START INDEX

WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 147

REVIEW OF PRESENT KNOWLEDGE OF PLANT INJURY BY AIR POLLUTION

by

E. I. Mukammal

Report of the CAgM Rapporteur on Non-radioactive Pollutants
of the Biosphere and Their Injurious Effects on Plants,
Animals and Yields

WMO - No. 431

Secretariat of the World Meteorological Organization - Geneva - Switzerland

START INDEX

The WMO

The World Meteorological Organization (WMO) is a specialized agency of the United Nations of which 145 States and Territories are Members.

It was created:

- To facilitate international co-operation in the establishment of networks of stations for making meteorological and geophysical observations and centres to provide meteorological services and observations;
- To promote the establishment and maintenance of systems for the rapid exchange of meteorological information;
- To promote standardization of meteorological observations and ensure the uniform publication of observations and statistics;
- To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;
- To encourage research and training in meteorology.

The machinery of the Organization consists of the following bodies:

The *World Meteorological Congress*, the supreme body of the Organization, brings together the delegates of all Members once every four years to determine general policies for the fulfilment of the purposes of the Organization, to adopt Technical Regulations relating to international meteorological practice and to determine the WMO programme.

The *Executive Committee* is composed of 24 directors of national Meteorological Services and meets at least once a year to conduct the activities of the Organization and to implement the decisions taken by its Members in Congress, to study and make recommendations on matters affecting international meteorology and the operation of meteorological services.

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The *Secretariat*, located at Geneva, Switzerland, is composed of an international scientific, technical and administrative staff under the direction of the Secretary-General. It undertakes technical studies, is responsible for the numerous technical assistance and other technical co-operation projects in meteorology throughout the world aimed at contributing to economic development of the countries concerned. It also publishes specialized technical notes, guides, manuals and reports and in general acts as the link between the Meteorological Services of the world. The Secretariat works in close collaboration with the United Nations and other specialized agencies.

START INDEX

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START INDEX

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START INDEX

CONTENTS

START INDEX

START INDEX

FOREWORD

In recent times there has been widespread and justifiable concern regarding the effect of pollutants on the environment. One of the less publicized but nonetheless important aspects of pollution lies in the harmful effects of air pollutants on plants which may lead to direct visible damage and to a reduction in crop yield. Such harmful effects are of particular significance in view of the serious world food problems and the consequent need to expand agricultural production.

A detailed review of plant injury by air pollutants was published in WMO Technical Note No. 96 entitled *Air pollutants, meteorology, and plant injury*. As a follow-up to this work, the WMO Commission for Agricultural Meteorology at its fifth session (Geneva, 1971) appointed a rapporteur (Mr E. I. Mukammal) to review further progress in research on the meteorological aspects of the injurious effects of non-radioactive pollutants in the biosphere on plants, animals and yields.

The rapporteur's report is now published in the present WMO Technical Note. I am confident that this publication will be of great value to workers concerned with the agricultural aspects of air pollution.

It gives me great pleasure to express to the author the appreciation of the Organization for the time and effort which he has devoted to the preparation of this important report.

D. A. Davies.

D. A. Davies
Secretary-General

START INDEX

SUMMARY

The effects of various air pollutants on economically important crops and ornamentals have received little public or governmental attention despite the world-wide concern regarding the environmental quality of our biosphere due to increasing domestic and industrial pollution. It should be borne in mind that many damaging pollutants are produced from natural sources rather than from human activities. Soil acts as an efficient sink for several pollutants and many pollutants are in fact valuable nutrients and in moderation may enhance crop growth, particularly when such nutrients in the soil are in short supply.

Considerable attention has been and is being directed by scientists towards defining the biochemical and physiological responses of organisms to air pollutants. Air pollution may directly or indirectly modify a wide variety of factors leading to an increase or decrease in plant diseases, although neither the detrimental and the beneficial factors, nor the ways in which the effects are produced are known. Variability in response to pollutants is known to depend on several factors such as the species of plants, stage of development and the plant environment. For injury to plants to occur, the pollutants or their by-products must reach living cells within the plants. Thus, it is only the flux of pollutants through the stomata that normally causes the plant injury.

A comprehensive model for the quantitative evaluation of the damaging effects of a single and/or multiple pollutant at all stages of the plant for both acute and chronic exposure over a wide range of concentration and time and under varying environmental conditions is greatly needed.

Chapter 1 describes the role of plants and agriculture as sources of pollutants and Chapter 2 gives a review of present knowledge regarding the effect of pollutants on plants and includes a brief discussion on pollutants beneficial to vegetation, pollutants and plant diseases and protection of vegetation against pollutants.

Chapter 3, which constitutes a major portion of the publication, is devoted to the results of growth-chamber investigations on plant response to air pollutants, the limitations of these results, the role of meteorology in the dispersion and transport of air pollutants, micrometeorological methods of evaluating the vertical fluxes of matter and studies relating to pollutants uptake within a vegetation canopy. This chapter also enumerates agricultural requirements for meteorological information for operational and research programmes. Mention is also made of simulation models employed for quantitative estimates of the damaging effects of pollutants on plants.

Chapter 4 deals with meteorological data and instrumental requirements for computing concentrations and dosages of pollutants. Recent developments in this regard are outlined and the potential role of remote sensing techniques in pollution studies is discussed.

An extensive bibliography concludes the report.

RÉSUMÉ

L'action que les divers polluants de l'air exercent sur les plantes cultivées pour leur valeur économique et sur les plantes d'ornement n'a guère attiré l'attention du public ou des gouvernements, malgré les craintes que suscite dans le monde entier la dégradation de la qualité de l'environnement de notre biosphère, consécutive à l'augmentation de la pollution d'origine domestique et industrielle. Il convient de ne pas perdre de vue le fait que beaucoup de polluants délétères proviennent de sources naturelles plutôt que d'activités de l'homme. Le sol contribue efficacement à l'élimination de plusieurs polluants et un grand nombre de polluants sont d'ailleurs des substances nutritives qui, en quantités modérées, peuvent avoir un effet bénéfique sur la croissance des plantes, particulièrement lorsque le sol est naturellement pauvre en ces substances.

Les scientifiques ont accordé et continuent d'accorder énormément d'attention à la définition des réactions biochimiques et physiologiques des organismes aux polluants de l'air. La pollution peut influer directement ou indirectement sur des facteurs fort variés qui tendent à accroître ou à diminuer les maladies des plantes, bien qu'on ne sache pas encore très bien quels sont les facteurs néfastes et les facteurs bénéfiques, ni de quelle manière ils exercent leurs effets. On sait, par contre, que la réaction des plantes aux polluants dépend de plusieurs facteurs tels que l'espèce, le stade de développement et l'environnement de la plante. Pour que la plante subisse des dégâts, il faut que les polluants ou leurs sous-produits atteignent ses cellules vivantes. C'est donc seulement si les polluants circulent à travers ses stomates que la plante peut subir des dégâts.

Le besoin se fait fortement sentir d'un modèle réellement complet qui permette d'évaluer quantitativement les effets néfastes d'un polluant unique ou d'un ensemble de polluants, à tous les stades de croissance de la plante, que ce soit à la suite d'une attaque aiguë ou d'une action prolongée dans toutes les conditions possibles de concentration, de durée d'exposition et d'environnement.

La section 1 expose le rôle des plantes et de l'agriculture en tant que sources de polluants, tandis que la section 2 fait le point des connaissances actuelles en ce qui concerne les effets des polluants sur les plantes et analyse brièvement les sujets suivants : effets bénéfiques des polluants sur la végétation, polluants et maladies des plantes et protection de la végétation contre les polluants.

La section 3, qui est la section maîtresse de l'ouvrage, est consacrée aux résultats des recherches effectuées en atmosphère conditionnée, dans les phytotrons, sur les réactions des plantes aux polluants de l'air, aux précautions qui doivent être prises dans l'interprétation de ces résultats, au rôle de la métérologie dans la dispersion et le transport des polluants de l'air, aux méthodes microméteorologiques pour évaluer les flux verticaux de matière et aux études sur le mouvement ascendant des polluants sous un couvert végétal. Cette section énumère également les besoins de l'agriculture en matière de renseignements météorologiques pour les programmes d'exploitation et de recherche. Il y est également fait mention des modèles de simulation utilisés pour estimer quantitativement les effets néfastes des polluants sur les plantes.

La section 4 traite des besoins en matière de données météorologiques et d'instruments pour calculer les concentrations et effectuer les dosages de polluants. Elle fait état des progrès récents effectués en ce domaine et du rôle ouvert aux techniques de télémesure pour l'étude de la pollution.

Le rapport est complété par une biographie très copieuse.

РЕЗЮМЕ

Несмотря на всемирную озабоченность относительно качества окружающей среды нашей биосферы вследствие возрастающего бытового и промышленного загрязнения, влиянию различных загрязнителей в воздухе на экономически ценные культуры и декоративные растения уделялось небольшое внимание со стороны общественности и правительств. Следует иметь в виду, что многие опасные загрязнители появляются из естественных источников, а не в результате человеческой деятельности. Почва является эффективным поглотителем многих загрязнителей, и многие загрязнители являются ценными питательными веществами и в определенном количестве могут благоприятно воздействовать на произрастание культуры, особенно в том случае, когда питательные вещества в почве находятся в небольшом количестве.

Значительное внимание уделялось и уделяется со стороны ученых определению биохимических и физиологических реакций организмов на воздушные загрязнители. Загрязнение воздуха может прямым или косвенным образом изменить большое количество факторов, от которых зависит увеличение или уменьшение болезней растений, хотя вредные или благоприятные факторы, а также пути их влияния не известны. Различие в реакциях на загрязнители зависит от нескольких факторов, таких как виды растений, степень развития и среда, окружающая растение. Чтобы повредить растение, загрязнители или их вторичные субстанции должны попасть в живые клетки растений. Таким образом, только поток загрязнителей через устьицу обычно причиняет повреждения растению.

Весьма необходимо создание всеобъемлющей модели для количественной оценки разрушительных влияний односоставного и/или многосоставного загрязнителя на всех стадиях роста растения для сильного и постоянного воздействия высоких уровней концентрации в течение продолжительного периода времени и при изменяющихся условиях окружающей среды.

В разделе 1 описывается роль растений и сельского хозяйства как источников загрязнителей. В разделе 2 дается обзор существующего состояния знаний о влиянии загрязнителей на растения; в краткой форме говорится о загрязнителях, оказывающих положительное воздействие на вегетацию, на болезни растений и о защите вегетации от загрязнителей.

Раздел 3, который составляет основную часть публикации, посвящен результатам исследований о реакции растений, помещенных в камеры, на воздушные загрязнители, недостаткам этих результатов, роли метеорологии в дисперсии и переносе воздушных загрязнителей, микрометеорологическим методам оценки вертикальных потоков вещества и исследованиям о попадании

РЕЗЮМЕ

загрязнителей в купол вегетации. В этом разделе перечислены требования сельского хозяйства к метеорологической информации, необходимой для оперативных и исследовательских программ. В указанном разделе также рассказывается об имитирующих моделях, используемых для количественной оценки вредного воздействия загрязнителей на растения.

В разделе 4 рассказывается о метеорологических данных и потребностях в приборах для расчета концентрации и доз загрязнителей. Резюмируются последние достижения в этой области и обсуждается потенциальная роль методов дистанционного зондирования в исследовании загрязнителей.

