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PLANTS AS BIOLOGICAL INDICATORS OF AIR POLLUTION

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Foreword

This report is based on work done while I held a NERC Fellowship in 1974-76. The report is much shorter than I had intended when I began to investigate the problem. I approached the subject, with which I already had some experience, by making as full as possible a study of the literature, and by discussing their work personally with many of those engaged in research on relevant topics in Britain, the United States of America, Scandinavia, the Netherlands, Germany and other parts of the world. I was fortunate, as editor of the international scientific journal *Environmental Pollution*, to see many papers on this subject before they were available to the general public (and have had to be careful not to refer to any unpublished results without consulting the authors).

There is a great deal of information available, and it would be possible to produce many volumes on the subject. Earlier drafts of this report outlined possible discussions on the physiological relations of plants to different pollutants and combinations of pollutants, and included detailed descriptions of the physical lesions sometimes produced. However, I decided that much of this material did not require to be republished. This decision was made when I saw how, recently, others had published accounts covering much of the subject more thoroughly than I could attempt, and as these were often prepared by those who had devoted years of research exclusively to these topics, it seemed foolish to duplicate their efforts with, inevitably, inferior results.

Thus, when biological indicators are mentioned, the first group of plants which comes to mind is the lichens. Late in 1976, a book entitled "Lichens as air pollution monitors" by D. L. Hawksworth and F. Rose appeared, giving an authoritative account of the practicalities of this subject, written by two writers with many years of research experience, a book which it would be difficult to better. A slightly earlier book, published in 1973, "Air pollution and lichens", edited by B. W. Ferry, M. S. Baddeley and D. L. Hawksworth, includes authoritative contributions from nineteen leading scientists, and gives much of the background information.

In the case of flowering plants, which include trees of importance in forestry and all crops exploited by agriculture, there is an even greater wealth of information. This information is now summarised well in several books. One of these, "Responses of plants to air pollution", edited by J. B. Mudd and T. T. Kozlowski, appeared in 1976. Here, twenty-one of the leading research workers in the United States summarise the work done throughout the world on the physiological and morphological effects of all the important air pollutants on many types of plants; they even include an excellent 35-page chapter on lichens and bryophytes. I could not attempt to digest this work any further. Except for some work published since 1975, I could find no significant gaps in the bibliographies, which are comprehensive and amount to over 1,000 entries. Though the authors are working in North America, they show themselves to be fully aware of the extent of work done in Europe and other parts of the world.

We also have a publication by the Society for Experimental Biology, "Effects of air pollutants on plants", edited by T. A. Mansfield, and published late in 1976. This book gives a greater emphasis to the metabolic effects of pollutants, and, although there is some overlap, the text is largely complementary to that of Mudd and Kozlowski. Though published as long ago as 1970, the book "Recognition of air pollution injury to vegetation: a pictorial atlas", edited by J. S. Jacobson and A. C. Hill, gives a comprehensive description of the major physical effects of various pollutants. Thus, there is now little excuse for any scientist entering this field claiming that there is any difficulty in becoming aware of the scope of the work already done. There may even be an embarrassment of riches.

However, the existence of these excellent summaries does not mean that there are no further problems to investigate. They do indeed frequently draw attention to gaps in our knowledge, and to fields which require further investigation.

It might not be illogical for me to stop this report at this point, and to state that my investigation of biological indicators was largely a waste of time. I might have produced a digest of the relatively small amount of work (none of which is particularly revolutionary) which has appeared since Mudd and Kozlowski's, and Mansfield's books have appeared. However, I think that it is still possible to produce something of interest to those concerned with research on air pollution, provided that I restrict my field mainly to matters not already included in these earlier publications.

This report therefore sets out to deal with the ways in which plants can be used, practically, as air pollution monitors. I try to indicate the advantages, and the shortcomings, of different methods and those using different plants. I indicate that certain rather crude measurements can be made by those without much scientific knowledge and experience, and that these results may, in some circumstances, be valuable. I show that it may be possible to use selected cultivars which are very sensitive to various pollutants as a warning system to indicate when these pollutants reach levels of biological importance. I also stress the fact that such observations may have only a limited value, and that, in this, as in all other fields of research, the serious investigator has to learn much for himself, and that he must generally work out his own techniques best suited to his own problems. The literature quoted, and the substance of this report, can only take him a very short distance along the road to success.

Introduction

Air pollution is a very complicated subject. Serious and damaging pollution, such as that caused by many industries in Britain and other western countries in the nineteenth century, is easily recognised. However, even "pure" air at sites far removed from man's activities contains traces of substances which, at higher levels, may damage property and harm living organisms. The difficulty is to recognise when levels rise sufficiently to be harmful, in fact to produce pollution.

In studying air pollution, we will always need accurate chemical measurements of the substances present. However, by themselves, these data may be of little significance. They must be related to the effects on both the living and material environment.

