CHAPTER 1

AIR POLLUTION IMPACTS ON CROPS AND FORESTS: AN INTRODUCTION

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1. Introduction

In Europe and North America, air pollution has been recognised as a cause of injury to vegetation over the past few centuries. Early air pollution impacts characteristically caused severe, but localised, effects close to emission sources and in urban and industrialised areas. One of the best known case studies of such localised pollutant effects occurred at a smelter complex in Sudbury, Canada during the 1900s. Entire forest communities were lost up to a distance of 15 km downwind of the complex as a result of sulphur dioxide (SO_2) and metal emissions, with other ecological effects extending to a greater distance. The effects are still in evidence today even after the introduction of significant emission reductions during the 1980s (Winterhalder, 1996).

More recently air pollution problems have become regional as well as local in extent. Regional problems associated with photochemical air pollution became apparent with observations of severe forest decline in parts of North America during the early 1960s. Chlorosis (yellowing) and premature senescence of needles of ponderosa pine trees in the San Bernardino National Forest were found to be principally

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a result of elevated tropospheric ozone (O_3) levels in the region (Miller and McBride, 1999). Similar effects of long-term O_3 exposure on conifer forest ecosystems were experienced throughout this southern Californian mountain range region and were related to the transport of polluted air masses for considerable distances from urban source areas (Hoffer *et al.*, 1982). Similar instances of regional forest decline which have been recorded in other regions of both North America and Europe have been attributed, at least in part, to regionally elevated O_3 concentrations (Chappelka and Samuelson, 1998; Skärby *et al.*, 1998). As well as effects on forest trees, detrimental effects of photochemical oxidants were observed on agricultural crops in the U.S. during the late 1940s and 1950s (Middleton *et al.*, 1950). Ambient concentrations of O_3 are now thought to be capable of decreasing the productivity of a wide range of crops in Europe (Fuhrer *et al.*, 1997) and North America (Tingey *et al.*, 1993).

The increased understanding of the damage that air pollutants such as O_3, SO_2 and nitrogen oxides (NO_x) were causing by acting directly on vegetation resulted in an awareness of the need for air quality management strategies to reduce ambient pollution levels. These strategies were based on the identification of air quality guidelines for the pollutant receptors of interest (i.e. human health, vegetation and materials) which could then be applied to assess the need for, and benefits of, pollution control measures. For example, in order to establish causal relationships between air pollution and regional scale vegetation damage, numerous field surveys and experimental studies were performed in both North America and Europe, as discussed in Chaps. 2 to 5. These studies enabled the development of dose-response relationships for different vegetation types that were used to define acceptable levels of air quality and provide targets for emission reduction strategies. Dose-response relationships were also used to indicate the current scale of the problem; for example, estimates of economic crop losses due to O_3 in the U.S. were calculated as being in excess of US\$3 $\times$ 10^9 per year (Adams *et al.*, 1988). The application of dose-response relationships in economic assessments of crop loss is discussed further in Chap. 15.

The use of air quality guidelines to inform emission reduction strategies has gone some way to improve air quality in both Europe and North America. However, much of the reduction in levels of some atmospheric pollutants in these regions has also been due to other factors such as economic restructuring and changes in energy policy. In contrast to the situation in Europe and North America, air pollutant emissions have been increasing over the last two decades in many developing countries of Latin America, Africa and Asia (UNEP, 1997). This has been primarily due to rapid economic growth in many of these countries resulting in increases in urbanisation, transportation, industrialisation, and energy generation (World Resources Institute, 1996). The contribution of different sector emissions to air pollution problems varies considerably across regions resulting in variable pollutant climates in different countries. However, it is possible to identify the major pollutants produced by these human activities as SO_2, O_3, suspended particulate matter (SPM) and NO_x (World Resources Institute, 1994). It is the impact of these pollutants in developing countries which is the prime focus of this volume.

Air pollution impacts can be divided into two classes — direct and indirect injury. In this book we deal primarily with the former, which constitutes injury resulting directly from exposure to the pollutant (e.g. gaseous uptake of the pollutant by vegetation resulting in internal cellular damage or changes to biochemical or physiological processes). SO_2 and NO_x can also contribute to acidification of sensitive soils, which may be accompanied by a depletion of base cations, affecting the local vegetation over relatively long timescales (e.g. Grennfelt *et al.*, 1994). NO_x and ammonia emissions can also cause long-term eutrophication of nutrient-poor terrestrial ecosystems, although the additional nitrogen deposition may also lead to short-term stimulation of growth. Given the scarcity of information describing responses of vegetation in developing regions, and the relatively short period of elevated emissions in many regions, it is crucial to ascertain the immediate effects of air pollutants before considering these longer-term impacts.

Furthermore, a recent global assessment by Kuylenstierna *et al.* (2001) showed that modelled deposition of acidity in 1990 only exceeded critical loads for soil acidification in small areas of China and Southeast Asia outside Europe and North America, although this situation was predicted to change significantly by 2050. There is also little evidence that productive crop systems are sensitive to acidification, while deposition of atmospheric nitrogen deposition is usually significantly smaller than the inputs from organic and/or inorganic fertilisers in agricultural systems. Since it is the impact of air pollutants on crop production which is likely to be of greatest concern in most developing countries, the focus on direct impacts of atmospheric pollutants in this volume reflects the likely economic significance of the issue.