В конце отчета дана обширная библиография.

RESUMEN

La acción que los diversos contaminantes del aire ejercen en los cultivos importantes desde el punto de vista económico y en las plantas ornamentales ha recibido del público o de los gobiernos en general muy poca atención, a pesar de la preocupación que despierta en el mundo entero la degradación de la calidad del medio ambiente de nuestra biosfera, degradación debida al aumento de la contaminación de origen doméstico e industrial. Conviene tener presente el hecho de que gran número de contaminantes perjudiciales provienen de fuentes naturales, más que de las actividades del hombre. El suelo constituye un sumidero muy eficaz para la eliminación de diversos contaminantes y muchos de ellos son de hecho sustancias nutritivas que, en cantidades moderadas, pueden tener un efecto benéfico en el crecimiento de las plantas, particularmente cuando el suelo es naturalmente probre en tales sustancias.

Los científicos han otorgado y continúan prestando una enorme atención al problema de definir las reacciones bioquímicas y fisiológicas de los organismos frente a los contaminantes del aire. La contaminación puede influir directa o indirectamente en factores muy variados que tienden a aumentar o a disminuir las enfermedades de las plantas, aun cuando no se sabe de manera precisa cuáles son los factores perjudiciales y los factores benéficos, ni de qué manera esos factores ejercen sus efectos. Se sabe, por otra parte, que la reacción de las plantas a los contaminantes depende de varios factores tales como la especie, el grado de desarrollo y el medio en que se desenvuelve la planta. Para que la planta sufra daños, es necesario que los contaminantes o los subproductos de los mismos penetren en las células vivas de aquélla. Por consiguiente, normalmente sólo cuando los contaminantes circulan a través de los estomas de la planta se producen daños en esta última.

Se ha hecho sentir de manera muy acusada la necesidad de disponer de un modelo realmente completo que permita evaluar cuantitativamente, en todas las fases del crecimiento de la planta, los efectos nefastos de un contaminante único o de un conjunto de contaminantes bien como consecuencia de un ataque agudo o de una acción prolongada de contaminación en todas las condiciones posibles de concentración, de duración de exposición y de condiciones diversas del medio ambiente.

En la Sección 1 se describe la función de las plantas y de la agricultura como fuentes de contaminantes, mientras que en la Sección 2 se analizan los conocimientos actuales en lo que respecta a los efectos de los contaminantes en las plantas, y se examinan sucintamente las efectos benéficos de los contaminantes en la vegetación, los contaminantes y las enfermedades de las plantas, y la protección de la vegetación contra los contaminantes.

La Sección 3, que constituye la parte fundamental de la publicación, se consagra a los resultados de investigaciones sobre el crecimiento de las plantas, efectuadas en laboratorio y relativas a la forma en que reaccionan las plantas con respecto a los contaminantes del aire, a la precaución o cautela con que deben interpretarse esos resultados, al papel de la meteorología en la dispersión y transporte de los contaminantes del aire, a los métodos micrometeorológicos de evaluación de los flujos verticales de la materia, y a los estudios sobre el movimiento ascendente de los contaminantes bajo cobertura vegetal. En esa sección se enumeran asimismo las necesidades de la agricultura en lo que respecta a la información meteorológica que se requiere para los programas de explotación y de investigación. También se mencionan modelos de simulación utilizados para estimar cuantitativamente los efectos prejudiciales de los contaminantes en las plantas.

La Sección 4 trata de las necesidades en materia de datos meteorológicos y de instrumentos para calcular las concentraciones y llevar a cabo una dosificación de los contaminantes. En la misma se exponen los recientes progresos realizados en esa esfera, y se examinan las posibilidades que ofrece la utilización de técnicas de medida a distancia en los estudios de la contaminación.

Al final del informe figura una bibliografía muy completa.

START INDEX

CHAPTER 1

AGRICULTURE AND AIR POLLUTION

1.1 Introduction

In recent years, there has been increased world-wide concern regarding the environmental quality of the biosphere as a result of the general strong upward trend in the kind and amount of industrial and domestic pollutants in the atmosphere, although there are slight downward trends in many cities due to control activities. However, the main interest has been focused on the detrimental effects on human health and water quality. The effects of various air pollutants on economically important crops and ornamentals have received relatively little public and governmental attention despite the great and urgent need for increased food production to feed many hungry populations throughout the world. The reasons put forward are that sufficient information is already available on this subject and that abatement and control programmes will substantially decrease or eliminate the threat of damage to plants by air pollution. Heck *et al.* (1973) rightly refute the above argument by identifying the many research needs and by pointing out that the most sensitive plant species could not tolerate even the low concentrations presumably to be achieved by abatement and control. Nor should the point be overlooked that it is not always possible, nor even practical, to reduce or eliminate emissions. Moreover, atmospheric pollutants, other than SO_2 and fluoride, are produced more by sources of natural rather than human activity, and cause well over ninety per cent of losses to vegetation, either directly by mortality, growth reduction or impaired reproduction, or indirectly by impaired quality. Robinson and Robbins (1970) have shown that the oxides of nitrogen and hydrocarbons, which are the main compounds in the photochemical reactions forming oxidants, such as ozone and peroxyacetyl nitrate (PAN), are produced ten and five times more respectively, by natural (biotic and abiotic) sources than by human sources. Stasuik and Coffey (1974) report that "estimates of the quantity of ozone advectively transported into New York State are more than one order of magnitude greater than estimations of the potential photochemical generation of ozone and hydrocarbon emissions within New York State". De Muer (1975) postulates that surface ozone in Belgium comes from the free troposphere and is transported downwards rather than being generated by photochemical reactions.

Appreciable decreases in major man-made air pollutants appear unlikely for a long time to come. Therefore, plants and their ecosystems must adjust to this environmental impact, which may cause fundamental changes in the character of plant ecosystems and their components which we need to understand.

The meteorologist's interest and involvement in plant injury by air pollution stems from the fact that the atmosphere is responsible for the dispersion and dilution of the pollutants. The meteorologists can offer much valuable assistance on the questions of what happens between the emission source and the point at which pollutants are encountered, and of what can be done to reduce damage by incorporating meteorological knowledge into control programmes. Correlating observations of plant damage with meteorological conditions may also assist in identifying sources. This is particularly useful when damage is cumulative (as, for example, with fluorides). Alternatively, the symptoms on plants have frequently served as a kind of early warning system for the build-up of pollutants in the air, and thus plants may be used as tracers of atmospheric transport and dilution. When source emissions, plant injury and meteorology are all known, an estimate of dilution mechanisms can be formed.

Accurate statistical information on damage to plants is not available, particularly on reduced productivity caused by invisible injury; also visible injuries are not well documented even in conditions with advanced experimental techniques. Heggestad (1968) estimated that the losses due to these causes in the United States are about 500 million dollars per annum, about one quarter in California alone. Benedict *et al.* (1971) have calculated the total annual U.S. crop loss at $85 million, of which $78 million were due to oxidants, $3.5 million to SO_2, and $4.25 million to fluorides. Total loss to ornamentals was about $46 million, of which $43 million were ascribable to oxidants, $3 million to SO_2 and $175,000 to fluorides. These losses were based on fuel consumption data for 1963 and agricultural crop-value data for 1966. However, the emission data were not adjusted to include the effects caused by meteorological factors which could increase or decrease their concentrations. Also, no consideration was given to other factors, including: susceptibility and resistance of species in the estimates of loss to individual crops; natural sources of pollutants and visible and invisible effects of air pollutants on yield or growth. The above total losses might be underestimates which could certainly vary from year to year depending on weather conditions and edaphic and biotic factors. These are still significant, even though the dollar loss as a percentage of the total dollar value of all U.S. commercial crops (U.S. Department of Agriculture, 1965) was only about 0.5 per cent, contrary to Benedict *et al.* (1971) who estimate them at 1.2 per cent. On the other hand, losses due to plant diseases and insects have been placed at 10 per cent to 12 per cent and those due to weeds at 6 per cent to 8 per cent.

1.2 Plants and agriculture as sources of pollutants

The current increased public concern over air pollution has intensified the search for all sources of pollutants, including those emitted by vegetation and by means of agricultural and forestry practices. Many have already been discovered. Some, such as CO, are toxic to humans and animals, while others are injurious to plants either directly (e.g. nitrogen dioxide), or indirectly by interaction with other pollutants.

1.2.1 *Plants*

Carbon monoxide is a major product of the biological activity of terrestrial green plants, fungi and germinating seeds (Babich and Stotzky, 1972). Forests emit a significant amount of hydrocarbons in the form of volatile terpens, while wild forest fires, because of oxygen deficiency, contribute substantial amounts of particulates and hydrocarbons to the atmosphere. Vegetation produces other organic pollutants, such as ethanol, methanol, formaldehyde, acetaldehyde and formic acid, which are liberated from a variety of germinating seeds and seedlings. Ethylene is another organic pollutant whose production in the United States via agriculture, such as emissions from apples, is estimated to be 2.0×10^4 tons/year (Abeles *et al.*, 1971). Rotting vegetation and bacterial reduction of nitrates, such as in closed silos, contribute significantly to natural emissions of nitrogen oxides. Junge (1963) postulates that the nitrogen deficiencies in acid soils result when NO is formed from HNO_2. Then in the sunlight these agriculturally generated pollutants contribute significantly to the amount of photochemical oxidants. Other pollutants such as H_2S, though causing only very slight damage to plants, are produced by anaerobic bacterial activity on the sulphur in decaying vegetation, mainly in swamps, bogs and tidal flats (Munn and Phillips, 1975).

1.2.2 *Agricultural practices*

Heck *et al.* (1973) estimate that the production of hydrocarbons from burning agricultural residues is very nearly the same as that from automobiles. Agricultural fertilizers are sources of ammonia.

Controlled slash burning during the month of September in British Columbia, Canada, has been considered responsible for seriously inhibiting the normal development of red colour on apples as a result of a reduction in ultra-violet radiation (personal communication), although heating or cooling effects should not be ruled out as a contributing factor. Reliable ultra-violet radiation data are scarce and practically non-existent for agricultural and forestry areas polluted by forest fires or by other primary and secondary materials. Relevant data must be inferred from other sources, e.g. measurements of the depletion of ultra-violet and visible solar radiation due to smog clouds over Los Angeles have been reported by Stair (1955) and Ajello *et al.* (1973).

1.2.3 *Pesticides as air pollutants*

Farmers practising pesticide control measures have greatly improved the world production of foods. At the same time, these practices have lately caused such serious concern as potential sources of pollution that they have been severely controlled or prohibited, while efforts have been expended to seek alternate methods for limiting pest populations.

Measurements of ground deposits of chemicals, observations of mortality of fish, insects and wildlife in off-target areas, and subjective reports of carrier oil odour many miles away from spraying operations suggest that significant quantities of toxic chemicals have missed their targets during large-scale aerial spraying of forests for insect pest control.

Many pesticides are very persistent and consequently accumulate in soils, water, animals, and in man himself. As a result of both their persistence and their transport mechanisms, they are found in fields, rivers, and oceans far removed from their points of application. Transport may be by the atmosphere, by water, or simply by predators which move over large areas. Hay *et al.* (1971) give several examples of plants which are injured by pesticides leaving the target area either by droplet and vapour drift and by wind blow-off from treated surfaces or by drift with soil. Bergsteinsson and Baier (1971) give more details on the meteorological aspects of pollution in relation to agricultural pesticides, and AFA Technical Report No. 13 (1973) gives very useful discussions and recommendations on the Pesticide Accountancy Workshop.