In fact, every living organism may be thought of as an indicator of the effects of pollution, as it will be damaged by sufficiently high concentrations, but in this report I shall generally use the term in the commonly-understood manner, i.e. in respect of plants which are particularly susceptible to, and are affected or damaged by, specific substances, so that they may, under favourable circumstances, be used to give an early warning of pollution before the levels rise sufficiently to cause severe and general environmental deterioration. I will also consider plants which accumulate pollutants in their tissues.

It has long been known to farmers, horticulturalists and foresters that some plants cannot be grown successfully in urban and industrial areas; these are therefore those from which indicator species would seem likely to be most easily selected. Thus, in the United States of America, growers have learnt from experience that cultivars of tobacco which grow successfully in areas with few industries and low densities of petrol-powered automobiles may prove uneconomic in other areas because they are seriously damaged by quite moderate levels of air pollution. In the Netherlands, the bulb industry recommends growers near cities to avoid varieties found, by experience, to suffer under these conditions.

Tobacco and some ornamental bulbs, for instance gladioli, have thus been used for some years as pollution indicators. The susceptible cultivars develop characteristic lesions which may be easily recognised, and which can, to some extent, be correlated with particular atmospheric levels of ozone, sulphur dioxide or fluorine. The great advantage of this system is that the observer can measure real damage to a living organism; there is thus no doubt that the conditions are unfavourable for that organism. Unfortunately, however, the results may not always be easy to analyse and to interpret. They can seldom be used, by themselves, to give accurate quantitative measurements of any individual chemical.

Biological indicator plants have thus their advantages and their disadvantages. A limited amount of significant information about the pollution - or cleanness - of the environment may easily be obtained by unskilled observers. They have some use in giving an integrated picture of the incidence of pollutants over a period. In some cases, this period may extend over years, in others it may cover only hours or minutes. Indicators react when conditions are such as to damage the plants, but they cannot easily indicate whether a pollutant has reached a high level for a short time or a medium (but eventually harmful) level for a much longer period. As will be shown, different types of indicator must be considered if significant results relating to these different periods are required. Except in areas of known pollution, all results must be interpreted with considerable caution.

Most indicator plants are used because, in some conditions, they are damaged. However, this damage may arise in a variety of circumstances. As has already been mentioned, it is often suggested that specific lesions in susceptible plants may be accurately associated with definite levels of particular pollutants. This is a serious over-simplification of the situation. A whole series of factors may influence the result. These include climatic conditions such as temperature, humidity, sunshine, air movement, levels of carbon dioxide and rainfall. The general health and nutritional status of the plant, and its previous acclimation to environmental conditions, are also important. There are also many cases where lesions caused by pathogens have been thought to have been caused by air pollution, and pollution effects which have been attributed to pathogens. In fact, in unskilled hands, there are serious dangers in the use of indicator plants, which can mislead the unwary as easily as they can help those who can use them correctly.

In general, indicator plants are of most use when the nature of the likely pollutant is already known. Thus, if we know that there is a risk of fluorine emission from a new smelter, various plants may help to monitor this, if, in fact, it occurs. But the observer must take care to ensure that other causes of potential damage, for instance sulphur dioxide, are also studied, for levels of these may be raised by the same industrial operations. There have been many instances where research workers have wrongly concentrated on one pollutant which, in the event, may not have been the most serious. Indicator species may not be able to reveal such mistakes.

Indicator plants have been considered to constitute those most susceptible to particular pollutants. They may be observed in different ways. Thus, specific lesions may be noted in growing plants, e.g. blotches on tobacco or gladioli. However, some of the most extensive studies have included few records of actual damage to plants, but have concentrated on the distribution of species of varying susceptibility. Thus, where there is a long history of high levels of sulphur dioxide, as in most urban and industrial areas, many species of lichens which grew there before the industrial revolution have long been eliminated. There are studies where new high-level pollutants have been shown to damage these susceptible lichens, but, as a whole, these plants seem most useful for very long-term studies of integrated levels, particularly of sulphur dioxide.

Indicator organisms may also be used to detect potential pollutants, occurring in the environment at low levels, in a quite different way. They may concentrate substances in their tissues, so that they may be more easily detected by chemical analysis. It is well known that fish may concentrate substances such as organochlorine pesticides occurring in water by a factor of as much as x100,000. Plants are seldom able to give such striking results, but nevertheless analyses of their tissues, and of materials deposited on their surfaces, can be valuable. The accumulation may take place in or on the living plant.

This technique has been widely used for the study of heavy metals in the environment, and lichens in the Arctic have been found to accumulate radioactive isotopes. In many cases, the plants which are accumulating these substances are not adversely affected even by quite high levels of, for instance, lead or other metals. No damage from radioactive isotopes has been demonstrated, though genetic effects on plants may possibly occur. Sulphur and fluoride, on the other hand, may often kill lichens and bryophytes. The accumulation of the pollutants may then continue after death in mosses and lichens. Nylon bags containing dead sphagnum moss have been found particularly useful for accumulating heavy metals. This use may be stretching the meaning of "biological indicator plants".

