F. MORIARTY

ECOTOXICOLOGY

The Study of Pollutants in Ecosystems

Second Edition

Ecotoxicology

The Study of Pollutants in Ecosystems

2nd Edition

F. MORIARTY

*Member of the IUCN Commission on Ecology,
Gland, Switzerland*

1988

ACADEMIC PRESS
Harcourt Brace Jovanovich, Publishers

London San Diego New York Berkeley
Boston Sydney Toronto Tokyo

ACADEMIC PRESS LIMITED
24/28 Oval Road
London NW1 7DX

United States Edition published by
ACADEMIC PRESS, INC.
San Diego CA 92101

British Library Cataloguing in Publication Data

Moriarty, F.
Ecotoxicology—2nd ed.
1. Environment. Pollution
I. Title
363.7'3

ISBN 0–12–506761–5
ISBN 0–12–506762–3 Pbk

Typeset in Great Britain by Photo·graphics, Honiton, Devon
Printed in Great Britain by T.J. Press (Padstow) Ltd. Padstow, Cornwall

Ecotoxicology

Preface to the first edition

I can still recall quite clearly one remark by the schoolmaster at the first lesson I ever had in geometry: one cannot learn any geometry until one knows some. I have concluded since then that ecotoxicology illustrates the same maxim. The subject is primarily a blend of toxicology and ecology, and I have become steadily more frustrated by a seemingly widespread failure to combine the two approaches. I have attempted therefore, from a synthesis of these and other disciplines, to present my view of how far the subject of ecotoxicology has developed.

The book falls into two main sections. After the introduction, the next three chapters discuss the relevant aspects of populations, communities and genetics, and indicate the implications for ecotoxicology. Three chapters in the second half of the book then discuss topics of more immediate relevance—toxicology, and the prediction and monitoring of effects—followed by a final, brief, chapter with a few general comments. I have not tried to write a textbook, nor have I attempted a comprehensive review of the literature: I doubt whether that would be feasible or worthwhile, for the literature is both enormous and, in large part, trivial. This book is best regarded as a series of closely linked essays, in which I have selected examples from the literature to illustrate ideas that may have some more general relevance. There is perhaps a bias towards a historical account, both because this is often the easiest way to comprehend a subject, and because discarded ideas are sometimes still influencing current ways of thinking.

Experience tells me that not all of the arguments advanced in this book are likely to be accepted by all who chance to read them. Once I was chided, very politely but firmly, for "political naïvety". I had published an opinion, with supporting evidence. The opinion was not challenged on the available evidence, but the complaint was that my opinion would be distorted and used by those who wished to deny that pollution can and does affect wildlife. I still do not see how suppression of facts and opinions can help our understanding of a subject, and scientists involved in any subject should be able to recognize distortion when they meet it. I hope that those who may disagree with any of my suggestions will be sufficiently stimulated to produce the contrary evidence or scientific argument.

Preface to the second edition

It is reasonably likely, at the time of writing this preface, that this new edition will appear five years after the first edition, which I find particularly appropriate given the suggestion in the introductory quotation that we need to revise our ideas every five years.

I have, of course, revised details throughout the text, and the new accounts of melanism and shell-thinning provide two interesting examples of how ideas can indeed have to be modified. There are new sections on interactions between pollutants in their biological effects, the regulation of new chemicals, QSARs or quantitative structure–activity relationships, and a new chapter with four case-studies. The theme of animal size (or weight) has received greater emphasis, important *inter alia* for amounts of pollutant within organisms, for the interpretation of shell-thinning and perhaps of other biological effects, and for monitoring.