1.3 Soil as a sink for pollutants

Soil may act as an efficient sink for several pollutants. In the presence of sunlight and atmospheric moisture, SO_2 forms sulphate aerosols and sulphuric acid droplets, which are removed by precipitation, causing acidification of soil and water. Summers and Hitchon (1973) reported that "about 32 per cent to 46 per cent of the sulphur emitted as SO_2 in Alberta, Canada is removed by summer-time convective storms and deposited on the ground as sulphate and sulphur within a radius of twenty miles of the source". On the other hand, they found that less than two per cent of the sulphur emission was deposited by snow in winter conditions, suggesting that rainout and not washout is the efficient mechanism for clearing the air from sulphurous pollution. However, these results may be contradicted by the findings in a Norwegian report (Anonymous, 1972), namely that in winter sulphuric acid and sulphate form in the atmosphere at a higher rate. It is possible that other acidifying substances or catalytic agents near industrial areas in Norway may have contributed to acidification of the snow, e.g., NO_2 or NO accelerates oxidation of SO_2 to SO_3.

An increase in acid precipitation represents an environmental stress resulting from greatly increased leaching of important plant nutrients, such as calcium in top-soil, thereby causing a decrease in forest productivity. As the pH level of precipitation approaches a level below pH 4 a sharp increase in calcium leaching is generally observed. In the Laurentian Shield area of North America there is increasing concern that acidification may be occurring, causing a reduction in agricultural and forest yields.

Deposition of atmospheric trace gases caused by absorption in soil must directly or indirectly influence the soil microflora and the root system of plants. Rasmussen *et al.* (1968) report that "the volatile organic components of the atmosphere are absorbed in significant amounts by components in the soil", wild populations of fungi utilize the organic volatile emanating from tropical foliages as the sole carbon source for growth; and microbial life growing ephytically on the vegetation surface uses organic volatile beneath the canopy.

Ethylene, which is highly toxic to vegetation at a threshold of about 10 ppb (parts per billion) and which is produced by burning agricultural waste, by forest and brush fires and by motor vehicles, is removed from the air by a number of mechanisms, including microbial decomposition in the soil (Abeles *et al.*, 1971), reaction with ozone and photolysis with nitric oxides. During a conference co-sponsored by SIDA and FAO several useful papers were presented on the effects of pollutants on microbial activity and the associated soil degradation (Rosswall, 1973).

START INDEX

CHAPTER 2

POLLUTANTS AND PLANTS

2.1 **Major air pollutants damaging to plants**

The major air pollutants causing heavy damage to vegetation either singly or collectively are ozone, peroxyacetyl nitrate (PAN), oxides of nitrogen, sulphur dioxide, fluorides, agricultural chemicals, ethylene, and other hydrocarbons. Less important noxious atmospheric materials are aldehyde, chlorine, hydrogen chloride, ammonia, hydrogen sulphide, etc.

Visible injuries caused by the more important air-borne gaseous contaminants have been investigated for many years and have been the subject of a fairly extensive literature. Most information regarding dosage, injury and environmental factors is obtained in the laboratory, while little is acquired from field experimentation. Very often plant injury is discussed without quantitative data on either pollutant dosage or plant effects which might be valuable in predicting damage. Sometimes species are even chosen which yield characteristic symptoms for specific pollutants.

2.1.1 *Pollutant concentration and plant injury*

At present there is no recognized procedure for assessing acute and chronic air-pollution damage to vegetation. Several agencies, such as the U.S. Environmental Protection Agency, attempted to compile the pollution criteria for several well-known contaminants and their various receptors, including plants. However, as different species of plants, and even different varieties of a single species, and at times the same variety itself, may have considerable variations in susceptibility to the same contaminant because of variations in both environmental conditions and pollutant contributions, they could not present exact expressions of cause and effect. Instead, criteria were given either as precautionary statements about the time required by a pollutant to reach a certain concentration or as dose/response relationships for a specific plant in certain environmental conditions prior to, during, and after exposure. Thus while the former have no operational value, the latter may only be useful if similar conditions were to prevail.

The readily observed effect of air pollutants and that which gives rise to the most characteristic patterns of injury is the collapse of tissue and development of necrotic patterns. However, some degree of chlorosis is frequently found with the development of such necrosis. In some cases the first symptom of air-pollution injury is chlorosis. For example, in citrus and corn, fluorides often produce a characteristic chlorosis without any necrotic pattern.

Certain characteristic colours of the necrotic areas are often associated with a specific toxicant. SO_2 injury is usually an ivory to tan colour, while fluoride injury is a brown to red colour. A narrow dark brown band at the boundary of the necrotic area is frequently seen with fluoride injury.

Several publications (Haut and Stratman, 1970; Hindawi, 1970; and Jacobson and Hill, 1971) have presented good colour photographs of the symptoms caused by air-pollution damage. Many documents on air-quality criteria for important pollutants (U.S. Department HEW, Nat. Air Poll. Control. Admin., AP50, AP63, AP64 and AP84) and several papers contain good reviews of the visible effects of air pollutants. WMO Technical Note No. 96 (1968) gives patterns and dosages of injury due to specific pollutants.

Dosages for the following pollutants have been suggested for adoption as criteria in plant injury.

Sulphur dioxide

Thresholds for acute injury by SO_2 are about 0.25–0.30 ppm (parts per million) and for chronic injury about 0.05 ppm on a seasonal or yearly average. Linzon (1973) concludes that there is a risk of SO_2 damage to forests and lichen when the following concentrations are observed: 0.02 ppm averaged over one year; 0.35 ppm averaged over four hours; 0.55 ppm averaged over two hours.

Fluorine

Fluorine affects plants either by causing direct damage to them or by producing excessive incorporation in foraging animals, primarily cattle, which could suffer from pathological alterations if fluorine enrichment in fodder should exceed about 40 ppm. Guderian (1971) reports that certain types of clover and grass showed fluorine contents up to 8.7 mg/100 mg dry substance for dosages as low as 0.855 $\mu g/m^3$ air over sixteen days, i.e. a fluorine enrichment constituting an animal hazard. However, experiments with a concentration of 1.1 μg produced only slight leaf damage with no significant effect on growth. Both gladiolus and Ponderosa pine were injured at 0.98 $\mu g/m^3$ hydrogen fluoride for 24 hours (Adams *et al.*, 1956). From 0.67 to 0.59 $\mu g/m^3$ for six and eight days respectively separated by one week resulted in reduced flow and corn production in gladiolus (Hitchcock *et al.*, 1962) and reduction in growth and yield of Milo maize (Hitchcock *et al.*, 1963). Brandt (1971) suggested the following sensitivity classification for certain plants according to the cumulative amount of fluorine contained in their tissue:

(*a*) Very sensitive plants (less than 50 ppm)—many Iridaceae and Liliaceae, special conifers, citrus types, and Rosaceae;
(*b*) Sensitive plants (50 to 200 ppm)—In this group are further representatives of the plants mentioned in (*a*) as well as several grass types;
(*c*) Resistant plants (more than 200 ppm).

Ozone

For ozone the following concentrations are reported to cause slight injury to sensitive vegetation grown under the most sensitive conditions: 0.15 ppm for 0.5 hours for beans (Heck, 1968*b*); 0.08 ppm for one hour for tomatoes (Heck *et al.*, 1970*a*); 0.05 ppm for four hours for tobacco (MacDowall *et al.*, 1964); 0.03 ppm for eight hours for beans (Heck, 1968*a*); 0.02–0.03 ppm for 24–29 hours for peanuts (Applegate and Durant, 1969).

PAN

Field symptoms have been seen when analytic data indicated levels of 0.01 and 0.05 ppm. Petunias, tomatoes, dwarf meadow grass and romaine lettuce were injured in ambient air when exposed to 15–20 ppb (parts per billion) of PAN for four hours (Taylor and Maclean, 1970). Petunias were injured in controlled experiments when exposed to 200 ppb for half an hour, to 100 ppb for one hour, and to 50 ppb for two hours (Drummond and Wood, 1972).

Nitrogen dioxide

Chronic exposure to 0.15 ppm NO_2 and acute exposure to 2.5 ppm caused observed damage to tomatoes and to other species of commercial value.

Ethylene

Ethylene concentrations as low as one ppb could cause a response in certain sensitive species (Heck *et al.*, 1970*b*).

2.1.2 *Multiple pollutants and plant injury*

One problem that has lately been recognized as worthy of more attention than it has received is that of assessing plant injury caused by simultaneous exposure to various pollutants, particularly for very low concentrations, as usually found in natural conditions. Symptoms attributed to a single pollutant in an outdoor environment may in fact be the resultant effect of several, unless the particular pollutant has a high concentration or is highly correlated with another. Therefore, careful laboratory research with elaborate quasi-simulation of environmental conditions may shed some light on single- and multiple-pollutant effects.

Tingey *et al.* (1971*b*) found that five different plant species may be damaged in time periods as short as four hours when exposed to a mixture of low levels of NO_2 and SO_2 (about 0.10 ppm each). If these two act synergistically, perhaps very low concentrations of each may cause injury.

A combination of sub-lethal concentrations of SO_2 (0.24 ppm) and ozone (0.03 ppm) in two-hour fumigations produced injury to tobacco plants (Menser and Heggestad, 1966). When the exposure time was doubled, the severity of damage was approximately doubled but no response occurred when fumigation consisted of either pollutant alone. However, Middleton *et al.* (1958) reported that a ratio of SO_2 to ozone less than 4:1 made the plants less susceptible to ozone damage, but a ratio greater than or equal to 6:1 had no effect.

The first positive synergistic results have recently been reported utilizing mixtures of HF and H_2SO_4 gases. Macross and Surecross corn fumigated continuously by 0.5 $\mu g/m^3$ HF plus 0.75 ppm SO_2 for about 12 days developed injury symptoms greater in degree than the sum of the effects of the two contaminants acting independently. Either contaminant caused incipient symptoms on corn but acting together the response was enhanced (personal communication from Jacobson of Boyce Thompson Institute, New York).

2.2 **Damaging mechanisms**

Sulphur dioxide

SO_2, like other noxious gases, may cause acute or chronic plant injury (U.S. Dept. HEW. Nat. Air Poll. Control Admin., 1969). The latter, arising from long-term accumulation, may appear as loss of pigmentation (chlorosis) which in the acute stage is aggravated into necrotic discoloration. SO_2 may be photo-oxidized in leaves and accumulate as sulphate at termini of the transpiration stream. Inhibition of photosynthesis by acute but sublethal doses may be accompanied by cholorplastic thylakoid swelling (Wellburn *et al.*, 1972) which is rapidly reversed by repair mechanisms and compensated for by a period of stimulation (Thomas and Hill, 1937). Injury is increased by stimulated stomatal opening if the relative humidity is above 40% in 0.25 to 1 ppm SO_2 (Majernik and Mansfield, 1970, 1971) which may explain stimulation of apparent photosynthesis at those concentrations (Thomas and Hill, 1937). When the sulphur content of the leaf increases to two per cent the absorbed SO_2, as sulphurous acid, will convert chlorophyll to phaeophytin; also chlorophyll synthesis will suffer by interference from the iron metabolism (U.S. Dept. HEW Nat. Air Poll. Control Admin., 1969).