It will be seen that my general conclusion, set out in this report, is that biological indicator plants should be used with some caution. Experienced research workers, studying an environment with which they are reasonably familiar, when the major pollutants to be expected are known, can find them invaluable. The careless and inexperienced may be easily misled.

Major changes over wide areas may be studied by the inexperienced, e.g. lichen surveys by school children may give a reasonable correlation with sulphur levels, if they receive the minimum amount of detailed instruction. But, in all cases, indicator plants must be used together with accurate chemical analyses, not as a substitute for them.

Lichens

Lichens have been used more widely than any other types of plants as indicators of air pollution. There is a very extensive literature on the subject. Fortunately, towards the end of 1976, the new publication "Lichens as pollution indicators" by Dr. D. L. Hawksworth and Dr. F. Rose (Hawksworth and Rose, 1976) appeared. This admirable booklet should enable anyone with only a basic biological training to understand how lichens may be used, and it indicates where they may easily find the literature, should they aspire to become authorities in this field. As mentioned in the foreword, I believe that it would be otiose for me to try to duplicate information so admirably set out by Hawksworth and Rose, so in this section I propose to restrict myself to general comments and discussion of the uses and limitations of lichens as pollution indicators.

Lichens are composed of two different organisms, a fungus and an alga, living in symbiosis. Most of the fungi exist only in lichens, i.e. they cannot live independently. On the other hand, most of the algae are identical or similar to species which can also enjoy an independent existence. Lichens have no true roots, and are often found on tree trunks or stones from which they obtain only limited amounts of nutrient salts. This statement needs some qualification. Calcareous rocks are, as a rule, more heavily covered with lichens, particularly in areas of moderate air pollution, than are igneous rocks. The reason would appear to be that, on limestone for instance, acid pollution may be neutralised to a considerable extent.

Essential chemical nutrients - and pollutants - reach lichens mainly as a result of dry deposition by dust on, or the adsorption of gas by, the thallus (i.e. on the general surface of the growing organism). Nutrients in rainwater are important, though quantitatively most substances are derived in only small amounts from direct wet deposition in the rainwater itself. It is not known how much dry deposition is directly absorbed into the thallus; lichens have no stomata to allow gasses to reach the living cells within the mass of the thallus. It is likely that most absorption takes place when the rain wets the thallus surface, dissolves the salts on the surface and thereby allows them to be absorbed.

Rain will fall directly from the sky on lichen thalli; it will also run down tree trunks ("stemflow") and over the surface of rocks, picking up deposited salts, before reaching the plants. The extent of this enrichment is know to be considerable (e.g. Eaton *et al*, 1973) so the effect on the lichens is also likely to be appreciable. The concentration of salts in stemflow is highest after long dry spells, and lowest in wet weather, when deposits are soon washed away. This may be one reason why, in areas of equal air pollution, lichens are most plentiful where the rainfall is high, for they will then seldom experience concentrated solutions of salts and of pollutants in stemflow.

It is true that, though lichens can survive considerable periods of drought, they generally grow most luxuriantly under moist conditions. Some workers (e.g. Rydzak, 1969) have suggested that many of the results linking lichen abundance with pure air, and their absence with atmospheric pollution, can better be explained by studying the correlation with rainfall and air moisture. This view has been conclusively disproved by many other workers (e.g. Gilbert, 1970; Hawksworth, 1971; general review by Coppins, 1973). They do not deny that moisture affects the luxuriance of growth, and that local dry habitats may support rather fewer plants than those under wetter conditions, but data based on the "presence or absence" of lichen species can clearly be used to indicate levels of atmospheric pollution .

It is often stated that lichens as a group are unusually susceptible to the effects of air pollution, particularly by SO_2. This statement is not strictly true. Different lichens differ very greatly in their reactions, and this is why different members of the group are of so much use as indicator species. A few lichens, e.g. *Lecanora conizaeoides*, are in fact able to flourish in all but the most highly polluted areas in Britain. On the other hand, some of the leafy species are eliminated when average SO_2 levels are below 30 $\mu g/m^{-3}$; higher plants including some of agricultural importance in sulphur-poor soils may suffer from sulphur deficiency under these conditions, and greater yields may be obtained in more "polluted" air (Central Unit of Environmental Pollution, 1976).

Most of the published work on lichens and air pollution relates the present distribution of a number of species to long-term integrated effects of air pollution, usually by SO_2. Studies have been made at all levels of sophistication. Results have been obtained by expert lichenologists, able authoritatively to identify all species and to relate these to conditions of micro-habitats. At the other end of the scale, school children only able to divide the plants into rough groups depending on their general growth form and appearance have produced remarkably reliable information.

