcock, A.E., Zimmerman, P.W., & Coe, R.R. (1962). Results of ten years' work (1951-1960) on the effect of flourides on gladiolus. *Contributions of the Boyce Thompson Institute for Plant Research*, **21**, 303-344.

Hitchcock, A.E., Zimmerman, P.W., & Coe, R.R. (1963). The effect of fluorides on milo-maize (*Sorghum Sp.*). *Contributions of the Boyce Thompson Institute for Plant Research*, **22**, 175-206.

Hitchcock, A.E., Weinstein, L.H., McCune, D.C., & Jacobson, J.S. (1964). Effects of flourine compounds on vegetation, with special reference to sweet corn. *Journal of Air Pollution Control Association*,**14**, 503-508.

Hull, H. M., & Went, F. W. (1952). Life processes of plants as affected by air pollution. In: *Proceedings Second National Air Pollution Symposium*. Pasadena, Los Angeles Country, California, pp. 122-128.

James, H.A. (1963). Losses in Cattleya orchids attributed to air pollution in the Bay area. Bay Area Air Pollution Control District, San Francisco, California Information Bullitin, pp. 8-63.

Juhren, M., Noble, W., & Went, F.W. (1957). The standardization of Poa annua as an indicator of smog concentrations–I: Effects of temperature, photoperiod and light intensity during growth of test plants. *Plant Physiology Lancaster*, **32**, 576-585.

Katz, M. (1949). Sulfur dioxide in the atmosphere and its relation to plant life. *Industrial Engineering Chemistry*, **41**, 2450-2465.

MacDowall, F.D.H., Mukammal, E.I., & Cole, A.F.W. (1964). Direct correlation of air-polluting ozone and tobacco weather fleck. *Canadian Journal of Plant Science*, **44**, 410-417.

McKee, H.C. (1961). Use of vegetation to measure air pollution. In: *Annual Technical Meeting*, Institute Mexicano de Ingenieros Quimicos, A.C., Mexico.

Middleton, J.T. (1961). Photochemical air pollution damage to plants. *Annual Review Plant Physiology*, **12**, 431-448.

Middleton, J.T., Kendrick, Jr. J.B., & Darley, E.F. (1955). Airborne oxidants as plant-damaging agents. In: *Proceedings Third National Air Pollution Symposium*, Pasadena California, pp. 191-198.

Middleton, J.T. & Paulus, A.O. (1956). The identification and distribution of air pollutants through plant response. *Archives Industrial Health*, **14**, 526-532.

Noble, W.M., & Wright, L.A. (1958). A bio-assay approach to the study of air pollution. *Agronomy Journal*, **50**, 551-553.

Posthumus, A.C. (1976). The use of higher plants as indicators for air pollution in the Netherlands. In L. Karenlampi (Ed.), *Proceedings Kuopio Meeting on Plant Damages Caused by Air Pollution.* Wageningen, The Netherlands, pp 115-120.

Posthumus, A.C. (1981). De invloed van lucht verontreiniging op planten. *Natuur en Techniek*, **49**, 488-507.

Prinz, B., & Scholl, G. (1975). The increased uptake and effects of gaseous and particulate air pollutants during episodes. In: *Schriftenreihe der Landesanstalt für Immissions - und Bodennutzungsschutz des Landes Nordrheim-Westfalen* (Essen),**36**, pp. 62-86.

Scheffer, T.C., & Hedgcock, G.G. (1955). Injury to Northwestern Forest Trees by Sulfur Dioxide from Smelters. U.S. Department of Agriculture, Technical Bulletin, 1117. Washington, DC.

Stephens, E.R., Darley, E.F., Taylor, O.C., & Scott, W.E. (1961). Photochemical reaction products in air pollution. *Air and Water Pollution International Journal*, **4**, 79-100.

Steubing, L.,& Kirschbaum, U. (1982).Bioundibation vonuftschadstoffen un Ballungsraum Frankfurt/M. mittels Flechten and hoherer pflangen.*Staub- Reinhalt*, **42**, 273-280.

Steubing, L., Kirschbaum, U., Poof, F., & Corneluis, R. (1983). *Monitoring mittels bioindicators in Belastung.* Umland der Band, Frankfurt. 180 pp.

Thomas, M.D. (1951). Gas damage to plants. *Annual Review Plant Physiology*, **2**, 293-322.

Weinstein, L.H. (1961). Effects of atmospheric flouride on metabolic constitutents of tomato and bean leaves. *Contributions of The BoyceThompson Institute for Plant Research*, **21**, 215-231.

Wolverton, B.C., McDonald, R.C., & Watkins, Jr. E.A. (1984). Foliage plants for removing indoor air pollutants from energy-efficient homes. *Economic Biology*, **32**, 224-228.

Zimmerman, P.W., & Hitchcock, A.E. (1956). Susceptibility of plants to hydrofluoric acid and sulfur dioxide gases. *Contributions of The Boyce Thompson Institute for Plant Research*, **18**, 263-279.