Fluorides

Fluorides produce necrosis and chlorosis in plants by multiple primary mechanisms (Marier and Rose, 1971; McCune, 1971; Nash, 1973). Following entry to root or shoots fluorides are conducted in the transpiration stream and accumulate in active phloem parenchyma (Treshow and Pack, 1970) and leaf tips. They have deep-seated metabolic effects by acting as inhibitors of molecular control at the level of DNA (Mohamed, 1969) and RNA, affecting the nucleotide ratios (Chang, 1968, 1973; Pilet, 1969). Fluoride is a classical inhibitor of enclose in glycolysis (Weinstein, 1961) but its specific effects are more widespread and include on attack on respiratory succinic dehydrogenase (Lovelace and Miller, 1967) with an apparent uncoupling of oxidative phosphorylation (Yu and Miller, 1967). An initial enhancement of oxygen uptake with a subsequent decrease are opposite to the effects of ozone. Increased concentrations of organic acids and amino acids contribute to this stimulation (Yang and Miller, 1963). Chlorosis, increased acidity and growth retardation are among the chronic effects of fluorides (Yang and Miller, 1963; Anderson, 1966; Leonard and Graves, 1972).

Photochemical oxidants

The photochemicals ozone, nitrogen dioxide (NO_2) and peroxyacetyl nitrate (PAN) act as strong oxidants (Dugger and Ting, 1970*a*, 1970*b*; Mudd, 1969; U.S. Dept. HEW Nat. Air Poll. Admin., 1971; Rich, 1964; Treshow, 1970). They inflict death by irreparable damage of the cell membranes, where they oxidize sulphydryl groups (Mudd, 1969; Adedipe *et al.*, 1972), required by some enzymes for activity, the double bonds of free unsaturated fatty acids (Mudd *et al.*, 1971*a*) and of other compounds. Metabolic pathways alternate to those with impaired enzymes may wield the *coup de grâce* (Mudd *et al.*, 1971*b*; Tomlinson and Rich, 1971). Endegenous-reducing substances counteract these effects both by direct anti-oxidant action and by providing a ready substrate for biosynthetic repair processes (Hanson *et al.*, 1971; Ting and Mukerji, 1971). Besides loss of differential permeability of plasma membranes (Evans and Ting, 1973) early effects are seen in the processes carried out by inner protoplasmic membranes, including uncoupled oxidative phosphorylation and subsequent interference with electron transport. Respiration is at first inhibited by ozone and this is followed by rampant oxygen uptake as visible damage appears. Long-term or chronic injury by ozone and NO_2 is evident as chlorosis (Thompson *et al.*, 1970) and retarded growth (Tingey *et al.*, 1971*a*; Hoffman *et al.*, 1973; Taylor and Eaton, 1966). This also undoubtedly has a broad basis in other damaging mechanisms including stomatal closure (Adedipe *et al.*, 1973; Howell and Kremer, 1972; Rich and Turner, 1972) and inhibition of the syntheses of growth hormone (Hope and Ordin, 1971) and cell wall (Ordin *et al.*, 1971). PAN is particularly toxic to cell-wall growth (Ordin *et al.*, 1971) so it attacks younger leaves at the points of entry. Ozone is rapidly exchanged with other gases by the mature palisade cells of leaves where its acute effects are first evident (Howell and Kremer, 1972; Turner *et al.*, 1972). Nitrogen dioxide is less toxic and less specific.

Ethylene

Although ethylene is not strictly a plant hormone it is nearly one, since it is produced endogenously and regulates many physiological processes including dormancy, swelling and elongation, hypertrophy, adventitious rooting, epinasty, leaf expansion, flow induction, exudation, ripening, senescence and abscission (Abeles, 1972). Ethylene is produced very rapidly by the most actively growing cells. The amount evolved by plants into the air is about 0.1 per cent of that produced by human activities, but under more polluted circumstances less is released. The results of its action are deep seated and complex, but a single site of attachment is suspected. Ethylene regulates and promotes RNA synthesis (Holm *et al.*, 1970), controls auxin biosynthesis, retards auxin transport and increases sensitivity to auxin. It has little effect on isolated enzymes and on membrane permeability but does influence cellulose synthesis (Horton and Osborne, 1967) and secretion from cells (Jones, 1968). To summarize, ethylene appears to speed up the life cycle.

2.3 **Pollutants beneficial to vegetation**

Many pollutants are in fact valuable nutrients. In moderation they may enhance crop growth, particularly when such nutrients in the soil are in short supply. For example, Prince and Ross (1972) and Cowling *et al.* (1973) report that while SO_2 is highly toxic to vegetation, it may, at low non-injurious concentrations, increase the yield of several crops.

The fact that SO_2 can be utilized after absorption through the shoots may be of great significance in crop nutrition in some industrialized countries where the soil is sufficiently alkaline (Cowling *et al.*, 1973). However, Bell and Clough (1973) showed decreases in yield for rye grass in opposition to Cowling *et al.*, who had found increases both in yield and sulphur content when fumigation was maintained for as long as 59 days with a mean concentration of 131 $\mu g/m^3$. The reason given for this discrepancy is that the sulphur content of the soil in Bell and Clough's experiment was not specified and that the plants were exposed to high dosages (191 $\mu g/m^3$ for 182 days and 343 $\mu g/m^3$ for 63 days). Cowling *et al.* (1973) conclude that "the fact that SO_2 did not depress yields, even when sulphate-S was added to the soil (as in the field through rainfall) suggests that present concentrations near the ground are not injurious to rye-grass in most areas" of the United Kingdom where the average concentration (50 $\mu g/m^3$) was less than that used for fumigation. Prince and Ross (1972) conclude from several studies that no injury resulted when vegetation was fumigated with 400 $\mu g/m^3$ or less of SO_2. For a higher concentration, a relationship of the form $C - 400\ t = 1700\ \mu g\ h^{-1}\ m^{-3}$ (where C is concentration and t is time in hours) may be adopted (Munn and Phillips, 1975).

Plants were less susceptible to SO_2 and produced high yields when grown in areas naturally deficient in SO_2 and/or nitrogen, and showed increased root development with low ozone concentration (Munn and Phillips, 1975).

2.4 Pollutants and plant diseases

Great interest has lately been shown in aerobiology, but the complex interactions of host pathogens, insects, and associated microflora with air pollution have not received sufficient attention in presenting the whole picture of aerobiological influences on plants. Evidence from the literature indicates that pollutants may directly or indirectly modify a wide variety of factors leading to an increase or decrease in plant diseases, although neither the detrimental and beneficial factors nor their manner of producing these effects are known.

It is possible that the synergistic effects of pollutants on aerobiological organisms and their hosts may at times have a greater biological significance than mere toxicity to plants. For example, pathogens might either lose their capacity to overcome pollution injuries, thus shortening life of spores and their time for spreading, or develop increased tolerance to contaminants, producing increased susceptibility to disease. Changes in host physiology and vigour resulting from pollution injury may render plants more susceptible to insect attack (e.g. from beetles: Stark *et al.*, 1968) and perhaps to many other infections by insect-vectored pathogens. Treshow (1968) postulates that the invasion by the wood-rooting fungus may be due to a decline in host vigour. Other pollutants such as particulates which are deposited on leaves may cause clogging of the stomata and therefore may be detrimental in reducing photosynthesis but beneficial in interfering with pathogens that invade through the stomata.

Pollutant effects on micro-organisms vary considerably. Parmeter *et al.* (1962) and Wilde (1971) show a reduction in fungus root (Mycorrhizae) on trees damaged by pollution. Parmeter *et al.* (1972) postulate that "air pollutants may impair mycorrhizal formation and thereby affect both host nutrition and host defense against root pathogens." They further add that the spread of disease may be influenced by pollutants acting directly and indirectly on insect vectors or acting directly on pathogens as demonstrated *in vitro* (Treshow, 1965; Hibben, 1966); also it may reduce diseases through its effects on alternate hosts such as those for rusts.

2.5 Protection of vegetation against pollutants

Considerable attention has been and is being directed towards defining the biochemical and physiological responses of organisms to air pollutants with some recognition of the environmental factors and of the biological potential for improved resistance. Several reviews (Dugger *et al.*, 1970*a*, 1970*b*; Heck, 1968*a*; Mudd, 1969) discuss the background literature on this subject in detail.

Of some interest is the research conducted to find both long- and short-term solutions for combating the effects of pollutants, particularly strong oxidants such as NO_2, ozone and PAN, through application of antioxidants either as soil additives or as a foliar spray (Pellissier *et al.*, 1972). Application of these materials to lower layers of leaves is the most effective measure but may reduce the commercial value of the products. More recently the systemic fungicide benomyl has been shown to reduce ozone injury (Taylor, 1970; Pellissier *et al.*, 1971, 1972) when applied as a soil drench. Leaves with high sulphur content are also protected from ozone (Adedipe *et al.*, 1972).

Rich and Taylor (1960) report that tobacco fields which were shaded with cloth painted with anti-ozonant (reducing agents) were protected until the reducing agent was exhausted.

Selection of crop varieties suitable for growing in polluted areas may be based on the considerable differences in the magnitude of stomatal-opening suppression in light with increased CO_2 concentration (Majernik and Mansfield, 1972). Experimental results indicate that while CO_2 stimulates stomatal opening in moist air it can produce partial closure in certain crop varieties at high ambient levels. Since CO_2 concentration increases appreciably in polluted air, the selection of a species with sufficient partial-closure-response may protect the plant from injury but may at the same time decrease its productivity.

Although retarding chemicals have been used to protect several plants against pollutants, the long-term method of overcoming the menace of these toxicants is to select cultivars or to breed pollution-resistant strains of plants which have large genetic differences in susceptibility.

START INDEX

CHAPTER 3

ENVIRONMENTAL STUDIES OF AIR POLLUTION

3.1 Experimental enclosures and plant response

There has been considerable recognition of the role of environmental factors in plant injury by air pollution. However, unless all the interactions of organisms with their environment, on whatever scale, are integrated, there is little prospect for understanding the various physiological, biological and meteorological processes and their interactions. In order to comprehend the effects of plant injury, to identify their causative agents and to ensure effective results there is an urgent need for concentrated, co-ordinated research and for better communication between the various disciplines involved.

3.1.1 *Growth chambers*

Most research into the environmental factors and their biological effects has been carried out by biologists in laboratories using artificial environmental growth chambers. In general, one pollutant at a time has been studied under one set of environmental conditions. Such studies yield useful results, obtainable sometimes in no other way, but are unlikely to reflect the actual natural responses of organisms, since these are exposed in the outdoor environment simultaneously with various pollutants and with the resultant effect of several environmental parameters and conditions. It is not easy to isolate meteorological variables, because changes in one set the air in motion and cause changes in others. In addition, most experiments have involved short periods with concentrations higher than those in the ambient air, where an organism is usually exposed to a low level of pollution over a long period.

One of the chief criticisms levelled by physicists against chamber experiments is the existence of major differences in the turbulent characteristics between the air inside and outside. Differences in the thickness of the boundary layer, in the scale and intensity of turbulence and in the gradients are bound to develop according to the size and geometry of the enclosure, the orientation and location of the ventilating device, and the distribution of the plant cover. At the same time, major changes in the stability of the lower atmosphere outdoors, which produce different rates of diffusion resulting from changes in the boundary-layer thickness and in the profiles up to appreciable heights, are difficult to simulate in the growth chambers.