F. Moriarty
Cambridge, CB3 7HD, UK

Acknowledgements

I am indebted to the following holders of copyright for permission to reproduce some of the figures and tables in this book: Academic Press Inc. for Figs 2.12, 2.13, 6.5, 6.7 and 6.8; Academic Press Inc. (London) for Figs 5.3, 5.13 and 5.15; the American Association for the Advancement of Science for Fig. 1.3; the American Chemical Society for Fig. 6.3; the editors of the *Annals of Applied Biology* for Fig. 2.9 and Table 5.3; ASTM, 1916 Race Street, Philadelphia, Pennsylvania 19103 for Fig. 7.8; the editor of *Bird Study* for Fig. 2.10; Blackwell Scientific Publications for Fig. 3.3; Dr J.D. Burton and The Royal Society of London for Figs 1.6 and 1.7; Cambridge University Press for Figs 2.1, 5.6, 7.1 and 7.2, and Table 3.3; Dr J. M. Davies and The Royal Society of London for Fig. 6.6; Dr J. P. Dempster for Fig. 2.6 and Table 2.2; Dr W. Dickson for Fig. 1.5; the editor of *Environmental Pollution* for Figs 7.5 and 8.3, and Tables 5.1, 5.5, 5.6 and 6.4; the editor of *Food and Cosmetics Toxicology* for Fig. 5.12; Dr D. L. Hawksworth for Fig. 7.10 and Table 7.3; Heldref Publications for Fig. 5.16; the editor of *Heredity* for Figs 4.6 and 4.7; the editor of the *Journal of Applied Ecology* for Figs 4.5 and 5.4; the editor of the *Journal of Ecology* for Fig. 3.11; the *Journal of the Fisheries Research Board of Canada* for Fig. 6.4; the Council of The Linnean Society of London for Table 6.1; Macmillan Journals Ltd for Fig. 7.3 and Tables 4.5 and 5.2; Mr I. A. Nicholson for Fig. 1.4; North-Holland Publishing Co. for Fig. 3.7; Oxford University Press for Fig. 4.4; Pergamon Press Ltd for Fig. 7.9; Plenum Publishing Corp. for Fig. 6.1 and Table 4.6; Springer-Verlag for Fig. 2.8 and Tables 5.8, 6.6, 6.7 and 6.8; the University of Chicago for Fig. 2.7; The Wildlife Society for Table 6.2; J. Wiley & Sons Ltd for Figs 2.11 and 5.11; and The Zoological Society of London for Figs 5.1 and 8.2. I am also indebted to J. Wiley & Sons Ltd for permission to reproduce the passage on pp. 170–171.

I particularly thank Dr D. J. Jefferies for the loan of a print for Fig. 5.3, and Dr D. A. Ratcliffe and the publishers T. & A. D. Poyser for copyright permission and the loan of the original drawing for Fig. 5.5. I also thank Dr L. M. Cook for permitting me to see two papers that were only at the proof stage.

ACKNOWLEDGEMENTS

The copyright of Fig. 3.8 and Table 3.4 was held by the late Professor R. H. Whittaker, whose untimely death is a great loss to the scientific community.

I have, of course, a general debt to the scientific community, for work past and present, much of which is not specifically mentioned in this book but which has influenced my thinking in various ways. I would also like to thank some individuals who have had a more immediate and direct impact: I am grateful to Professor A. D. Bradshaw, FRS, Dr J. P. Dempster, Dr S. Dobson, Mr A. V. Holden, Dr D. J. Jefferies, Dr E. E. Kenaga, Professor K. Mellanby, Professor N. W. Moore and Dr M. B. Usher for information, opinion and advice during the preparation of the first edition. Similarly I would like to thank Dr I. Denholm, Dr A. L. Devonshire, Dr H. F. Evans, Dr M. O. Hill, Dr A. J. Southward, Dr E. C. Southward, Mr J. L. Vosser and Dr D. Wainhouse for their help with the second edition.

I also owe much to my wife, for help and encouragement at all stages of what was, on occasion, an onerous task. To combine marriage and writing without a forbearing wife would be a hazardous enterprise.

„Es ist schlimm genug", rief Eduard, „dass man jetzt nichts mehr für sein ganzes Leben lernen kann. Unsre Vorfahren hielten sich an den Unterricht, denn sie in ihrer Jugend empfangen; wir aber müssen jetzt alle fünf Jahre umlernen, wenn wir nicht ganz aus der Mode kommen wollen."

Die Wahlverwandtschaften
Johann Wolfgang von Goethe (1809)

"It is too bad", cried Eduard, "that we can no longer learn anything for our entire lives. Our predecessors could rely on the formal instruction of their youth; but now we have to revise our ideas every five years if we are not to become completely out of date."