2. Pollutant Emissions

The pollutants considered in this book are emitted from a number of different sources that can be grouped according to different sectors (e.g. industry, power generation, transport, biomass burning, etc.). Knowledge of the sources of different pollutants is crucial to an understanding of the variable nature of the changes in pollutant concentrations, and the resulting pollutant mixtures, found in different countries. The following section briefly describes the sectors primarily responsible for the emissions of each of the different pollutants in turn. It then considers data on emission trends from different sources in various regions of the world.

2.1. *Pollutant Sources*

Sulphur dioxide (SO_2)

The main source of anthropogenic SO_2 is from the combustion of fossil fuels containing sulphur. These are predominantly coal (especially poor quality, high sulphur content brown coal or lignite) and fuel oil, since natural gas, petrol and diesel fuels have a relatively low sulphur content. In general, combustion of coal in power stations is the most important source of SO_2 emissions. Other sectors that contribute significantly to SO_2 emissions include other industrial processes, as well as domestic and commercial heating, although sector contributions will vary by country and region. SO_2 is a primary pollutant (i.e. one that is released directly into the atmosphere from pollutant sources) and therefore concentrations tend to be directly related to the extent of local emissions and the height of emissions; as such, high levels of SO_2 are typically associated with urban or industrial areas. Use of tall stacks for major industrial processes and power stations can effectively reduce ground-level concentrations, although they are less beneficial in terms of long-range transport. Levels of SO_2 in the atmosphere are highest under meteorological conditions that lead to poor dispersal of low-level emissions, for example under temperature inversions with low wind speeds.

Nitrogen oxides (NO_x)

Both nitric oxide (NO) and nitrogen dioxide (NO_2) are known to have impacts on vegetation. NO_2 is predominantly a secondary pollutant formed mainly by reaction between emissions of the primary pollutant nitric oxide (NO) and O_3. The rapid conversion of NO to NO_2 results in the atmospheric burden of NO_x (as the sum of the two compounds is known) being predominantly NO_2 at locations away from sources. As for SO_2, these pollutants are produced during combustion processes but whilst SO_2 emissions increase with the sulphur content of the fuel, NO_x emissions depend upon other factors. The major source of NO_x is from high temperature (>1400°C) combination of atmospheric nitrogen and oxygen during combustion. There is also a smaller contribution from the combustion of nitrogen contained in the fuel. Combustion of fossil fuels from stationary sources (heating and power generation) and from motor vehicles are the main sources of NO_x.

Ozone (O_3)

Unlike other gaseous pollutants, O_3 occurs naturally at relatively high background concentrations. Background surface O_3 concentrations have been steadily rising from between 10 to 20 ppb at the beginning of the 20th century to values in the range 20 to 40 ppb in recent years (Volz and Kley, 1998). These concentrations are the result of two different processes; O_3 transfer from the stratosphere into the troposphere and photochemical reactions. The latter involve O_3 formation from the recombination of atomic and molecular oxygen via the phytolosis of NO_2, and O_3 destruction by reaction with NO to reform NO_2. Net production of O_3 leading to elevated O_3 concentrations occurs in atmospheres polluted with hydrocarbons and NO_x. In such situations, hydrocarbon degradation produces free radical species that react with NO producing NO_2, thereby facilitating net production of O_3. O_3 concentrations tend to be higher in suburban and rural locations as reaction with NO leads to local-scale depletion of O_3. O_3 can cause damage to ecosystems located considerable distances from the source of the primary pollutants. The main sources of NO_x have been described above; emission sources of volatile hydrocarbons include natural sources such as release from forest trees. In urban areas, road transport tends to be the major contributor, although use of solvents, for example in paints and adhesives, can be a significant source. Emissions from road transport include both the evaporation of fuels and the emission of unburned and partially combusted hydrocarbons and their oxidation products from vehicle exhausts.

Suspended particulate matter (SPM)

The term suspended particulate matter (SPM) includes finely divided solids or liquids that range in size from 0.1 to approximately 25 μm in diameter. However, the most common measure of particles used to quantify pollutant concentrations in developed countries is now PM_{10}, the abbreviation for particulate matter having an aerodynamic diameter less than 10 μm. This is the size range that includes the majority of the total suspended particles in the atmosphere by mass (Beckett *et al.*, 1998). SPMs can be categorised into two groups. Primary particles are emitted directly from source (e.g. from vehicle exhausts), while secondary particles are formed by interactions with other compounds, e.g. nitrate formation from the photo-oxidation of NO_x. In general, most coarse particles (i.e. those between 2.5 to 10 μm) are made up of both natural and organic particles whilst the fine fraction (i.e. < 2.5 μm) tend to mostly be of anthropogenic origin, including nitrate and sulphate aerosols. SPM tends to be an urban pollutant; however this does depend on the size of the particles under consideration. This is the reason for higher rates of deposition closer to particle emission sources and the classification of SPM as a local pollutant. Emission sources of SPM in developing regions may well differ from those in developed regions; for example forest fires, local industry and less developed infrastructure may contribute significantly to atmospheric SPM load.

Fluorides

Fluoride (F) compounds are recognised as common gaseous or particulate pollutants produced from many industrial processes. The most important F-emitting industrial sources are aluminium smelters and fertiliser phosphate factories. As such, fluoride [as hydrogen fluoride (HF)] did not become a major air pollutant problem in North America and Europe until the expansion during the 1940s of the aluminium smelting and phosphate fertiliser industries (Wellburn, 1994). Coal combustion, steel works, brickyards, and glass works may also significantly contribute to F emissions.