The ability to predict these differences and their corresponding effects is severely limited except that we can say that the effective eddy size tends to be smaller inside the enclosure than outside. However, to predict it would require a knowledge of the range of eddy sizes which contribute materially to the flux of pollutants for conditions both in the natural environment and in different enclosures. This is true because different ranges in the spectrum of turbulence may relate to quite different energy and flux processes. As Deardorff (1970) remarks, even when ventilation within the chamber equals that outside, at the same height, a considerably greater vertical mixing rate is likely to occur inside as a result of large vertical motions induced by the walls. It is the author's opinion that it is only by chance that conditions in chambers may sometimes simulate those outdoors for the transfer processes which determine the rate of pollutant uptake by plants.

3.1.2 *Open-top chambers*

With the increased realization that controlled chambers, green-houses and field fumigation experiments cannot simulate plant response to pollutant in ambient field conditions, although they may provide useful information for standard conditions, field open-top chambers, made in different sizes, have been introduced to measure this response. A blower forces air into the bottom of each chamber through a plenum. The air may be either unfiltered or filtered by activated carbon which removes oxidants and some other pollutants but not, for example, ethylene, which is generally found in significant amounts near urban areas. Mandl *et al.* (1973) in describing such a

START INDEX

chamber state that it produces homogeneous air distribution and uniform pollutant concentrations within the volume of foliar mass.

It is also doubtful whether an open-top chamber, although an improvement over the green-house, would allow simulation of natural conditions in which the wind shear provides the drive for turbulent exchange within the canopy. This process produces a relatively large value of apparent diffusivity at the top of the canopy decreasing to relatively small values at the bottom; in opposition to this, the open-top chamber would obviously produce a high value at the bottom since air is forced into the bottom. Moreover, the air flow which is directed towards the centre is bound to create a jet, with the walls acting as limiting boundaries, so that an extremely complex distribution for the eddy coefficient of diffusion would result. Thus, photosynthetic activity and pollutant exchange for a volume of foliage inside may not be related to that of a similar volume outside, since at lower levels in a relatively dense canopy the radiation energy is attenuated and cannot stimulate the stomata to be completely open. Thus powerful oxidizing pollutants such as ozone entering the chamber at the bottom may be destroyed by the lower leaves and branches with little or no entry into the partially open stomata. Consequently, at the upper levels where the stomata are wide open, the amount of remaining ozone may be so slight that the plant would not be injured as much as if it were exposed to natural concentrations. Flow into the chambers might be increased to compensate for the ozone destroyed but could not diminish the complexity of the exchange processes. Mandl *et al.* (1973) have estimated a vertical velocity of 80 cm s^{-1} inside these chambers, which is greatly in excess of that generally found outdoors. Further testing of the aerodynamics of these chambers is required in order to determine several pollutant-concentration profiles inside and to evaluate associated environmental factors before results can be extrapolated to outdoors.

3.1.3 *More complex chambers*

Hill (1967, 1971) used an improved chamber in which temperature, humidity, light and wind velocity could be carefully controlled to within acceptable limits; special consideration was given to the problem of simulating natural wind conditions. Air pollutant and CO_2 were maintained at constant pre-determined concentrations by automatic or manual replenishing systems. Comparison of uptake rates for SO_2 by alfalfa showed that plants absorbed 20 per cent less in the field than in the chamber, even though the wind 15 cm above the canopy was stronger in the field (10 vs. 6 km h^{-1}). Under similar meteorological conditions it would be expected that higher wind speeds would generate greater gas exchange, suggesting that the plants in the chamber might have absorbed more SO_2 had the winds been as strong as those outside. However, according to Hill (1971), wind speeds of these magnitudes are above the range where their effects on uptake are important. Accepting the validity of this statement, the differences in uptake are perhaps still within acceptable limits of experimental error. If so, the performance of this chamber may be considered encouraging, particularly in light of the impressive results of Bennett *et al.* (1973) for profiles of pollutant, wind, CO_2 and temperature.

3.2 **Physical environmental factors and plant response**

Studies in the 1970's on how the physical environmental factors under which plants are grown or exposed influence their susceptibility to phytotoxic air pollutants have not revealed much beyond earlier findings; even the most recent results seem only to confirm their earlier ones. Since these investigations have been conducted mainly in chambers, the same limitations of the data apply as mentioned in 3.1.1. WMO Technical Note No. 96 (1968) and other literature quoted in the references cover much of the information available on this subject, and therefore this report is confined to a few cursory remarks. The main factors considered are light, temperature, humidity and water supply.

It is conceivable to expect factors controlling plant development such as the duration of light (photoperiod), intensity, and quality of light prior to, during, and even after exposure to influence the sensitivity of plants to air pollutants and in turn the degree of damage. Brandt and Heck (1968) report that "pinto beans and tobacco grown under an eight-hour photoperiod are much more sensitive to photo-toxicants of the photochemical complex and to ozone than plants exposed to a 12- or 16-hour photoperiod". Plants are more sensitive to PAN and ozone when grown under high and low light intensities respectively. In general the sensitivity of plants during ozone fumigation depends on stomatal opening below a certain threshold of intensity, above which it increases as the intensity approaches full light conditions. Menser *et al.* (1963) for tobacco and Davis and Wood (1973) for Virginia pine found that long dark exposures enhanced injury, whereas plants maintained in light for 22–24 hours prior to fumigation were not injured.

Plants are highly resistant to SO_2 in complete darkness, but the resistance decreases with increasing light intensity up to about 3 000 foot candles. However, plant injury response to nitrogen dioxide is increased in the dark (Taylor and MacLean, 1970).

Little or no recognized work is available on the quality of light and the degree of damage. However, Brandt and Heck (1968) report that "research with green-house plants and plants grown in growth chambers strongly suggests that light quality does not affect sensitivity and could be an important factor when considering differences between green-house and field-grown crops".

Temperature effects on plant response are somewhat masked by the positive correlation existing between light and temperature. Reports indicate that the sensitivity to pollutant is generally less for plants grown in cooler temperatures, possibly due to less development of water stress, while response to oxidant increases with temperatures from 4° to 38°C. However, when plants are exposed to ozone under controlled light conditions there is an inverse relationship between temperature and sensitivity as the temperature is raised from 18°C to 29°C. This suggests that light intensity may be predominant in the direct relationship between sensitivity and temperature found under field conditions (Heck *et al.*, 1965). A plant is much more resistant to SO_2 at temperatures below 5°C, i.e. in winter.

The effect of air humidity is still little understood. Results are contradictory, perhaps due to the use of relative humidity, which is a poor indicator of the evaporative demands of the atmosphere. Findings show that susceptibility of plants to SO_2 generally tends to increase with an increase in relative humidity provided light and soil moisture are not limiting. Others seem to suggest that plants are more sensitive when they are grown and/or exposed to oxidants under higher humidities, e.g. Otto and Daines (1968) found a marked reduction in sensitivity of pinto beans and tobacco exposed to ozone at 26 per cent as opposed to 51 per cent relative humidity. In general, these and other similar results are usually interpreted as being due to the fact that high relative humidity maintains the plants in a turgid condition, favouring the more general opening of the stomata, whereas low humidity tends to produce wilting conditions, particularly under low soil moisture conditions, rendering plants less susceptible.

Plants grown with ample water supply are much more susceptible to pollutants than those grown without, so that drought conditions produce greater resistance. MacDowall *et al.* (1963) report that a six-hour fumigation with 0.45 ppm ozone in daylight resulted in 85 per cent to 100 per cent damage to two turgid tobacco plants, whereas two wilted plants escaped injury. In the same test, a wilted plant watered before fumigation recovered sufficient turgidity to suffer 30 per cent damage. No effects of susceptibility were observed when the leaf surface of a turgid plant was wetted.

3.3 **Meteorology**

3.3.1 *Meteorological role*

The rates of emission, dispersion, transport, chemical reactions and sinks determine the ambient concentrations of a pollutant at a given location. Thus a wide range of contaminant concentrations and a variety of new chemically generated pollutants are encountered, even though the amount and types of pollutant discharged may remain constant. Three scales of motion, micro, meso and macro, govern the movement of all man-made waste products and natural contaminants of gaseous and particulate matter in the atmosphere. The path is controlled by certain atmospheric motions which indicate the direction and rate of bulk transport, while the extent of dilution is controlled by certain atmospheric motions generating turbulent eddies responsible for dispersing pollutants as they move with the mean motion.

The air pollution meteorologist's principal role is to evaluate the effects of weather and physiographic features on the concentration of the effluent as it travels from source to receptor. However, in the case of plant injury by air pollution the meteorologist must further be responsible during operational periods for predicting weather conditions conducive to injury based on vegetative environmental conditions affecting the absorptive capacity of the plant and on the downward turbulent transport of pollutant. This would greatly reduce damage and make possible the initiation of emission control and/or issuance of advance warning to agriculturalists to take protective measures.

Eddy transfer is the main mechanism of dispersal, not only of particles and gaseous pollutants but also of momentum, heat, moisture, carbon dioxide and other air-borne matter. The eddies may range in size from the order of a millimetre to several kilometres as in the case of thunderstorms. A brisk surface wind accompanied by thermal instability would offer the most favourable eddy conditions for vertical transport.

The presence of eddies in the atmosphere can be seen by the geometrical features of a spreading smoke plume, or by the fluctuations in continuous recordings of wind speed and direction, which show a highly variable, wide-range eddy spectrum, superimposed on the mean atmospheric flow. The energy distribution among the various turbulence frequencies is closely related to the degree of diffusion in time and space. This energy is aquired from the mean or large-scale motions and from buoyancy forces. Eddies that have dimensions comparable to those of the body of polluted air are most capable of diluting pollution by turbulent transfer.

Turbulent transfer processes may be classified as mechanical (frictional) or convective, depending on their cause. Mechanical turbulence results from the shearing stress caused by the unusual roughness of the terrain and by changes in wind speed with height in a field of strong free air flow. Thermal turbulence results from a steepening of the vertical temperature lapse rate. This results in convective cells that are considerably larger and more organized than the turbulent cells caused by frictional effects. Both types of turbulence are often present in combination but in general one form dominates.

In considering atmospheric diffusion the configuration of the source in relation to wind direction and speed is quite significant. Sources are generally grouped in three classes, point source, line source and area source. The first two classes are further divided into instantaneous and continuous sources. These may at times originate from mobile sources, such as in the case of automobile emissions and crop-spraying aircraft. According to Munn (1974), industrial and urban areas may be considered as point sources on the regional scale, and vertical mixing through the surface mixed layer is complete at the downward distances of interest, i.e. at a distance ⩾ 65 km. Moreover, at short distances from large area sources edge effects may be ignored by assuming infinite lateral sources.

Certain characteristic weather patterns are associated with adverse meteorological conditions for the dispersion and dilution of the pollutants, producing abnormal concentration levels above the tolerance limits of the plants. The vertical rise of pollutants effectively ceases at the top of the mixing layer, that is, the layer experiencing extensive turbulence. Mixing layers may extend through thousands of metres, the tropopause being the upper limit, although they more commonly have depths of 300 to 3 000 metres. Once the pollutants are lifted above the surface boundary layer, turbulent dispersal is still a major factor, but meso-synoptic, or large-scale motions are the dominant factors in transporting the pollutants over long distances.