Elective Affinities

Contents

Preface to first edition . . . vii
Preface to second edition . . . ix
Acknowledgements . . . x
1 Introduction . . . 1
2 Population Dynamics . . . 17
3 Communities . . . 45
4 Genetics of Populations . . . 71
5 Effects on Individual Organisms . . . 103
6 Prediction of Ecological Effects . . . 141
7 Monitoring . . . 179
8 Case Studies . . . 213
9 Conclusions . . . 237
References . . . 243
Index . . . 279

1

Introduction

The term ecotoxicology was coined by Truhaut in 1969 (see Truhaut, 1977), as a natural extension from toxicology, the science of the effects of poisons on individual organisms, to the ecological effects of pollutants. However, the transition from the study of single organisms to that of ecosystems has brought complexities which do not yet appear to be fully appreciated. On occasion, the only difference between toxicology and ecotoxicology appears to be in the species selected for toxicological tests: acute toxicity is measured on the water flea instead of on the laboratory rat. This misses the essential difference between the two sciences. Toxicology is concerned with effects on single organisms; ecotoxicology is concerned with effects on ecosystems. The immediate effects of pollutants are on individual organisms, by either direct toxicity or altering the environment, but the ecological significance, or lack of it, resides in the indirect impact on the populations of species. The fact that a pollutant kills, say, half of the individuals in a species population may be of little or no ecological significance, whereas a pollutant that kills no organisms but retards development may have a considerable ecological impact. In addition, some pollutants have no direct effects on individual organisms, but still have considerable ecological consequences.

The widespread concern about possible ecological effects of chemicals developed during the 1950s and 1960s, when some agricultural pesticides were found to affect wildlife (Carson, 1962; Rudd, 1964; Moore, 1966a; Sheail, 1985). In retrospect, given that pesticides are non-specific poisons and are released into the environment deliberately, these effects were perhaps not too surprising, but both the form that some biological effects took, and the subsequently discovered effects of other pollutants on wildlife, were completely unexpected by most people. One striking example, not strictly ecological, must suffice.

Tomato crops grown in glasshouses in Essex showed symptoms of damage from herbicide, for no apparent reason, in 1973. Eventually, it was established that the damage was caused by the herbicide 2,3,6-TBA, present in both mains water and river water used for watering the plants (Williams *et al.*, 1977). The source was a factory near Cambridge, 130–170 km by river and artificial channel from the glasshouses. Effluent from the factory had contained small amounts of TBA for the previous 15 years, with no previously reported damage to crops, but this source of water had only just come into use for the glasshouses, and tomatoes are particularly sensitive to this herbicide.

This example illustrates a pathway, persistence and sensitivity that were not anticipated. Many such unforeseen incidents have occurred with wildlife, but, for reasons developed in this book, the determination of cause and effect is usually more complicated and difficult than in this horticultural example.

The focus of interest is not always on the possible effects of pollutants in the environment on all species, but on the implications for our own species. Effects on other species are then appraised principally for the possible impacts on ourselves. Contamination of food species is one obvious example. Studies of this type may be seen more accurately as part of environmental toxicology: the effects of chemicals in the environment on human beings (see Doull *et al.*, 1980; Guthrie and Perry, 1980).

It has been estimated that, world-wide, about 63 000 chemicals are in common use (Maugh, 1978), with 3000 compounds accounting for almost 90% of the total weight of chemicals produced by industry (IRPTC, 1983). It is commonly said that the world's chemical industry now markets an estimated 200–1000 new synthetic chemicals each year, for which we need to predict what ecological effects, if any, they are likely to have. This need is perceived as being so important that many countries now have legislation that requires tests for ecological effects. The first legislation, the Toxic Substances Control Act (ToSCA), was enacted in the United States in 1976 (Draggan, 1978).

This is possibly the first time in history that legislation has posed the problems for scientific research. I say problems for research because one thing is abundantly clear: we do not know how to predict the effects of chemicals on ecosystems, nor how best to monitor for these effects. Indeed, it is arguable that we never will be able to predict with absolute certainty, but there is scope for improvement on our present performance. Certainly, we know enough to tackle some relevant questions: How useful are acute toxicity tests? What are the relevant measurements for a species or a community in its usual environment? Do model ecosystems tell us anything that we cannot discover more easily in other ways? How should we monitor for the effects of pollutants?

The rest of this chapter considers two topics, the nature of pollutants and of ecosystems, which will provide the context of the ensuing chapters.

*

A pollutant is defined, in this book at least, as a substance that occurs in the environment at least in part as a result of man's activities, and which has a deleterious effect on living organisms. Less restricted definitions are sometimes used, which then embrace disparate phenomena.

It is sometimes useful to distinguish between a contaminant and a pollutant: a substance released by man's activities is a contaminant, unless there is reason to suppose that it is having biological effects, although the term pollutant is frequently used loosely to cover both situations. Often, of course, it is an open question whether or not a contaminant is having any biological effects.