Hawksworth and Rose (1976) summarise work using at least 85 different lichen species whose presence indicates various winter mean levels of atmospheric SO_2. They show how up to ten different zones, with SO_2 levels ranging from over 170 $\mu g/m^{3}$ down to "pure" (in this case under 20 $\mu g/m^{-3}$ and including areas with the natural background of approximately 5-10 $\mu g/m^{-3}$). They show how allowances must be made for the effects of the acidity and nutrient status on the barks of different trees and different substrata such as calcareous or other rocks and asbestos roofing in lichen growth.

It should not be imagined that, although so many details are now readily available, work at this level is easy or should be lightly attempted. The inexperienced will require to make some considerable effort before he can identify even a restricted number of lichens with certainty. As most results depend on negative observations (the absence of certain species), care must be taken to discover whether the substrates have been in position long enough to allow lichen cover to develop. Even the most authoritative publication cannot include all the information needed for studies under a multitude of field conditions. But for the serious research worker studying air pollution, the lichen is a very useful tool to add to his armoury.

However, lichens can also be used by much less skilful workers. Gilbert (1974) gives the results of an exercise organised in Britain by the Sunday Times newspaper and the Advisory Centre for Education in Cambridge. Over 1,000 children, average age 13-14, from all parts of Britain were issued with a "kit" which illustrated the types of lichen found associated with different degrees of air pollution. The children were seldom able to identify by name more than a few species, but they could easily observe the general growth pattern of these plants. This they mapped for different transects in their home area. The kit stated the general rule on which their observations might be based - "the more it (the lichen) sticks out, the cleaner the air". The results of all the surveys were centrally analysed, and a general map produced. It showed no significant discrepancies from that produced by the much more sophisticated methods used by Hawksworth and Rose (1976) and their collaborators.

Too much must not be made from this finding. It is clear that quick, widespread general surveys which probably correlate closely with mean SO_2 levels can be made by quite inexperienced observers. But detailed studies involving particular emittors of pollution, and changes in the rate of emission of various toxic substances, require quite a different approach.

Lichens are long-lived, slow-growing plants. Some on tombstones of known age are probably over a hundred years old. As has been indicated, they are generally used to give long-term results integrating air conditions over months or years. They are seldom used to show sudden changes in pollution levels. They have been shown to develop characteristic pathological symptoms when submitted to a new form of pollution, but measurements of these symptoms are seldom practicable. Where old records exist for lichens in the pre-industrial period, changes in distribution of named species may indicate how the quality of the atmosphere has deteriorated. But, in general, measurements are of long-term, often gradual, changes, seldom of sudden (and possibly brief) incidents of air pollution.

As mentioned in the introduction, indicator plants are of most use when the nature of the most likely pollutant is already recognised. In Britain, more SO_2 than any other gaseous pollutant is being liberated, and raised levels are to be found in almost all parts of the country. As will be indicated below, in some cases, lichens are being more seriously affected locally by other pollutants, but these effects seem to be very local (with much higher pollution gradients than for sulphur) and do not upset the general picture obtained by expert lichenologists or school children.

Fluoride pollution of the air also occurs in Britain, and can be monitored by lichens. Sites near to aluminium smelters and brickworks are generally "lichen deserts" (Mazel, 1958; Gilbert, 1973). Obviously, if one is relying on "presence or absence" data, it is impossible to distinguish between the effects caused by different toxic emissions. It may be possible to be reasonably certain that fluoride and not sulphur is to blame by the configuration of the area apparently affected. Fluoride levels tend to be high near sources of emission, but then to fall off rapidly so as to have little effect beyond, say, 10 km. Thus, we may sometimes find a large area of moderate sulphur pollution with, superimposed, a smaller area of more intense fluoride damage. It is not difficult for the experienced worker, with his observation and intuition backed by a comparatively small number of chemical analyses, to elucidate the situation. But, without the analyses, his conclusions will be essentially speculative.

Acute effects of new and serious sources of fluoride pollution have been studied by noting how they may damage existing and healthy lichen populations. This has been possible as aluminium smelters have been established in recent years in areas where, previously, the air was very clean. The most comprehensive study is still in progress in Anglesey (Perkins, 1975). Here, it was possible to map the existing lichens before the beginning of the operation of the aluminium smelter, so that reasonable baseline figures were obtained. As the results are given in detail in Dr. D. F. Perkins' excellent report, they will not be repeated here in any detail. The main points to be noted are that, soon after the smelter went into operation, the lichens, particularly the species known to be susceptible to pollution, began to show pathological symptoms, including a weakening of the attachment of the thallus to the substratum, colour changes and eventual chlorosis and bleaching.