During prolonged periods of air stagnation air-borne pollutants may be trapped for long periods in the lower layers over an area, thus resulting in the build-up of pollutants to abnormal concentration levels. Local effects such as lakes and topographical features, which greatly affect air flow and diffusion near the surface, influence the dispersal and concentration of pollutants. Another effective mechanism in reducing transport is the semi-permanent subsidence inversion found on the west coasts of continents throughout the world. Africa, the Iberian Peninsula, South America and the south-west coast of the U.S. all have this typical vertical turbulence lid created by the subsidence associated with the semi-permanent high pressure areas of the eastern subtropical oceans. If, as in the case of Southern California and Chile, there is also a mountain barrier, the meteorological state is set for man and his technology to create a persistent air-pollution problem. In a study of tobacco-weather fleck in Canada, Mukammal (1965) reports that on most occasions of high ozone concentration the tobacco-growing region was under the influence of a weak pressure configuration with very little circulation as a result of a large amplitude ridge extending from the Bermuda High. Occasionally a SSW flow was established behind anticyclones or broad ridges which moved in from the W or NW and occasionally from the SW, bringing into Southern Ontario warm moist pollutant-laden air which had been stagnant for some time over southern areas. Under such conditions lake breezes and meso-scale systems forming as a result of the physiographical features of the Great Lakes dominate the weather picture and are the key mechanisms by which ozone generated by photochemical reactions of oxides of nitrogen and hydrocarbons is advected and brought down to the surface.

Numerous mechanisms may cause the removal of atmospheric impurities. Particles are deposited with and without precipitation by impaction, sedimentation, inertial deposition due to the effects of turbulence, Brownian diffusion, agglomeration, precipitation scavenging and electrostatic deposition (Mukammal and McKay, 1971). Gaseous removal is affected by sink mechanisms such as wet precipitation (one of the most efficient) and absorption and reaction at the Earth's surface, including plant uptake, chemical reaction and production of other gases within the atmosphere and transport into the stratosphere (Whelpdale and Munn, 1975).

Visible plant injury caused by primary pollutants is controlled by the amount of dilution and dispersion and is rarely found more than a few miles beyond the source. On the other hand, injury caused by the major pollutants such as ozone and PAN (peroxyacetyl nitrate) which are generated by photochemical reactions in the primary pollutants are more widespread and they may, under favourable meteorological conditions, be observed at considerable distances from their sources.

3.3.2 *Diffusion and transport predictions*

Ambient pollutant levels may be estimated by means of atmospheric diffusion models whose procedures range in complexity and sophistication from a few simple calculations to thousands of computer calculations. The formulation of most models demands steady-state homogeneous conditions not likely to be met in the applications to agricultural areas, where the sites are, more often than not, non-uniform both mechanically and thermally. Particular care and judgment should also be exercised in applying these models to calm wind situations where there is a local flow pattern such as a land- or sea-breeze or drainage and in areas influenced by local disturbances such as buildings, hills, mountains and other obstacles unless these are smaller than the dimensions of the diffusing cloud (Pasquill, 1962).

The present models may be classified into three atmospheric diffusion models. In the first, the K theory, attempts were directed towards solving the differential equation of flux in a steady state. In the planetary boundary layer and under certain source configurations some reasonable results were obtained when the effect of wind shear, varying surface roughness, and thermal stability were introduced into the solution of the diffusion equation. However, the use of this model has been largely empirical through the assumption of constant eddy diffusivity derived mainly from experimental data. In practice the K theory is useful in the free atmosphere where average plume diffusivity rapidly becomes dependent upon quite large eddies. As stated in WMO Technical Note No. 96 (1968): "this approach, while useful, has obvious limitations until the largest time and space scales are reached, as is the case for hemispheric or global diffusion. At this scale, K can be defined within reasonable limits and very useful results have been obtained."

The second model was developed along the lines of the statistical theory of turbulent diffusion following Taylor's statistical theory of turbulence. In this approach, the assumption is made of continuity conditions and that the distribution of concentrations produced by plumes follows either the exponential function or the Gaussian distribution and also that the dimensions of the diffusing cloud are represented by the variance of the cross wind, along the wind and vertical displacement of the material. In expressing in this manner the spatial distribution concentration, it would be necessary to measure Langrangian properties, but as these are extremely difficult to evaluate or measure except at short distances, various possible functional forms replacing statistical airflow properties by modified Eulerian fixed-point measurements are used instead.

The third approach is based on the similarity or dimensional analysis theories in which basic properties of airflow are expressed in non-dimensional form and in turn are related to diffusion rates.

In general, transport and diffusion models provide an essential link between emission and removal and represent a useful framework for the identification of variables and processes, but should only be used over moderate travel distances (of the order of 100 km) when steady-state conditions exist, i.e. during the time of the day when a well-mixed layer exists and the height of the mixing depth is constant and well defined. However, non-steady-state conditions are more the rule than the exception because of the diurnal cycling of wind and of the mixing depth. There is therefore considerable doubt as to the validity of the application of the models for other than very short distances from the source.

Lately a time-dependent model of regional meso-meteorological flow has been developed to calculate pollution trajectories. This approach will undoubtedly yield more realistic situations where local wind circulations, such as land- and sea-breezes and slope winds, prevail (Munn and Phillips, 1975).

Atmospheric chemical reaction schemes of varying complexity have been vigorously developed and deserve attention. They have been incorporated into dispersion and transport models (Seinfeld, 1970; Nordo, 1973, 1974) but results show that many assumptions are necessary, mostly because of an imperfect understanding of pollutant generation and removal mechanisms. Other outstanding problems remain, such as: the breakdown of diffusion equations for episodes with light variable winds; accounting for the purely physical transformation of pollutants, such as absorption of gases on particles; and smaller accuracy of computed values for greater distances.

Over the next decade, as a result of the great public concern and interest in air-pollution problems, improved diffusion prediction capabilities, at least on the synoptic scale, are bound to evolve.

Synoptic models based on air trajectories are at times used to infer the movement of regional pollution in order to indicate whether the path or trajectory of the pollution plume will cross the area of interest. This approach predicts the position of the plume and not the field concentration. However, estimates made from the wind fields of successive surface and upper-air weather charts may present uncertainties, due to insufficient knowledge of the three-dimensional wind field, particularly when changing with time, and also due to insufficient information about the initial height of the centre of gravity of the cloud of material (Whelpdale and Munn, 1975). On the other hand, successful results were obtained using constant-volume balloons developed by Pack (1962).

In considering biological response to pollutants, the distribution of concentrations about the mean emission is of great importance in estimating injury dose. It is commonly represented by the peak-to-mean ratios which are a function of the sampling time for the contaminant and of the orientation of the sampler with respect to the lateral and vertical position of the source. Typical peak-to-mean concentration ratios in the vicinity of a tall stack are of the order 100/200. With increasing time of sampling and with increasing distance from the source, these variations are slowly reduced to about a factor of two at distances of the order $\leqslant$ 10 to 50 km.

A large number of "practical" diffusion methods of calculating pollutant concentration at different distances from the source have been extensively described in the literature. The following references give good reviews: Pasquill (1962); Moroz (1968); Slate (1968); Turner (1969); Seinfeld (1970); Worley (1971); Shaw and Munn (1971); Hoffert (1972); WMO Technical Note No. 121; EPA (1970) and an annotated bibliography of Air Pollution Meteorology by the Air Pollution Control Association, 1968.

3.3.3 *Pollutant transport to plant cover*

The transport through the surface boundary layer by turbulent transfer processes of any entity such as moisture, heat, momentum, CO_2, gaseous pollutants and small suspended particles, depends on the vertical concentration gradient of the entity and the effectiveness of turbulent mixing in the lower air layer to transfer a property down its mean gradient. The transfer agent, which is generally referred to in the literature as the eddy diffusivity or the transfer coefficient, is dependent on the turbulent characteristics of the air as affected by surface roughness, wind shear and atmospheric stability in the boundary layer. Under steady conditions a change in either the gradient of the entity or turbulence of the air will alter the rate of diffusion out of or into the surface. Complexities will arise when horizontal non-uniformity of the surface along and across wind is encountered, resulting in an incomplete adjustment of the air to the new surface, that is, insufficient fetch. Changes in concentration or fluxes at the surface and/or changes in surface roughness would produce such insufficient fetch. In such circumstances the horizontal exchange, that is advection, which is extremely difficult to evaluate, must be accounted for in an assessment of the net flux.

3.3.3.1 *Micrometeorological methods*

A number of techniques known as micrometeorological methods have been developed to evaluate vertical fluxes of matter, including gaseous pollutants and air-borne particulates, in the boundary layer. Of these are: the aerodynamic or profile approach, the energy budget technique, the eddy correlation technique, the resistance method and the box approach.

In the aerodynamic technique, the flux is the product of the eddy coefficient of diffusion and the gradient. The last may be obtained from measurements of the entity at different heights using very sensitive and accurate equipment, because of the generally small differences encountered. For example, ozone gradients in the first several metres above the surface may be as small as one part per billion per metre or even smaller at times over rough surfaces such as forests. Thus the choice of appropriate measuring instruments may determine success or failure in obtaining a reliable estimate of the flux. Even more difficult to evaluate is the coefficient of eddy diffusion, or transport coefficient. There is no instrument available at present capable of measuring this important parameter, and it is necessary to resort to indirect approaches. The eddy transfer for momentum obtained from wind profiles is generally used, after modification for adaptation to transfer of matter and adjustments to atmospheric stability following treatments such as those suggested by Dyer (1963,1967), Dyer and Hicks (1970) and Panofsky (1963). When dealing with particles their settling velocities must be taken into consideration.

It is the author's opinion that the conditions for the validity of the aerodynamic formulae are not likely to be realized over vegetated surfaces (Mukammal *et al.*, 1966; King, 1966), although its successful application has been claimed by other workers (Lemon, 1960).

Further complications arise when the above technique is used to derive transfer within the plant canopy because of steep temperature gradients, inhomogeneity and turbulence characteristics. As pointed out by Legg and Monteith (1975), there are serious theoretical and practical objections to deriving vertical transport of heat and mass in various crop stands from the product of a non-dimensional transfer coefficient and a vertical concentration gradient. The method most used in deriving the eddy coefficient of diffusion as a function of height in a plant stand is the momentum balance method where the drag coefficient for foliage elements and the foliage area density are introduced into the formulation by assuming that the drag is constant, independent of wind, and that its mean value may be estimated from analysis of the wind profile above the canopy.

Uchijima and Wright (1964) found that the eddy coefficient of diffusion in the canopy decreased exponentially with depth in the top half of the canopy. They expressed their result in a mathematical form as a function of a parameter derived from the previously described momentum method.

The energy budget technique has been widely used in determining the latent and sensible heat of vegetation when no large horizontal divergence exists. This method appears to give fairly good results (Mukammal, 1966; Fritschen, 1966; Tanner, 1966). In this method, following a relationship based on Bowen's ratio, accurate measurements of net radiation and the gradients of both heat and water vapour are required. For pollutant flux estimates, the gradient of the particular pollutant is introduced instead of either the water vapour or the heat gradient. It must here again be emphasized that accuracy of measurement is vital to obtaining reliable findings. This technique has also been utilized in determining the transfer coefficient at any height within the canopy by measuring the downward flux of net radiation, soil heat flux and the gradients of heat and/or water vapour in several layers within the canopy (Lemon, 1970).