There are many ways of classifying pollutants, and the appropriate choice depends on the purpose (Holdgate, 1979). It is not the aim of this book to characterize every pollutant—Duffus (1980) gives an excellent introduction to that topic, developed further by Connell and Miller (1984)—but two general points need to be made.

First, some pollutants, in the amounts produced, do not have any apparent direct effects on living organisms, but do so alter the physical and chemical environment as to affect the ability of species to survive. Potentially the most far-reaching of these is probably carbon dioxide, a trace gas in the atmosphere with a natural concentration of about 0.03% (Anon, 1970). Carbon dioxide emitted by the combustion of fossil fuels is increasing the amount in the atmosphere by about 0.2% each year, which will, according to some predictions, elevate global temperatures, which would then affect other physical aspects of climate too. The net result would be radical alterations in the distribution of species throughout the world. It should be emphasized that this possibility is speculative. There is no doubt that the atmospheric concentration of carbon dioxide is increasing—it is undoubtedly a contaminant—but it is difficult to calculate with any degree of certainty the secondary consequences for climate, and hence for the fauna and flora. Another example is the eutrophication of inland waters and coastal seas—their enrichment with inorganic nutrients derived from sewage and agricultural fertilizers—which again affects the distribution of species, by altering the chemical characteristics of the environment in which they live (Lund, 1971).

Secondly, for pollutants that are toxic (sometimes distinguished from those that alter the environment by the term toxicant), a major theme of this book is that effects depend on exposure and dose. The type, or sector, of the environment has some influence on exposures, and we will consider a few pollutants from different sectors which, between them, both illustrate points of general significance and provide much of the material for subsequent chapters. We will consider first one of the major air pollutants, sulphur dioxide (see Brimblecombe (1986) for a general discussion of air pollutants).

Sulphur is one of the elements essential for life. Too severe a deficiency causes death, of both plants and animals, but excessive quantities can be toxic too. Sulphur is abundant in the earth's crust, with an average concentration in soils of 0.1%, and it cycles naturally between various parts of the environment (Fig. 1.1). However, man's activities are now releasing considerable quantities of sulphur (Fig. 1.2)—air pollution from the combustion of coal has been a local nuisance since the thirteenth

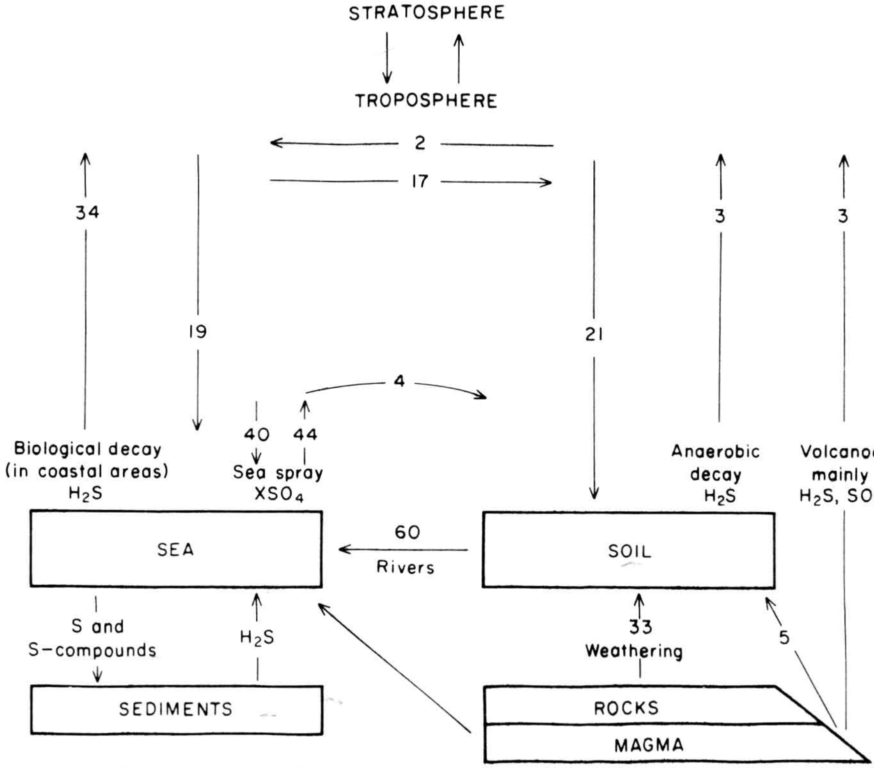

Fig.1.1 The sulphur cycle: a model for the movement of sulphur between different parts of the globe, before man's activities made a significant impact. XSO_4 indicates compounds ith sulphate. All quantities are expressed as Tg sulphur/year ($Tg=10^6$ tonnes). (Data from Granat *et al., 1976.)*

century (Brimblecombe, 1987)—and an initial appraisal of the magnitude of this contamination can be made by assessing the extent to which man's activities are disturbing the normal rates at which sulphur circulates between different parts of the environment.