Photographic records, in colour, of the lichens undergoing damage, and those growing (slowly) in unpolluted control areas were also made. A particular value of this investigation was that regular chemical analyses of the lichens at different distances from the smelter were also made. Analyses (reduced to F ppm dry matter) made it possible for a map showing "lichen isofluors" to be drawn. The numerical data here cannot be directly related to emissions or to levels of fluorine in the air, but can be directly associated with biological effects on a range of lichen species.

Lichens are clearly efficient at taking up fluoride, apparently at a rate which bears a definite relation to the levels in the air. They operate during life, and also *post mortem*. It appears that many lichens die when they take up more than 80 ppm of F (Nash, 1971), though some are more resistant (LeBlanc *et al*, 1971). The highest result recorded by Perkins (1975) is 1525 ppm; this lichen was obviously dead, and the dead plant material was acting very much as a "moss bag" (see page 9 below).

Lichens have been found to be susceptible to damage by many other pollutants, including car fumes, dust, heavy metals and pesticides. However, they do not seem to be of particular value as indicators of these substances. It is possible that if, in an otherwise clean environment, we had a gradient of levels of, for instance, lead, lichens could be used to measure that gradient. Unfortunately, environmental situations are seldom as simple as this, and I think it is unlikely that there will be many situations where a study of this kind would be productive. It is clear that some species of lichen react to low levels of sulphur and do not appear to be harmed by heavy metals at what, to mammals, would appear to be more dangerous levels. So, although there may be other ways in which lichens may indicate various pollutions, either by pathological reactions, or by particular distribution patterns, I do not think that these will be common or consistent enough to suggest that they will have many wider applications as indicator species.

However, as with fluoride, and with sulphur, lichens may actively accumulate many other substances, so that amounts in the thalli (dead or alive) may be related to environmental levels. Thus, it has been shown that healthy lichens in areas of metal contamination may accumulate many metals, including chromium, copper, iron, lead, manganese and nickel (Seward, 1973). A level of iron of 90,380 ppm (9 per cent) was recorded.

Lichens in the arctic tundra have been found to accumulate radionuclides arising from the explosion of atomic bombs (James, 1973). They are said to be many times as efficient at this process as are flowering plants. Here, there is no evidence of the radioactive materials reaching levels which adversely affect the lichens, though possible genetic changes cannot definitely be ruled out. Concern has been expressed lest animals like caribou, which feed on lichens (and are thus "further up the food chain") may concentrate the radionuclides further, but again there is no evidence that this has yet yielded concentrations giving radiation levels of any serious significance. Dangers to man eating wild caribou meat, or the same species in its domesticated form (reindeer) would also seem to be insignificant. The lichens, on analysis, would seem to be useful biological monitors of radiation, either from nuclear explosions, or from leaks of waste products of nuclear reactors.

Bryophytes

Bryophytes - liverworts and mosses - include species which are susceptible to damage by air pollutants, and so are, potentially, possible indicators. However, there is little information available to enable these properties to be exploited. Liverworts are commonest in the wettest and least polluted parts of Britain, and it is difficult to distinguish whether dryness or toxic substances are responsible for the distribution pattern. Liverworts are slow-growing, and there are difficulties in deciding the cause of patterns of apparent damage to the thalli. It may be worth studying liverworts, together with other plants, in zones with changing levels of atmospheric pollution, but their more general use as indicators cannot, with present knowledge, be recommended.

More work has been done with mosses. They are said, as a result of "presence and absence" studies in urban and industrial areas, to be approximately as sensitive to air pollution as are lichens (Gilbert, 1968; Skye, 1968; LeBlanc and DeSloover, 1970). City centres are usually moss deserts as well as lichen deserts, or only a few resistant species may be present. There is little doubt that mosses are potentially nearly as useful as lichens as pollution indicators, but more work on them is needed before this potential can be exploited. On the other hand, mosses have not been shown to have any particular advantages over lichens, and experience may reveal unexpected difficulties, so work on them can hardly be given a very high priority.

Mosses have been reported to be sensitive to sulphur dioxide, fluoride, ozone and some heavy metals. They accumulate these pollutants in their tissues, and on their outer surfaces. This process goes on during life, and also *post mortem*.

Mosses appear to be particularly valuable in studies of heavy metals. The most extensive systematic studies have been made in Scandinavia by Rühling and Tyler (1968, 1969, 1971). Results here are obtained by analysis of the moss growing naturally at different sites.

The moss-bag technique is described by Goodman *et al* (1974). This method has been widely used in metal pollution surveys. The moss here is dead and has been soaked for days in 0.5 N nitric acid, and so is not strictly a "biological indicator", but, nevertheless, it is a useful technique for studying metal pollution.

Fungi

Fungi are clearly susceptible to the effects of atmospheric pollution, particularly by sulphur dioxide. There are many reports of the destruction of commercial mushroom crops by relatively low levels of sulphur in the air, sometimes arising from the flue gas from heating plants in the neighbourhood. Sulphur preparations are commonly used to treat fungal diseases in vines and fruit trees. It is possible, therefore, that fungi may provide biological indicators of pollution.