The eddy correlation technique is a direct flux determination at a certain point in the atmosphere through correlations between the fluctuations in concentration of the entity at that point and those in the vertical wind speed. For vertical flux, it is defined by $c_p\overline{\rho w'x'}$ where c_p specific heat, ρ air density, w' fluctuations of the vertical wind, and x' fluctuations of the entity and the bar denotes average (Goddard and Pruitt, 1966). One other non-turbulent vertical flux component, i.e. the flux by the vertical wind, should really be introduced. However, it is generally neglected in the vicinity of a boundary surface. This method will prove most valuable once rapid response sensors of both vertical wind and the entity capable of detecting fluctuations of periods less than a second become available. At present the technique, even when applied to evapotranspiration and sensible heat, is still used mainly for research and is not really yet operational.

In the resistance technique, the flux is obtained by multiplying the vertical concentration difference between the reference level and the surface with the reciprocal of the sum of the resistances of the surface to transfer. The resistances of interest in vegetation are stomatal resistance and aerodynamic resistance. For a perfect sink the surface concentration is zero, which may be the case in dealing with pollutant uptake by a plant, and only the concentration in the air stream outside a leaf is required. Monteith (1965) gives an extremely good review of the subject, while Chamberlain (1975) discusses resistances of crop canopies to uptake of ozone, SO_2 and iodine, and concludes that "the order of magnitude of the sum of the boundary layer and canopy surface resistances for all the three gases in crop canopies is greatly different from the bulk surface resistance of crop to transpiration (minimum values 30–50 s m^{-1} in good growing conditions, Monteith (1963)) when allowance is made for the molecular diffusivity".

The last method to be discussed is that where the atmosphere is contained in a real box or wind tunnel or part of the atmosphere is defined in some way. The rate of uptake of gases may be estimated from the rate of the difference between the concentration of gas going into and coming out of the box. This method suffers the same disadvantages as those of chambers discussed earlier.

The above is only a cursory review of this very broad topic, and the reader is referred to the extensive and excellent literature on this subject. The following are a few suggested readings:

Heat and mass transfer in the biosphere, 1975; ed. de Vries, D. A. and Afgan, N. H. Scripta Book Co., Washington, D.C., U.S.A.
Proceedings, evapotranspiration and its role in water resources management, 1966. Published by Society of Agricultural Engineers, St. Joseph, Michigan, U.S.A.
Practical microclimatology, Slatyer, R. O. and McIlroy, I. C., 1961, Unesco, Australia.
WMO Technical Note No. 96, 1968. Air pollutants, meteorology, and plant injury. WMO, Geneva, Switzerland.
Meteorological monographs, 1965, Vol. 6, No. 28. American Meteorological Society, Boston, Mass., U.S.A.
Descriptive micrometeorology, Munn, R. E., 1966. Academic Press.
Micrometeorology, Sutton, O. G., 1953. McGraw-Hill Book Co., Inc.
Prediction and measurement of photosynthetic productivity, 1970. Proceedings of the IBP/PP Technical Meeting. Published by the Centre for Agricultural Publishing and Documentation, Wageningen, Holland.

3.3.3.2 *Pollutant dose estimate*

The rate at which the pollutant is transferred downward to the vegetative surface and hence the rate at which it is absorbed by the plant are the ultimate problems which the agricultural meteorologist must face in determining the injury dose, no matter what atmospheric processes produce the existing level of pollutant at the place of interest. Injury to plants known to be in physiological and environmental conditions rendering them susceptible to a particular contaminant has usually been related to an exposure or dose defined as the integration of the products of time and corresponding contaminant level over a period of exposure. Such a time-concentration relation is not based on theory but is simply a mathematical form which appears to fit experimental data obtained from exposures limited in time. However, the rate of assimilation of pollutant by the crop is dependent on the vertical turbulent transport, given by the transfer coefficient and a vertical gradient of concentration. Injury and rate of pollutant assimilation should be highly correlated, but contaminant concentration and length of exposure alone often do not appear to be highly related to the degree of plant injury by air pollution. Mukammal (1965) reports that severity of injury to tobacco by ozone appears to depend not so much on the absolute magnitude of atmospheric ozone concentration as on the physiological features, including the stage of development of the plant as well as on micrometeorological influences which help determine the rate of downward flux of ozone in the lower layers for absorption by the plant.

A few studies have sought to obtain basic information useful for predicting pollutant uptake within a vegetative canopy. Rich *et al.* (1970) found that the same resistances that oppose outward water vapour diffusion from plants to the atmosphere also oppose inward diffusion of ozone, and it is generally accepted that the primary path for air pollutant entry into higher plants is by way of the stomatal openings. Then determination of the water transfer between the natural surface and the atmosphere may, in conjunction with the physiological response of the plant to pollutant, provide a valuable tool to relate amounts of plant pollutant uptake to changes in environment over short periods.

In the air layer above a plant stand, a fair estimate may be made of the total downward flux of a particular pollutant using the micrometeorological approaches. This is, of course, provided that there are no sources, sinks or chemical reactions for a particular pollutant and that its flux in the boundary layer is constant with height.

Galbally (1971) using a micrometeorological approach presents a formula for computing ozone from simple measurements, given values for the ozone destruction coefficient, the friction velocity, the ozone concentration observed at some level above the surface, and the resistance of the surface. The flux of SO_2 to a grass surface has been estimated by Saito *et al.* (1971) as varying from 2×10^{10} to 15×10^{-10} g cm^{-1} s^{1} using diffusivities derived from wind profiles and the SO_2 gradients, measured as ranging from 0.02 to 0.08 between 50 cm and 200 cm above the grass surface. Regener and Aldaz (1969) employed the direct measurement of the ozone flux over natural surfaces to determine the coefficient of the eddy coefficient of ozone, which was found to be near the value for that of heat diffusion.

Within the canopy the situation is rather more complex, as fluxes are no longer constant with height, and the assumptions of horizontal homogeneity and of similarity between the diffusivities are more in doubt here than in the air layer above the vegetation. Nevertheless, the application of micrometeorological approaches in separate

START INDEX

layers, despite the error-prone procedure for evaluating the change in concentration with height, has produced very useful results in determining the flux profile of CO_2, water vapour and heat (Denmead, 1970; Lemon, 1970). These methods also yield valuable information for air-pollutant fluxes in the canopy air layer.

It should be emphasized again that reliable results are possible only if instruments are available to measure the meteorological parameters and gaseous differential concentrations with sufficient precision to satisfy the requirements of the particular technique to be followed.

3.3.3.3 *Physiological factors*

For plant injury to occur the pollutants or their by-products must reach the living cells inside, mainly by penetrating through the stomata. High correlations between stomatal opening and degree of induced injury have been found by many workers (Heggestad and Middleton, 1959; Engle and Gabelman, 1966; Mansfield and Majernik, 1970; Rich *et al.*, 1970; Rich and Turner, 1972). Since the flux of pollutant passing through the stomata is primarily responsible for plant injury, a meaningful correlation between the amount of this flux and the extent of plant injury can be made. However, this flux cannot be assessed directly from the above-the-canopy measurement, but the total flux to the crop-covered surface can be determined. If stomatal flux is a sizable portion of this total, then a significant correlation between total flux and plant injury should exist. Reactive pollutants such as ozone may be destroyed at surfaces other than those within the leaf. The exterior plant surfaces and the soil may be large sinks for such pollutants and might even mask the stomatal flux in measurements of total flux. Studies in leaf chambers (Rich *et al.*, 1970) and plant chambers (Hill, 1971) have indicated a large degree of stomatal regulation of total ozone flux, but for natural surfaces Galbally (1971) found little difference between total ozone flux to a soil-dry grass surface and that to a lush grass cover.

A complicating factor in evaluating the role of stomatal opening in predisposing a plant to injury by air pollution is that the presence of air pollutants can influence stomatal behaviour. This interaction can be a defensive mechanism if closure is induced, but if opening is stimulated it is a liability to the plant, since this promotes increased injury.

Exposure to ozone tends to close the stomata of a wide range of plants (MacDowall *et al.*, 1963; Hill and Littlefield, 1969), but the degree of response depends on species, variety and water balance of the plant. Slightly water-stressed plants have been found to be more sensitive in this regard than unstressed plants (Rich and Turner, 1972). In onions, Engle and Gabelman (1966) were able to relate resistivity to injury of certain cultivars to their marked stomatal closure in the presence of ozone. However, not all air pollutants induce stomatal closure. Mansfield and Majernik (1970) found that broad beans (*Vicia faba*) at 18°C could respond to SO_2 by either a marked opening or closure of stomata depending on whether the relative humidity was above or below 40 per cent. The former response would tend to aggravate injury and might be a contributing factor in the synergistic response of ozone–SO_2 mixtures. Then if diffusion theory is to be used to predict potential absorption of air pollutants by plants the stomata-pollutant interaction is a factor to be considered.

Very few investigations have been made to determine plant damage as a function of stomatal opening and pollutant transfer. Such studies to obtain basic data relating damage to the total and stomatal fluxes for various atmospheric and crop conditions would certainly be rewarding, since they would enhance our understanding of the vital injury-controlling mechanism and perhaps yield useful numerical predictive and control values for developing exchange models to estimate damage under natural conditions.

Estimates of effective canopy stomatal resistances can be made from several methods (Monteith, 1965; Thom, 1971, 1972) which require above-canopy profiles of wind, temperature and humidity. A useful approximation of stomatal pollutant fluxes, which could serve as a check of the above methods, could be made from profiles of stomatal diffusion resistances as determined from diffusion porometer measurements and leaf area density providing the pollutant concentration within the canopy.

3.3.4 *Agricultural requirements for meteorological information*

Through research and collaborative efforts between the meteorologists and the agriculturalist and/or agronomist, losses due to plant injury by air pollution may be minimized despite the complexity of the problem. The magnitude and diversity of services required vary with the process contemplated for both the operational and research programme of such multi-disciplinary investigations. Protection of an agricultural area from harmful concentrations of air pollutant requires the establishment of a standard for sources and emissions defined in accordance with meteorological conditions in order to achieve the desired ambient air quality based on known criteria. The present information is based on laboratory work without being fully tested in the field. Thus much collaborative research in many scientific disciplines such as meteorology, plant physiology, ecology, physics, chemistry, etc. is still needed in order to develop criteria applicable for a variety of environmental conditions and a variety of plant species.

For agriculturalists the following two very vital questions arise: What will be, at a given location, the concentration of pollutants transported from nearby sources or remote areas; and what meteorological conditions are favourable for the downward transport of these pollutants for absorption by the plants? The meteorological problems associated with each question can be incredibly complex; the first requires forecasts of the meteorological potential for air pollution which must take into account information on emission rates, the efficiency of the transport and turbulent diffusion processes, the depletion, and the chemical reaction rates; the second requires highly technical forecasts of reception rates, which must consider such factors as the variations in crops, pollution and weather conditions, the turbulence as affected by local physiographical and meteorological features and must cover significant time and space scales.

Most pollution forecasts at present are non-quantitative in terms of pollution concentration, since the pollution emissions in the area affected are not known. Prediction models for pollution concentrations are being developed and used, and the judicious and intelligent application of these dispersion models to the specific type of pollution problem can prove fruitful. Perhaps the most difficult task is selecting the right model.

To date there have been only a few actual "before-the-event" predictions of pollutant concentration from observed weather conditions. Such forecasts can range from a single event under unfavourable diffusion conditions to the more complex circumstances requiring non-routine measurements of emissions, ambient concentrations and other meteorological parameters. *Post facto* estimates from observed data of concentration from point sources have been quite satisfactory, but the accuracy was better for longer periods such as a month or a year than for short periods of hours.