Several attempts have been made to estimate these rates. There are relatively few measurements for deposition of sulphur from the atmosphere, most of these having been obtained in Europe and the USA, where pollution is maximal, and because of this most budgets have overestimated the rate at which sulphur enters and leaves the atmosphere (Granat *et al.*, 1976). These authors approached the problem by first estimating flux rates for the pre-industrial era, when man's impact was negligible (Fig. 1.1). They made two assumptions:

(1) That the amount of sulphur in the soil (pedosphere) is constant. This enabled them to estimate the amount of sulphur deposited from the atmosphere on to the land.

(2) That the amount of sulphur in the atmosphere is also constant.

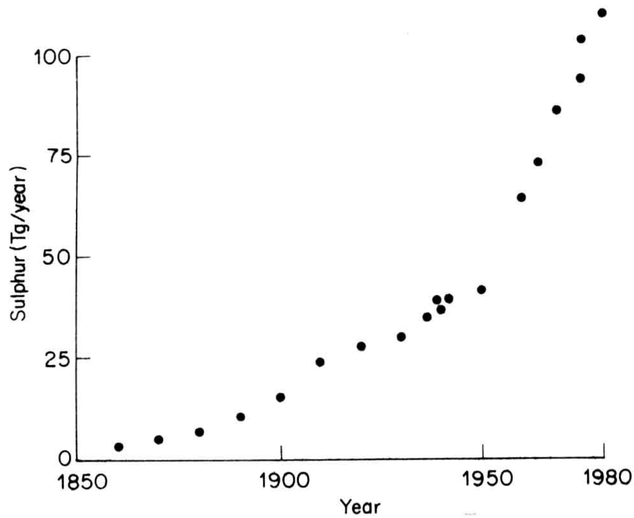

Fig. 1.2 Global emissions of sulphur into the atmosphere from human activities during the years 1860–1980. (From Ryaboshapko, 1983 (personal communication from Rodhe); original data from Katz, 1956; Robinson and Robbins, 1968; Cullis and Hirschler, 1980.)

This enabled them to estimate the amount of sulphur deposited from the atmosphere into the seas and oceans.

Some details in this scheme differ from those of earlier authors, and these estimates are not definitive (see Ivanov and Freney, 1983). There are considerable uncertainties because some flux rates simply cannot be assessed reliably. However, some features are generally agreed:

(1) Natural releases of sulphur into the atmosphere come from three principal sources. Amounts from volcanoes are difficult to estimate, but relatively minor. Sea spray is a major source of sulphate: bubbles bursting in the air produce an aerosol, but most of this sulphur is deposited back into the sea again. Most uncertainty centres on the third, biological, source, with doubts about both the types and amounts of sulphur compounds released. Much of the sulphur that passes into the atmosphere does so as volatile organic compounds, present in very low concentrations. Dimethyl sulphide appears to be the major compound (Steudler and Peterson, 1984) and, like most of the other naturally occurring organic sulphur compounds in the atmosphere, it is soon oxidized (Ryaboshapko, 1983).

(2) Inorganic sulphur compounds in the atmosphere range in their degree of oxidation from hydrogen sulphide to compounds of sulphate (Fig. 1.3), with many possible reactions for the oxidation of sulphur dioxide (Calvert *et al.*, 1985). The conversion from sulphur dioxide also involves a change of state from gaseous to particulate.