The "higher" fungi, which produce above-ground fruiting bodies ("mushrooms" or "toadstools") are, as has been noted, susceptible to pollution damage. However, the fruiting bodies tend to appear so erratically, that it would be difficult to rely on them if pollution is to be studied systematically. Both they and the subterranean mycelium are no doubt affected, but it would be difficult to relate this effect to particular pollution levels. The main damage probably affects the mycelium, and, if the sulphur etc. cannot readily reach it, toadstools may still appear in somewhat polluted areas (Ing, 1969), where new fungal infestations may not be easily established. Some mapping studies may be possible. Records of the appearance of particular species in areas with different amounts of pollution could be made, and might have some significance, but the same amount of information could probably be obtained more easily by other means. Nevertheless, this would seem to be a subject where more research is needed.

Parasitic fungi, however, can already be useful indicators. There have recently been extensive studies on the relationship between plant diseases and air pollution (Saunders, 1975). The situation is complex. Some diseases are abated by levels of pollutant which harm the pathogens and are tolerated by the host plants. In other cases, plants of economic importance debilitated by pollution are more susceptible to diseases. We are not concerned with these problems here, but only with the cases which can be used to measure atmospheric pollution.

It has been known for a good many years that the disease Black Spot in roses, caused by the fungus *Diplocarpon rosae*, disappeared from parks and gardens in Britain during the industrial revolution, but has reappeared in areas where air pollution control measures have been introduced. It has been established by Saunders (1966) that the fungus is controlled primarily by the level of SO_2 in the atmosphere, and, if this rises above 100 $\mu g/m^{-3}$, the fungus will be eliminated.

Another fungal disease, tar-spot of the sycamore tree *Acer pseudoplatanus* caused by *Rhytisma acerinum*, has proved an even more discriminating indicator (Bevan and Greenhalgh, 1967). The host, the sycamore, is widely planted in industrial areas in the north of England; the tree clearly tolerates quite high levels of SO_2 (i.e. no damage is noted with mean winter levels of over 200 $\mu g/m^{-3}$). The characteristic black blotches only appear on the leaves of the trees when sulphur levels fall below 90 $\mu g/m^{-3}$. However, Bevan and Greenhalgh have shown that a "Tar spot index" (TSI) can be calculated, and this can be well correlated with levels of SO_2 lower than 90 $\mu g/m^{-3}$. The method may be used at two levels of sophistication. For those with good laboratory and instrumental facilities, a system in which the areas of leaf affected are measured can be used. For laymen concerned with air pollution, leaves can be "unaffected", spots can be "rare", "infrequent", "frequent" or "many spots per leaf". These criteria have been found to be correlated with levels of SO_2 between 90 and under 25 $\mu g/m^{-3}$. Incidentally, the results correlate well with lichen observations in the same area, but the observations with tar-spot fungus are easier to make.

These results with fungi measure integrated sulphur levels during the summer weeks when the disease is developing on its host. Thus, results are obtained more rapidly than they are using lichens, though the element of long-term integration does not operate. It is likely that other fungal diseases of plants will be usable in this way. The advantage of the tar-spot disease is that the host is widespread in the polluted areas, and that the symptoms may be measured quantitatively. In addition, the host is not severely damaged, either by the pollution or the infestation. These criteria may restrict the use of many other diseases, but this also is a field for further study.

Flowering plants

As has already been indicated, many species of flowering plant have been used as biological indicators of atmospheric pollution. Some details of the possibilities of this technique may be obtained from the book "Recognition of air pollution injury to vegetation: a pictorial atlas" (1970) edited by J. S. Jacobson and A. C. Hill, and published by the Air Pollution Control Association of Pittsburgh, USA. This volume contains colour photographs of the typical lesions produced in some 125 different plants when exposed to damaging levels of ozone, sulphur dioxide, fluoride, oxides of nitrogen, "PAN", ethylene, chlorine, ammonia and certain mixtures of oxidants and other substances. Lists of plants, including crops, garden flowers, trees, vegetables and weeds, which are particularly sensitive to the different pollutants are also given. This Atlas is an essential practical tool for anyone working on the subject of atmospheric pollution.

However, as the text of the Atlas rightly stresses, an inexperienced worker cannot, in most cases, thumb through the volume, select a plant apparently suitable for his purposes, and proceed at once to obtain significant, quantitative results. It may, for instance, be difficult to distinguish damage from sulphur dioxide from that caused by hydrochloric acid, oxides of nitrogen, or photochemical smog with some plants. Another difficulty is that of obtaining seed or other propagation material of known provenance and genetic history. Well-known cultivars established in agriculture and horticulture may be variable, particularly in their reactions to environmental factors. Seeds obtained from even the most reliable commercial suppliers vary both within packets and from packet to packet, and material with the same trade description may come from different sources at different times. I fully agree with the view expressed by Dr. W. J. Manning of the University of Massachusetts (personal communication) that, until all workers can be sure of using plant material of as nearly as possible identical genetic composition, many results will be of limited value and comparability. The only reliable cultivar generally available is probably Bel-W3 tobacco, sensitive to ozone. Beans, spinach, onions or gladioli are often much more variable.