2.2. *Regional Variations and Trends*

A major driving force behind the increases in air pollution in many developing regions is the recent rapid increases in urban populations in these regions, leading to increased energy demand, industrial activity and road traffic. The different rates of urbanisation across the world are shown in Fig. 1. Since 1950, the number of people living in urban areas has risen dramatically from 750 million to more than 2500 million people (UNEP, 2000). The Asian and Pacific region has experienced the greatest absolute increase, with the urban population almost doubling between 1975 and 1995. Rapid increases in urbanisation are also occurring in Latin America and Africa, albeit rather more slowly compared to Asia. However, it is worth noting that the percentage of the population in urban areas is still highest in North America and Europe.

Similarly, Fig. 2 shows that the number of motor vehicles are also starting to increase in developing regions; the Asian and Pacific region has experienced the greatest increase amongst developing country regions with an increase of 40% between 1980 and 1995. This represents a greater rate of increase than in North America, though not as large

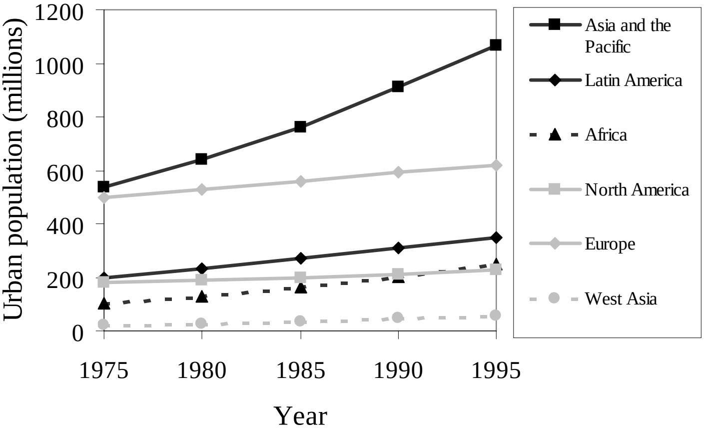

Fig. 1. Increases in regional urban populations from 1975 to 1995 (UNEP, 2000).

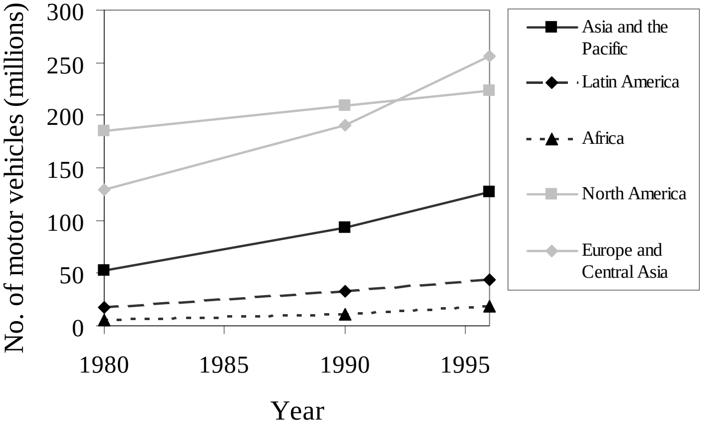

Fig. 2. Increases in regional numbers of motor vehicles from 1980 to 1995 (UNEP, 2000).

as increases experienced in Europe. If current rates of expansion continue there will be more than 1000 million vehicles on the road worldwide by 2025 (UNEP, 2000). In many urban areas, motor vehicles are the most important source of air pollutants; for example in Delhi and Beijing, emissions from motor vehicles represent 57% and 75% of total urban pollutant emissions, respectively (World Resources Institute, 1994).

Air pollution from industry has also become a feature of a number of developing countries. Although the sizes of many industrial plants have tended to be relatively small by western standards, the cumulative effect of many small industrial sources of pollution may be considerable. In addition, the displacement of polluting industries to countries where less emphasis is placed on emission control could cause significant regional problems in the future (Abdul Rahim, 2000).

The growth in energy demand in recent decades has been especially rapid in developing countries and regions. For example, growth in energy demand for the Asian and Pacific region was 3.6% year^{-1} between 1990 and 1992 compared with an average of 0.1% growth for the whole world (ADB, 1994). This has resulted in an increase in the consumption of coal; for example, the Asia Pacific region accounted for 41% of world coal consumption in 1993 (EIA, 1995). Large power plants in many developing countries often still use fossil fuels with a high sulphur content. As a result, these power plants comprise the greatest contributors to SO_2 emissions in these regions. Figure 3 shows that at the same time as SO_2 emissions have been decreasing in Europe and North America, the increased burning of fossil fuels in Asia has resulted in a dramatic increase in SO_2 emissions; these trends are projected to continue over the next decade.