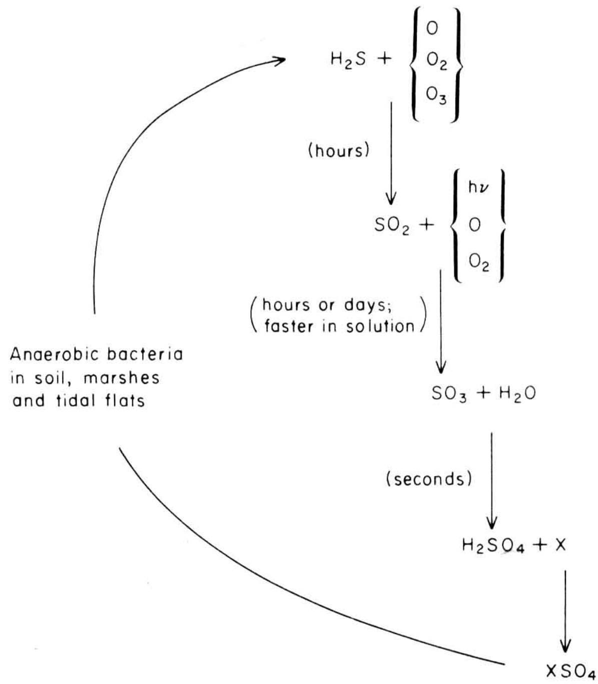

Fig. 1.3 Scheme of the transformations of sulphur in the lower atmosphere, with an indication of mean life-times (the reciprocal of the proportion removed in unit time). (From Kellogg *et al.*, 1972.)

(3) The return of inorganic compounds to the globe's surface depends on both the compound and the atmosphere's physical chemistry.

Man's activities have now approximately doubled the rate at which sulphur enters the atmosphere and hydrosphere (Ivanov, 1983). About 85% of all the sulphur emitted into the atmosphere by man's activities in 1976 came from the combustion of coal and oil (Cullis and Hirschler, 1980), with most of the remainder coming from smelting of ores and refining of petroleum. Over 95% of these total sulphur emissions were as sulphur dioxide (Kellogg *et al.*, 1972), with small amounts of a range of other compounds such as hydrogen sulphide and mercaptans. All told, these emissions are estimated to have contributed 41% of all the sulphur released into the atmosphere in 1976, with, at that time, an annual increase of 2.2% in the rate of atmospheric emissions from human activities. Additional inputs to the environment come via rivers: the use of artificial fertilizers has increased the rate at which sulphur is leached from soils, and some sulphides are also released from mines into rivers.

On a global scale, the impact of these emissions can be measured by the amounts of sulphur released by human activities and transferred each year into the seas and oceans and into the atmosphere above them. Ivanov (1983) estimated an input from human activities of 66 Tg sulphur/year from rivers into the seas and oceans, and 104 Tg sulphur/year transported in the troposphere from the continents to the atmosphere over the oceans.

However, for ecotoxicology, as distinct from global budgets, the important point is that these emissions from fuel combustion are distributed very unevenly around the globe, with the major concentrations in north-west and central Europe, and north-eastern USA and Canada (Schneider, 1986). Most of this sulphur returns to the earth's surface within about 3000 km of the source, so that any effects of pollution will be regional rather than global (Brown, 1982). In fact, the sources and pathways for a pollutant need to be studied in much greater detail before biological effects can be related to exposure.

Sulphur contaminants can affect biota in diverse ways, and to some extent this diversity is linked with the diversity of forms and routes that sulphur can take. We must therefore consider first the return of sulphur compounds from the atmosphere to the earth's surface. In general terms, airborne substances can be deposited on the earth's surface by either wet deposition, in solution or in suspension in rain, snow and other forms of precipitation, dry deposition, as particles or gases, or occult deposition of mist, fog and cloud droplets (Fowler, 1984). The proportion of sulphur deposited wet increases with distance from the source. A further distinction must be made, for wet deposition, between rainout and washout. Both terms refer to processes that transfer material to droplets of water, which can happen either in clouds before they descend as raindrops (rainout) or whilst they descend as raindrops (washout). Many mechanisms influence deposition. Deposits, wet or dry, may reach the earth's surface by the force of gravity, impaction, diffusion or turbulent transfer. Vegetation is therefore described as having a scavenging effect, when substances are filtered out of the air by the last three processes (Miller and Miller, 1980). Rain itself may reach the earth's surface under vegetation either as throughfall, or stemflow, and with both pathways rain washes filtered aerosols and gases off the vegetation and also contains leachates from the foliage (Miller, 1984). The degree of correlation between the rates at which sulphur is emitted and deposited decreases with time and distance from the source, because of variations in the rate at which sulphur dioxide is converted to sulphate and because wind speed and direction also vary (Goldmsith *et al.*, 1984).

The major effects of environmental contamination by sulphur include:

(1) The toxic effect of sulphur dioxide on plants. This is discussed later (see Chs 5 and 7), but it is noteworthy that air concentrations at one site can vary appreciably (Lane and Bell, 1984). Devilla Forest, central Scotland, has industrial regions to the south and south-west, and rural