As indicated in the foreword, the recent books edited by Mudd and Kozlowski (1975) and Mansfield (1976) give details of the ways in which various air pollutants affect plants of all types. They, like the Atlas described above, give long lists of plants which are susceptible or resistant to damage from the various pollutants. In some cases, they even give some indication of the dose (i.e. level of substance in relation to length of exposure) which may be necessary to produce a particular lesion. However, for reasons already explained, these figures must be treated with some caution.

Very little of Britain is covered with natural vegetation, so that the effects of pollution on the presence or absence of native species can seldom be used as a means of mapping pollution. The obvious exception is that of lichens, mentioned above; these are able to grow on buildings or trees in areas otherwise dominated by man. Few other plants have this facility. It has been found that coniferous trees, e.g. Scots pine (*Pinus sylvestris*), which seem to be damaged by levels of sulphur dioxide that do not harm deciduous species, are absent from the more polluted areas (Farrar *et al*, 1977), but it is difficult to be sure that existing trees have been damaged, and that the absence is not because none have been planted. Several species of conifers have been shown to develop characteristic lesions and to grow more slowly in polluted air, but, although this observation may have economic and silvicultural importance, it does not indicate that these reactions can be used easily to monitor pollution. The information may usually be obtained more easily by other methods.

Some weeds found in farms and gardens are said to be damaged by comparatively low levels of pollutants. Thus, bindweed and dock may be affected by SO_2. However, we have insufficient information to make it possible to show how such species might be used as indicators, though this is probably a subject worthy of further study. It is probable that many wild plants differ in their reactions to a variety of pollutants, and that their distribution is therefore affected, but, here again, the subject has received little attention.

The one case where it seems possible that a plant may be particularly valuable in investigating one form of air pollution is that in which the tobacco cultivar Bel-W3 is used to detect elevated ozone levels. It has been known for some years that, in many parts of the United States, levels of oxidants have been such as to do considerable damage to many crops. At first, it was thought that the problem was serious only in parts of California where the exhaust gasses from a myriad of automobiles, bright sunshine and frequent temperature inversions acted together to give high levels of ozone and, eventually, producing photochemical smog containing PAN (peroxyacetyl nitrate). We now know that larger areas of the Eastern States frequently experience levels of oxidants sufficient to damage the more susceptible plants - these in fact acted as biological indicators and detected the pollutants). In Britain, photochemical smog containing PAN has not been experienced as such, but levels of ozone approaching those which may be harmful have occasionally been detected (Bell and Cox, 1975). These have been confirmed by air analysis, but, at the moment, it is not practicable to introduce a network of stations covering the whole country. Under these circumstances, there is clearly a case to use the tobacco plant to investigate the situation.

An exercise on these lines is being organised in 1977 by Dr. J. N. B. Bell and Dr. M. Ashworth of Imperial College Field Station, Berkshire, with support from the Natural Environment Research Council. Some forty sites are being selected throughout Britain, and, at each, a series of tobacco plants will be grown from the same seed source and using plants raised under as nearly as possible the same conditions. Assessment of damage (if any) to the leaves will be made weekly, and the results will be centrally analysed. These assessments will not give direct measurements of ozone levels or exposure, but will indicate that levels are now sufficient to give some cause for concern. This is the ideal use of the indicator - to reveal that a problem exists, to give some indication of its magnitude, and to suggest how it may be further investigated.

No other plant appears at present to be equally useful for pioneer studies of any potential pollution problem. However, it is worth considering seriously whether it might not be possible to establish a network of biological monitoring stations to supplement other measuring systems, as part of the background studies of environmental change. It has been shown by Professor W. A. Feder, Dr. W. J. Manning and their colleagues at the Suburban Experiment Station at the University of Massachusetts at Waltham that school children and others can grow a wide range of species and can recognise when they are affected by air pollution. So far, this type of work is largely qualitative, and tends to confirm information already available, but it has potentialities for development, possibly to give quite accurate measurements.

What is needed is a reliable seed source of easily-grown plants with known susceptibilities to different pollutants. The literature suggests that spinach, gladiolus, petunia, various beans and, of course, tobacco could be used, but there are many other possibilities. Work needs to be done to isolate the most suitable cultivars for this purpose, and to grow these cultivars under controlled conditions to produce seed for testing. The plants will then require to be exposed to known levels of pollutants, both in growth chambers and out-of-doors, to try to obtain some quantitative data regarding their reactions (which will, of course, have to be related to climatic and weather conditions). With this material, it will be possible to organise widespread field trials, similar to those now proposed for tobacco and ozone.