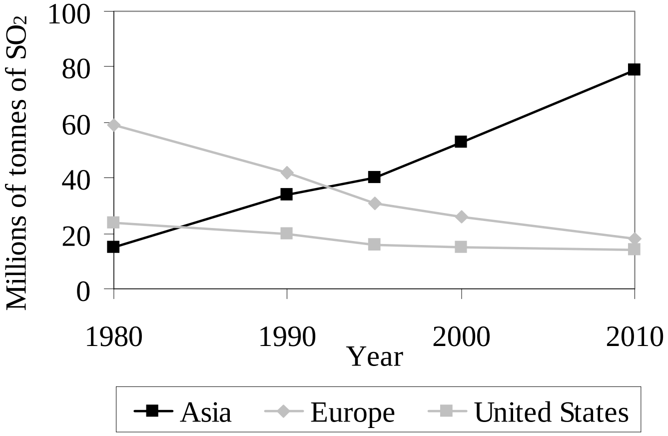

Fig. 3. Regional SO_2 emissions from fossil fuel burning (UNEP, 2000).

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In addition to air pollution emissions from road traffic, energy demand, industry, and power generation, deterioration in air quality in developing regions also results from a number of other activities including forest conversion and agricultural activities, refuse disposal and household heating and cooking. The widespread use of fire to clear previously logged forests has received recent international attention as a source of air pollution, and specifically of increasing SPM concentrations. Forest fires have become a major cause of air quality problems in countries such as Brazil, Indonesia and Malaysia (Glover and Jessup, 1999) and result in both urban and regional scale deterioration in air quality.

The broad global trends discussed above demonstrate a shift in air pollution problems from developed to developing countries. However, it is also apparent (e.g. from the comparatively large increases in numbers of motor vehicles, energy demand and industrial growth in the Asian and Pacific regions, compared to African and Latin American regions) that pollutant emissions and resulting pollution loads vary within the developing world. Some of the key regional differences are discussed below.

The **Asia and Pacific** region has seen energy demand rise faster than in any other part of the world; per capita commercial energy use more than doubled in most parts of the region between 1975 and 1995 (UNEP, 2000). Fossil fuels account for about 80% of energy generation; since both China and India rely heavily on coal, this has become the most utilised fossil fuel within the region (EIA, 1995) and has resulted in rapidly increasing emissions of SO_2. NO_x emissions from fossil fuel combustion have been shown to increase in line with SO_2 emissions (Hameed and Dignon, 1992). Transportation contributes the largest share of air pollutants to the urban environment; urban levels of smoke and dust are generally twice the world average and more than five times as high as in industrial countries and Latin America (ADB, 1997). The concentrations of air pollutants in this region are expected to increase in the future. For example, a study performed to characterise regional emissions in China estimated that SO_2 emissions are projected to increase from 25.2 million metric tonnes (Mt) in 1995 to 30.6 Mt in 2020; these projections allow for the fact that emission controls will be implemented on major power plants.

Emissions of NO_x are also projected to increase in China from 12.0 Mt in 1995 to between 26.6 and 29.7 Mt by 2020 (Streets and Waldhoff, 2000). These emissions will be concentrated in the populated and industrialised areas of China, which tend to coincide with areas where agricultural productivity is relatively high.

Atmospheric pollution has only emerged as a problem in **African** countries over the past few decades. This is in part related to the dramatic increase in commercial energy consumption, which has risen by 145% since 1973 (McCormick, 1997). Of anthropogenic SO_2 emissions estimated for 1990 at 6.9 Mt for the whole of Africa, 3.5 Mt resulted from fossil fuel burning. In contrast, industrial processes such as smelting contributed 1.6 Mt SO_2, and land-use changes and waste treatment 1.7 Mt SO_2 (Olivier *et al.*, 1996). The highest concentrations of heavy industries are found in Zambia, South Africa and Nigeria, with industry occurring on much smaller scales in other African countries (van Tienhoven, 2000). The most important sources of industrial emissions include thermal power stations, copper smelters, ferro-alloy works, steel works, foundries, fertiliser plants and pulp and paper mills (UNEP, 2000). In southern Africa, air pollution originates largely from thermal power stations; estimates for 1994 indicated that about 89% of the electricity generation in this region is from coal. Approximately 97% of this coal generated electricity is produced in South Africa where the coal sulphur content is about 1% (Siversten *et al.*, 1995). This dependence on coal-based thermal power is likely to persist into the future indicating that SO_2 pollution will remain a problem for many years to come. In addition, the world's richest mineral field runs through most of the southern African countries. Smelters processing ores from these mineral deposits represent one of the major sources of air pollution in southern Africa and future exploitation of these deposits make this industry an emission sector of growing concern.

In the countries of **Latin America and the Caribbean**, nearly three-quarters of the population are urbanised, many in megacities, with the air quality in most major cities rising to levels that pose a threat to human health. Reliable emission inventories for these regions are not readily available. Trends emerging from completed (Uruguay and Argentina) and preliminary (Costa Rica, Mexico and Venezuela) inventories suggest that more than 50% of emissions come from industrial production and energy generation (UNEP, 2000). In Central America, more than 50% of the energy produced is generated by hydropower. However, as exemplified by Brazil, there has recently been a re-direction of energy policy from hydroelectricity toward fossil-fuelled electricity generation, changes that are being supported by international and bilateral funding agencies (Rosa and Schaeffer, 1995). As such, energy-related pollutant emissions from the Latin America region might be expected to increase significantly in the future.