According to Davis *et al.* (1967), "an ozone advisory service was developed and implemented in 1967 for the benefit of the Shade Tobacco Industry of North Florida and South Georgia, U.S.A. Ozone sources and the relationship of ozone increases with weather patterns and phenomena were identified by the meteorologist. On the basis of these findings an ozone forecast procedure was developed and tested." It is claimed that this agricultural weather advisory service was instrumental in reducing weather-induced losses due to ozone.

In some instances despite all the measures taken to control emissions at the source, it is impossible on economic grounds to prevent some low concentrations of harmful gases or other waste products from entering the atmosphere. The meteorologist can be of assistance in such instances by providing forecasts of the expected adverse weather conditions so that those responsible can decide whether a temporary shutdown of industrial operations is necessary in order to avoid serious damage to vegetation.

Several protective measures, such as early harvesting, covering plants and using sprays, have been explored with fairly satisfactory results. Thus corrective or preventive action is possible following meteorological prediction of either unfavourable diffusion conditions or complex circumstances favouring the downward fluxes of contaminant to the canopy. In Canada, harvesting of mature tobacco leaves a day prior to the occurrence of meteorological conditions favourable to tobacco fleck was successful.

Meteorological forecasts to reduce plant damage by air pollution must not be measured by their meteorological feasibility alone, but must relate to methods of taking protective measures. To be economically useful, the predictions should, of course, be reliable and accurate, but they should also be designed and geared to provide sufficient advance warning to permit counter measures to be put into effect. In addition, there is the need for the meteorologist who is providing air-pollution forecasts to become familiar with the problems of the agriculturalist. He will need to know such factors as reduction in yield due to premature harvesting and other factors relating to the optimization of crop yield and economic benefits. This could probably be best brought about by direct liaison between the meteorologist issuing the forecasts and the agriculturalist or agronomist who will use them. Some of the forecasts could be highly technical and quite specific on areas covered and the time involved. Their content would have to be highly specialized and account for variations in crop and in plant environmental and biological conditions. It is possible that a daily bulletin on the state of the crops from the agriculturalist to the meteorologist would be of considerable benefit in guiding the meteorologist as to what parameters to emphasize and how to phrase and issue forecasts. There would be times when a special forecast during periods of expected adverse conditions would be more of value than any routine issuance.

According to Brandt and Heck (1968), "an understanding of environmental effects on plant sensitivity will enable the recommendation of certain cultural practices which could be instituted during times of air-pollution alerts". Thus, a forecast of air-pollution episodes would greatly assist the agriculturalist in taking the necessary measures to protect his crops.

There is also a recognized need in air-pollution climatology for relevant data directly available in a form suitable for the long-range planning of programmes to assist agriculturalists in assessing the pollution potential for better crop management, site selection and regional agriculture. This information would include factors for recognizing the weather patterns likely to introduce air pollutants to the area and statistics on the frequency that come from particular source regions.

3.3.5 *Simulation modelling*

There is considerable need for quantitative evaluation of the damaging effects of single and/or multiple pollutants at all stages of plant growth and development for both acute and chronic exposure, in the presence or absence of visible symptoms, over a wide range of concentration and time, and under varying environmental conditions. Effects on growth, yield and quality should be investigated for a wide variety of plant species, for simple ecosystems such as row crops and ornamental plants as well as for a complex ecosystem such as a forest. The complex nature of the system involves physical, biological and chemical processes which do not function independently but are part of the whole system. Thus available knowledge of the basic processes must be integrated in a multi-disciplinary approach to their mutual advantage so as to develop predictive simulation models for phenomena, and to understand and interpret properly the various parts of the system in relation to the remainder. This will provide a rationale for manipulation of the vegetation, for adaptation of agricultural practices to some acceptable pollutant levels, and for more efficient production of the needs of man.

However, models can only be as viable as their assumptions, the relationships chosen to connect their internal parameters, and the type and quality of the imput data. Perhaps a comprehensive model for meeting the above-desired objectives is not quite within the limits of current knowledge. Much additional co-ordinated research is needed to supply many essential inputs that are presently lacking. These are required at first to set up the parameters best suited for estimating the basic biological, chemical and meteorological processes, and then integrate the equations approximating the effect being studied. At least we do have quite a number of analytical equations that may be used with some degree of success to predict pollution concentration at a given point for given values of source and meteorological conditions. And we do also possess some knowledge, mostly limited to controlled conditions in the laboratory, of dose-response relationships and of the resultant effects of biological and chemical reactions to certain pollutants.

Generalized models of canopy exchange are under active development by several workers (Cionco, 1965; Waggoner *et al.*, 1969; Lemon *et al.*, 1972) with varying degrees of success. The publication, *Prediction and Measurements of Photosynthetic Activity, Proceedings of IBP-PP Technical Meeting*, (1970) gives an excellent review of quite a number of useful models. Moreover, additional knowledge is becoming available on applications of the flux-technique for estimating the portion of the pollutant absorbed by the plant. Waggoner (1971) has applied a canopy exchange model to ozone absorption but only for a particular set of observations and assumptions. Bennett *et al.* (1973) presented models for simulating the pollutant exchange between an isolated leaf and the free air immediately surrounding it. This type of model considers the relative significance of important factors, such as leaf and boundary layer resistances, surface reactivity, and pollutant solubility properties regulating pollutant transfer, and specific pollutant and leaf properties affecting the uptake process. A mathematical expression is derived to define an average internal reference concentration in terms of external concentration.

With the above available information and knowledge, although fragmentary and somewhat limited in scope, it may be possible through incorporation of edaphic factors for the site, such as soil moisture, pH, and nutrient levels, to formulate a family of simulation models. These may lead to identification of those environmental influences likely to be important, thus permitting prediction of their variations in a quasiquantitative way and may also lead to the sort of agronomic and genetic manipulation likely, in turn, to contribute to a reduction in plant damage by air pollution. The results from testing such simple models may suggest that the first estimates of the basic processes be revised for further input to obtain a better approximation. The results should also reveal what further experiments should be conducted and what additional measurements should be taken.

Refining and testing should be repeated until either a satisfactory result is obtained or until basic fallacies are uncovered. Clearly this requires close co-operation and good communication between the disciplines directly involved, including, occasionally, the field of growing plants in pollutant-free environments.

The *Proceedings of Workshop/Conference I* and *II* (University of Michigan, 1972, 1973) on the ecological-systems approach presented an ideal system model for the aerobiological materials, which with some modification may be applied to predicting the consequence of pollutant sources on biological systems, given the pertinent parameters.

START INDEX

CHAPTER 4

DATA ACQUISITION AND INSTRUMENTATION

4.1 Introduction

Suitable reliable data with adequate coverage are needed to make any progress in protecting agricultural crops from harmful pollutants. The amount and diversity of data required vary with the process involved in operational systems and research programmes which are both of necessity multi-disciplinary. Such programmes will include a variety of scientific subjects, mainly within the fields of meteorology, biology and chemistry.

Much progress has been made lately in developing sensitive and reliable instrumentation; at the same time greater access to electronic computers capable of handling complex mathematical and physical models allows quick evaluation of final results from massive data which could not be processed manually. However, major problems remain to be resolved, particularly: collecting and analysing representative physical, chemical and biological samples to meet objectives; measuring the various parameters with sufficient precision to meet the requirements of the formulae; selecting equipment with a sampling and response time consistent with the data's ultimate use; standardizing technology, procedure, units, methods of observation and analysis; and maintaining the accuracy of instruments (which, incidentally, still requires common sense and intelligence on the part of the user).

4.2 Remote sensing

Remote sensing of pollution and meteorological parameters in both the horizontal and vertical being actively investigated is proving very promising and may resolve many problems in sampling space-average values. Were it to be taken one step further, that is, to identify the type and degree of physical injury peculiar to a particular pollutant, remote sensing would serve as an invaluable tool in field surveys and in air-pollution studies. Such monitoring in combination with meteorological observations would be extremely useful in identifying sources, particularly when damage is cumulative. Much progress has been made using the laser beam to identify certain atmospheric pollutants and to determine their concentrations, although for short distances the measurement accuracy falls short of the required resolution. The reports of NASA (1971) and COSPAR (1972) reveal the progress achieved in the remote sensing of climatic indicators and pollution respectively.

4.3 Meteorological data

The meteorological data required by the various methods for estimating dispersion and transport are adequately described in the publications already referenced. The simple models usually employed to compute concentrations and dosages for operational purposes require only routine measurements of wind, temperature and temperature gradients (and sometimes an index of the intensity of atmospheric turbulence), obtainable from standard equipment used by most national Meteorological Services. Despite the increased need for an instrument for routine measurement of turbulent intensity, none has yet been developed, so that the standard deviation of wind direction as determined from a responsive wind vane and a compatible recorder is occasionally utilized. Computers are also used to accelerate the evaluation of complex formulae and to process minisonde and tetroon data so as to help in determining the vertical mixing for forecasts of pollution potential. Two experimental devices, the FM continuous wave radar and sodar (Derr, 1972) for identifying thermal and velocity inhomogeneities (or "turbulence") are being tested.

More reliable, intricate and sensitive instruments have been developed for research: e.g. a device to measure water stress and stomatal resistance for assessing pollutants absorbed by plants through their stomata; the three-dimensional sonic and pressure-sphere anemometers to measure turbulence structure and estimate dispersion coefficients; the Lyman alpha and infra-red hygrometers to measure humidity gradients and fluctuations for flux estimates by the eddy correlation and gradient techniques; the sensitive infra-red gas analyser to measure CO_2 concentration and gradient to assess photosynthetic activity; and the infra-red thermometers to measure surface temperatures. Substantial progress has also been made in developing more sensitive and reliable instruments for measuring and identifying pollutants which damage plants. Lately improvements have been made in the measurement of one of the most important offending gases (ozone). The most widely used method for the analysis of atmospheric total oxidants has been and still is the neutral-buffered KI method, which is accepted as the reference method for ozone determination. However, oxidizing substances, such as NO_2, H_2O_2, Cl_2, and substances such as SO_2 and H_2S may give a negative interference. Where the interfering substances occur, such as in the case of outdoor air, sampling procedures by the KI method could hardly be used specifically to determine ozone concentration. Thus, previous dose-response relationships derived from measurements of ozone by the KI method in the field and even at times in the laboratory should not be accepted unreservedly. Of the several other instruments for ozone measurements, the chemiluminescent technique (Guicherit, 1971) is gaining greater recognition as being highly specific for ozone with negligible reported interference. In this method, the light intensity emitted upon the reaction of ozone and certain organic compounds such as Rhodomine B is taken as a measure of ozone concentration. Sensitivity as low as ±0.1 ppb has been claimed for instruments using Rhodomine B. This is about one order of magnitude better than other techniques and is adequate in estimates where very small vertical ozone gradients are encountered. However, instrumental characteristics of this method still pose a problem, i.e. an activation period with an initial overshoot (Hodgeson *et al.*, 1970) when sudden extremely large increases of ozone concentration (0.2 ppm) are experienced; an extended time decay period of about ten per cent of the original signal. The latter is likely to produce an error in an instantaneous reading of ozone when used in methods such as the eddy correlation technique because of the residual signal from past ozone exposure.

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START INDEX

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START INDEX

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START INDEX

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