General conclusions

Air pollution is a serious problem, partly because the pollutants harm plants of aesthetic or economic importance to man. To combat pollution, we need to identify and measure the substances which cause damage. We need to discover the simplest and most reliable methods of making these measurements. It is clear that some plants, by reacting sensitively to low levels of pollution, can play a useful part in studies leading to pollution control.

However, we should be clear as to our objectives. We must be clear as to what we wish to discover, and why this information is required. In Britain, it appears that, today, only three pollutants produced by man's activities are giving rise to widespread levels which are substantially above the normal background levels - these are smoke, sulphur dioxide and ozone. These pollutants give rise to their own specific problems.

Smoke, and other particulate materials, were produced mainly by burning raw coal. This type of pollution is much less serious than it was thirty - or even a hundred - years ago. Few factories now produce black smoke in any quantities, and domestic heating is increasingly less polluting. Plants are affected by smoke and soot, but cannot be used easily to make quantitative assessments. As the problem is a decreasing one, and as we have many other efficient methods to measure smoke, there is little need for increased study of this subject, unless economic pressures cause more raw coal to be widely burned.

Sulphur dioxide is still produced in large amounts by industry and domestic users. Some six million tonnes are discharged each year into the atmosphere in Britain. This quantity is at present decreasing slightly, and ground level concentrations in our towns and industrial areas are falling substantially as the gas is discharged by higher chimneys into the upper air. However, there is some evidence that levels in rural areas may be rising slightly, and Scandinavian countries complain that sulphur from Britain and other industrial countries in Europe is causing pollution damage particularly to their oligotrophic rivers and lakes.

In Britain, lichen studies have enabled a map of sulphur levels for the whole country to be drawn. The results are found to agree closely with the results of the survey, using some 2,000 stations, organised by the Warren Spring Laboratory. As the same information could be obtained from the two sources, is there any particular value in the lichen studies? The answer is, probably, 'yes'. We are given an historical picture of the spread and increase of air pollution, and recent findings (of reappearance and regrowth of species previously damaged) suggest that, in many areas, pollution is abating. We need to be on the look out for any possible deterioration in the situation. Although the measurements by the pollution network would probably detect any change (for better or worse), indicator plants may give further and different information.

Particularly for sulphur pollution, we have indicators which act on various and different timescales. Lichen distribution measures changes which take place over many years. Fungi like that of tar-spot disease of sycamore trees give a response in a matter of weeks. Plants like spinach or gladioli may react to brief pollution episodes of a few hours. It would be impossible to obtain as much information by the use of sampling apparatus and chemical analysis, so there is clearly scope for more work in this field.

In Britain, ozone is a new problem. It may, or may not, be economically important. It is also the one problem where we have an indicator plant which may prove of great value. There are many other plants which may eventually be equally useful, and they should be studied further.

Other air pollutants are generally more localised. Fluorine is usually concentrated in a zone only a few kilometres round the source. Here lichens have been found useful, both because of their physiological reaction and because of their ability to absorb fluorine to high levels in their thalli. There are many other plants which have been shown to be sensitive (e.g. gladiolus, maize, tulip) and their use could probably be developed. The most serious economic damage by fluorine is probably to cattle and other animals grazing on contaminated herbage. Chemical analysis of such herbage may give the most useful information about the range of the pollution.

Various other gasses - ethylene, chlorine, etc. - are phytotoxic, and cause local damage to particular plants, which may indicate that dangerous levels have been reached.

Carbon monoxide is discharged into the air in large amounts. In sufficient concentrations it is lethal to many animals, acting by immobilising their haemoglobin. At similar levels, carbon monoxide appears to have little or no action on plants. There is little chance, therefore, that a plant could be used to detect it.

Lead, copper, arsenic, cadmium and other metals are discharged into the air and may be serious pollutants. At high enough levels, they are phytotoxic. Some species, and some strains of some species, are resistant to specific metals; others are generally resistant. It is possible to recognise an area with a high level of, for instance, copper, by examining the vegetation (in the same way that lime-rich soils can be recognised by the plants growing there). However, these highly polluted sites are usually localised, near the mines or smelters where the metals are extracted and processed. Much useful work on possible metal pollution at much lower levels depends on the analyses of plants, most of which have picked up the metals, (often on the outside of their cuticle) without being damaged or showing any physical reactions.

It will be seen that I consider that plants may sometimes be useful biological indicators of pollution, but that their uses are limited, and that other, chemical assessments are also essential. Indicator plants can obviously serve as aids to teaching at all levels, and as subjects for research. However, before any further large-scale investigations are made, it is essential that we decide what is the purpose of such investigations, and whether the use of indicator plants is likely to give these solutions more easily than other methods or techniques.

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