3. Pollutant Impacts

The air pollutants currently considered to be most important in causing direct damage to vegetation are SO_2, NO_x, O_3, F and SPM. Direct effects of air pollution can be further classified into visible and invisible injury. Visible injury normally takes the form of discolourations of the leaf surface caused by internal cellular damage. Such injury can reduce the market value of agricultural crops for which visual appearance is important (e.g tobacco and spinach). It can also lead to yield reductions, while the damaged parts of the leaf surface can provide points of entry for plant pathogens. Invisible injury results from pollutant impacts on plant physiological or biochemical processes and can lead to significant loss of growth or yield and changes in nutritional quality (e.g. protein content) (Ashmore and Marshall, 1999). Visible injury tends to be associated with short-term exposures to high pollutant levels whilst invisible injury is generally a consequence of longer-term exposures to moderately elevated pollution concentrations. While visible injury can be identified in the field, loss of yield can only be identified with suitable control plants, and so can go undetected especially if there is little awareness of air pollution issues.

A brief description of the process by which each of the five different pollutants cause injury to vegetation is given below; this information is summarised in Table 1. A small number of photographs from different countries, illustrating characteristic symptoms of visible injury caused by SO_2, O_3 and F, are distributed through the text. These are described in more detail in the relevant chapter. Appendix 1 also

Table 1. Summary of the major sources, impacts and scale of effects of the major pollutants considered in this book.

Pollutant	Major sources	Major impacts	Major scale of effects
Sulphur dioxide (SO_2)	Power generation; industry; commercial and domestic heating	Visible foliar injury; altered plant growth; elimination of lichens and bryophytes; forest decline	Local
Nitrogen oxides (NO_x)	Power generation; transport	Altered plant growth; enhanced sensitivity to secondary stresses; eutrophication	Local
Ozone (O_3)	Secondary pollutant formed from NO_x and hydrocarbons	Visible foliar injury; reduced growth; forest decline	Regional
Suspended particulate matter (SPM)	Transport; power generation; industry; domestic heating	Altered plant growth; enhanced sensitivity to secondary stresses	Local
Fluorides	Manufacturing and smelting industries	Reduced plant growth; fluorosis in grazing animals	Local

provides a brief reference table for inter-conversion of measurement units for the different pollutants.

Sulphur Dioxide (SO_2)

SO_2 enters leaves through the stomata, but is also deposited at significant rates to wet surfaces, where it may dissociate to form sulphite or bisulphite and react with cuticular waxes. This can affect the cuticle to such an extent that a certain amount of SO_2 can enter via the damaged cuticle (Wellburn, 1994). Critical to the impact of the internal SO_2 dose are the buffering capacities of the cellular fluids. Higher plants have some capacity to control intracellular gradients of acidity and alkalinity, but in lichens, such control mechanisms are relatively primitive. This is considered to be the reason why lichens are most severely affected by SO_2, resulting in “lichen deserts” in regions where SO_2 emissions are especially high (e.g. Nash and Worth, 1988).

SO_2 causes visible injury characterised by chlorosis of leaf tissue (whitened areas of dying tissue where the pigments have been broken down). Even when no visible injury is apparent, SO_2 can cause a reduction in growth and yield. However, in sulphur (S) deficient areas, low levels of SO_2 may actually be beneficial. Changes in fertiliser practice coupled with SO_2 emission reductions over the last three decades in Western Europe and North America have resulted in the occurrence of S deficiency in some agricultural species growing under specific soil types and climatic conditions (Blake-Kalff *et al.*, 2000). SO_2 can also indirectly affect crop yields through effects on the prevalence of plant pathogens and insect pests (Bell *et al.*, 1993), as can NO_x.

Nitrogen oxides (NO_x)

The predominant pathway of NO_x entry into plant leaves is through the stomata, although cuticular resistances to NO_2 entry are lower than for both SO_2 and O_3. The biochemical effects of NO and NO_2 are quite different and there is some uncertainty over which oxide is more toxic (CLAG, 1996). NO_x can reduce plant growth at high concentrations, although growth stimulations can be caused by low NO_x concentrations, generally under situations of low soil nitrogen (CLAG, 1996). However, even if growth is stimulated, exposure to NO_x can have adverse effects such as heightened sensitivity to drought, pests, and in some cases, to frost (CLAG, 1996). Rare instances of visible injury caused by exposure to very high concentrations of NO_2 are characterised by chlorotic areas on leaves associated with necrotic patches. Prolonged exposure to NO_x has been shown to suppress plant growth via inhibition of photosynthesis. The combination of NO_x with other pollutants has been found to cause synergistic effects on plants (i.e. affect vegetation to a greater extent in combination than individually). This is particularly true of NO_2 and SO_2 (Ashenden and

Mansfield, 1978) but synergistic effects have also been observed between NO_x and O_3 (CLAG, 1996).

Ozone (O_3)

Unlike SO_2 and NO_x, consideration of the toxicity of O_3 is not complicated by its role as a source of an essential nutrient. O_3 transfer via the leaf cuticle is negligible and O_3 uptake is almost entirely through the stomata. On entry to the sub-stomatal cavity, O_3 reacts with constituents of the aqueous matrix associated with the cell wall to form other derivatives which result in the oxidation of the sensitive components of the plasmalemma, and subsequently the cytosol. The inability to repair or compensate for altered membrane permeability can manifest itself as symptoms of visible injury, which are generally associated with short-term exposures to high O_3 concentrations. Symptoms of acute injury on broad-leafed plants include chlorosis, bleaching, bronzing, flecking, stippling and uni- and bifacial necrosis. On conifers, tip necrosis, mottling and banding are all common symptoms (Kley *et al.*, 1999). Chronic exposures may or may not result in visible foliar symptoms (usually characterised by chlorosis, premature senescence and leaf abscission). However, reductions in growth from chronic exposures are well documented and can result in crop yield losses, reductions in annual biomass increments for forest trees and shifts in species composition of semi-natural vegetation (Fuhrer *et al.*, 1997).

Suspended particulate matter (SPM)

SPM can produce a wide variety of effects on the physiology of vegetation that in many cases depend on the chemical composition of the particles. Heavy metals and other toxic particles have been shown to cause damage and death of some species as a result of both the phytotoxicity and the abrasive action during turbulent deposition. Heavy loads of particles can also result in reduced light transmission to the chloroplasts and the occlusion of stomata, decreasing the efficiency of gaseous exchange (and hence water loss). They may also disrupt other physiological processes such as bud-break, pollination and light absorption/reflectance. Indirect effects of particulate deposition such as predisposition of plants to infection by pathogens and the long-term alteration of genetic structure have also been reported. In contrast, a few instances of particle deposition producing positive growth responses have also been observed and related to the capture and utilisation of nutrient particles from the atmosphere (Beckett *et al.*, 1998).

Fluorides

Both gaseous and particulate fluorides are deposited on plant surfaces and some penetrate directly into the leaf if the cuticle is old or weathered. Fluoride dissolved in water on the leaf surface can be absorbed by diffusion through the cuticle (Brewer *et al.*, 1960). Gaseous fluoride is absorbed via the stomata and transported by the transpirational flow in the apoplast, and can accumulate at toxic levels in the tips and margins of the leaves (Jacobsen *et al.*, 1996). Plant species show a wide range of susceptibilities to fluoride; for example, studies have shown that young conifers and vines are especially sensitive, whilst tea and cotton are resistant to fluoride pollution (Wellburn, 1994). Leaf injury in the form of chlorosis and necrosis of leaf tips and margins has been described for a number of species in relation to emissions from aluminium smelters (Treshow and Anderson, 1989). Studies have also shown fluorides to cause reductions in photosynthesis, respiration and metabolism of amino acids and proteins. Accumulation of fluoride in plants has been associated with fluorosis in grazing animals. Animals grazing on pasture close to brickworks, smelters, and phosphate fertiliser factories, or fed forage gathered from such areas, may develop fluorosis, a condition characterised by damage to the musculoskeletal system including softening of teeth, difficulty in mastication, lameness and painful gait (e.g. Patra *et al.*, 2000).

4. Significance of Agriculture and Forestry

This book is primarily concerned with assessing the impacts of air pollution on crops and forests in developing regions. Therefore, it is worth considering briefly how agriculture and forestry in these regions has changed in recent years and the impact this may have, both now and in the future, on sustainable food production, and on forest provision for the needs of the human population. It is especially important to consider air pollution impacts in the context of other environmental constraints on agriculture and forest ecosystems, since the added stress of air pollution may well compound and exacerbate environmental problems that are perhaps currently more widely acknowledged.

Developing countries currently comprise about 52% of the world arable land and 75% of the world population. In the future, the area covered by arable land is expected to stay the same or decline, in contrast the population of developing countries is expected to increase to 90% of the world total by 2050. Furthermore, at least three billion (about 30% of the population) will live in arid and semi-arid regions with severe water shortage problems and desertification (Lal, 2000). Figure 4 clearly shows that the area of arable land available per head of population is decreasing in all regions (UNEP, 2000) and that the global availability of cropland has now fallen by 25% over the past two decades. This is in part due to the rapidly increasing global population but is also exacerbated by other factors that affect the availability and productivity of agricultural land. These include conversion of agricultural land to other uses (i.e. urbanisation and infrastructure development), human-induced degradation of soils and the shortage of renewable fresh water.

Soil degradation occurs for a number of reasons, some of which are briefly described here. The cultivation of marginal lands frequently results in nutrient depletion as a result of soil inputs being lower than the products harvested. Pollution and contamination of soils by disposal of urban and industrial wastes also results in soil degradation. Degradation of irrigated land by salinisation is a serious problem, with areas of land affected by soil salinity estimated at 14% of the total irrigated land area in India, 13.5% in China, 24.2% in Pakistan, 26.2% in Mexico, and 27.3% in Egypt (Lal, 2000). Farmers have traditionally satisfied increasing demand by ploughing new land (extensification) but opportunities for expansion are now limited primarily to marginal areas. Raising productivity (intensification) has therefore been central to increased grain production. Fertiliser use continues to rise in many

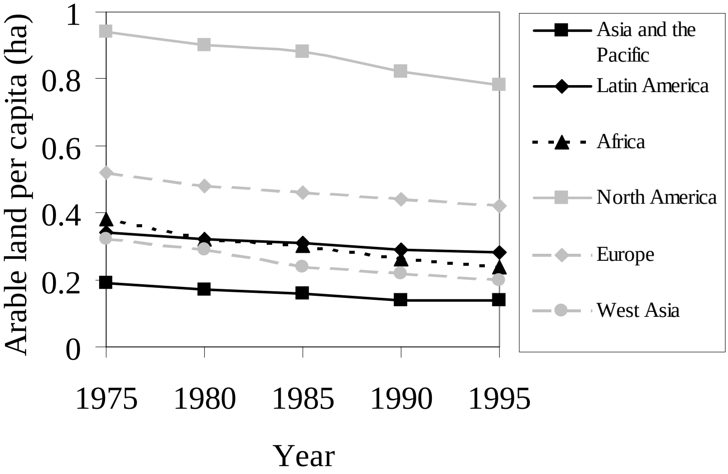

Fig. 4. Regional decrease in arable land per capita (UNEP, 2000).

developing countries, although there is concern about diminishing returns from increased applications and the threat of nitrate pollution of freshwater supplies and eutrophication. Irrigation has also been an important factor in providing increased grain yields with irrigated areas expanding at 2.3% yearly from 1950 to 1995 (FAO, 1997). However, such expansion is not sustainable over the long term and further increases in yield are likely to be limited by the availability of freshwater, with populous and arid areas most likely to be hardest hit in the future.

Breeders have significantly boosted the yield potential of cereals over recent decades, and the currently controversial use of genetically modified strains may do so further. However, crop-breeding programmes may also tend to select for higher values of stomatal conductance since this will increase rates of CO_2 assimilation. This may inadvertently be increasing the potential sensitivity of plants to air pollutants since the main pathway of pollutant uptake is through the stomata. This was suggested to be the reason for the greater sensitivity to O_3 of more recent wheat cultivars observed in Greece (Velissariou *et al.*, 1992).

In **Asia and the Pacific**, the extent of land conversion for agricultural activities varies within the region. For example, China now has

0.12 ha $capita^{-1}$ of arable land, which is less than half the world average. In addition, 60% of the Chinese arable land has some degree of quality constraints in terms of soil type, fertility, slope or climate. The most marked reduction in cultivated area is seen in the eastern coastal provinces where agricultural land has been lost due to the development of new industries, roads and housing, as a consequence of the high economic growth rates. This decline in total arable area has so far been negated with an increase in fertiliser use; for example, during the period 1980 to 1995 the total use of fertilisers increased by a factor of three (Aunan *et al.*, 2000). This increased use of fertiliser is likely to contribute significantly to increased emissions of NO_x, and it has been estimated that the N-fertiliser induced soil emission of NO_x may represent as much as 14% of present NO_x emissions in Eastern Asia (Chameides *et al.*, 1999).

In **Africa**, agriculture contributes about 40% of regional GDP and employs more than 60% of the labour force (World Bank, 1988). Land degradation caused by soil erosion, declining fertility, salinisation, soil compaction, agrochemical pollution and desertification poses serious problems throughout Africa. One estimate suggests that African crop yields could be halved within 40 years if the degradation of cultivated lands were to continue at present rates (UNEP, 2000). As a result of declining food security, the number of undernourished people in Africa nearly doubled from 100 million in the late 1960s to nearly 200 million in 1995 (UNEP, 2000). However, the agricultural potential of the country has not yet been fully realised; of an estimated 632 million hectares of arable land in Africa, only 179 million hectares are currently cultivated (FAO, 1997). Unfortunately, much of the land not currently utilised is often far from centres of population where infrastructure is poor. In addition, nearly 40% of this land is found in only three countries (the Democratic Republic of the Congo, Nigeria and the Sudan) so the potential for agricultural extensification and associated benefits are likely to be unevenly distributed across the region.

Latin America has the world's largest reserves of cultivatable land with the agricultural potential of the region estimated at 576 million hectares. However, almost 250 million hectares of land are affected by land degradation with soil erosion constituting the major threat (UNEP, 2000). In addition, the environmental costs of improved farm technologies have been high. For example, during the 1980s Central America increased production by 32% and its cultivated area by 13%, but doubled its consumption of pesticides (FAO, 1997). The depletion and destruction of forest resources to clear land for agricultural activities, especially in the Amazon region, is also of regional and global concern.

In terms of forestry, much of the remaining intact natural forested areas are to be found in the Amazon basin, Canada, central Africa, southeast Asia and the Russian Federation. These areas are of particular value since they contribute to local and national economic growth, provide recreational areas and are rich in biodiversity. For example, throughout Africa there has been an increasing demand for wood products, with consumption almost doubling during 1970 to 1994. At least 90% of Africans depend on firewood and other biomass for energy needs (FAO, 1997). Domestic wood shortage is occurring in some areas of Asia and the Pacific, such as the Philippines, Thailand and in South Asia. In many developing countries, forested areas are cleared as populations expand and pressures to exploit natural resources increase, with the cheapest means of clearing forested areas being by fire.

5. Issues and Lack of Current Knowledge

Most scientific investigations into the impacts of air pollution on vegetation have been conducted during the last 40 years in North America and western Europe. These studies have resulted in the definition of dose-response relationships or threshold concentrations for adverse effects for a number of different air pollutants and for a number of different species and cultivars. These dose-response relationships have been used in a variety of ways (discussed in detail in Chaps. 2 to 5 and 14) to assess the risk to vegetation of ambient pollution levels, with the overall aim of informing appropriate emission abatement policy. The information presented in Chaps. 6 to 13 clearly shows that current ambient levels of pollution in several developing countries are causing visible injury and losses in productivity of many species of agricultural crops and forest trees. However, it is very difficult to assess the full magnitude of damage and productivity loss due to air pollution in developing regions.

This introduction has described the recent increases in pollutant emissions in certain developing regions and shown that such trends are likely to continue into the future. In addition, evidence of both environmental and socio-economic constraints on the expansion of agriculture, and statistics describing decreases in arable land unit per capita, give serious cause for concern as to the ability of agriculture to satisfy future human needs. Chameides *et al.* (1994) emphasise the proximity of agriculture to fossil-fuel burning centres by identifying continental scale metro-agro complexes (CSMAPs) namely in North America, Europe, Eastern China and Japan. The proximity of agriculture to urban-industrial emission sources also occurs on a smaller scale in other developing country regions as described, for example, around the Cairo region in Egypt (Abdel-Latif, this volume) the Punjab region of Pakistan (Wahid, this volume) and peri-urban areas in India (Agrawal, this volume). These examples emphasise the potential threat to agricultural production caused by both present and future air pollution concentrations.

In addition, the clearance of forested areas has increased the importance of the remaining intact forest areas for wood products, economic growth, recreation and biodiversity. Carbon sequestration in forests is also a major component of the global carbon cycle. Any additional stresses caused by air pollution impacts could have serious implications for a wide range of forest-related socio-economic factors, especially in those forested areas located close to pollution sources. From the information collated in Chaps. 6 to 13, it is clear that most air pollution studies have focussed on investigating effects on agricultural crops rather than forest trees, even though severe local impacts have been identified for forests in some areas.

It is therefore crucial that stakeholders (e.g. in agriculture, forestry, industry and government) are made aware of the potential impacts of air pollution in different regions. This can only be achieved by identification of the magnitude and spatial extent of impacts resulting from current ambient air pollution levels, and assessment of how such impacts are likely to change in the future. This requires a number of different steps. Firstly, the impacts of air pollutants on different species and cultivars need to be clearly understood and reliable dose-response relationships defined for local varieties of important species. Secondly, monitoring networks must be established to record pollutant concentrations in rural agricultural/forested areas as well as urban/industrial locations. Thirdly, reliable air pollution transport models need to be developed to estimate current and future regional pollution levels. Finally, suitable methodologies must be developed to relate pollution to impacts, for use in risk assessment by policy-makers. For these policy assessments, it is of course important to consider impacts on crops and forests alongside those on human health and on the built environment.

A number of studies have already attempted to apply European and North American dose-response relationships to estimate crop yield reductions in developing countries (e.g. Chameides *et al.*, 1999; Chameides *et al.*, 1994; Aunan *et al.*, 2000). The fundamental uncertainty associated with these assessments lies in the use of dose-response relationships established for North American or European species and cultivars, and the assumption that local species or cultivars will respond in a similar way to pollutant doses. However, there may be significant differences in the responses of local varieties from developing country regions. Further research to establish local species and cultivar responses to air pollution should be a high priority for the future. Additional uncertainties that may alter plant response to air pollution have been identified as those associated with climate, agricultural management practices (e.g. the use of fertilisers, pesticides, herbicides and irrigation); crop phenology; and pollutant exposure patterns (Massman *et al.*, 2000). These and other complicating factors related to the potential transferability of dose-response relationships and impact assessment methodologies are discussed in detail in Chap. 14.

6. Aims and Objectives

The objective of this book is to assess existing evidence describing the impacts of air pollutants on vegetation in developing countries and regions. However, in order to put this evidence into context, Chaps. 2 to 5 first provides a summary of the effects of air pollution on vegetation in industrialised countries/regions (i.e. North America, Europe, Australia and Japan), where information is more extensive. This summary involves, for each region, a description of emission trends, vegetation composition and key observational and experimental evidence of air pollutant impacts on vegetation. Current dose-response and risk assessment methods are also discussed in relation to the scale of the air pollution problem. Chapters 6 to 13 is the central section of this book, describing evidence from developing regions of air pollutant impacts on vegetation, using country-specific case studies. Regionally selected experts (from China, Taiwan, India, Pakistan, Egypt, South Africa, Brazil and Mexico) collected evidence describing regional emissions, vegetation distributions and local pollutant concentrations. This information was related to observations and experimental evidence of injury to crops and forests in the field, in an attempt to define levels of ambient pollutant concentrations that cause vegetation damage. Key observations of damage, including instances of visible injury in the field, transect studies along pollution gradients and controlled experimental investigations of impacts on selected crop and forest species, were described for five pollutants. These pollutants, chosen for their prevalence and known phytotoxicity, were SO_2, O_3, NO_x, SPM and F.

The potential of using this information to define dose-response relationships is considered in Chap. 14. Information collected for SO_2 and O_3 has been collated and is compared with North American, European, Australian and Japanese exposure-response relationships in order to investigate the variability in response of different vegetation types to pollutants by region. Regional and global models describing pollutant concentrations have been used to give some indication of the spatial extent of air pollution problems. Results from a global O_3 and regional SO_2 model are presented to compare predicted air pollutant concentrations with the location of field observations of damage. This information is used to indicate the probable extent of vegetation damage both for the present day and in the future. Finally, Chap. 15 discusses how assessments of air pollution damage to crops and forests have been used to guide pollution abatement policies in industrialised countries, and considers how applicable these techniques are to the developing world. Chapter 15 also includes a case study describing research in peri-urban areas of India in which an innovative interdisciplinary approach has been used to assess the social and economic policy implications of air pollution damage.

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