Air pollution and food production in developing countries

A feasibility study

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- the development of agricultural systems within the framework of multifunctional land use.

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The research is divided among three themes:
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Summary

Anthropogenic air pollution can adversely affect crop productivity. Many reports on crop losses due to ambient air pollution are available. They mostly describe situations in developed countries. Relatively little information is available on the impact of air pollution on crop yields in developing countries. The aim of this study is to assess the impact of air pollution on crop yields in the developing world (Asia apart from Japan, Africa, South America and Central America).

Pollutants that disperse through the atmosphere to crop production areas, and that may cause damage (yield or quality loss) to crops, are investigated. Ozone, sulphur dioxide, and the nitrogen oxide complex (NO_x) are considered to be the most important gaseous air pollutants, heavy metals the most important particulates in the air. Ozone, probably the most important in terms of crop loss, is a secondary pollutant that is produced by photochemical reactions in which NO_x and volatile organic compounds are involved. Sulphur dioxide, NO_x and heavy metals are primary pollutants. These are emitted by several industrialisation and urbanisation processes like combustion of fossil fuels for energy production and traffic, and combustion of waste. In megacities in developing countries, industrialisation and urbanisation processes are taking place at a high speed, and consequently, noxious gas and particle concentrations in and around megacities are increasing.

Critical levels for effects of air pollutants on crop productivity are available for situations of developed countries, but not for developing countries. Measurements reveal that the critical levels are exceeded in several crop production areas of the developing world. Such events are reported for sites near Lahore, Pakistan (wheat yield reductions of 40% and rice yield reductions of 44%, attributed to ozone and NO_x), several sites in China (yield reductions between 5 and 25% for *e.g.* wheat, rice, maize and potato attributed to sulphur dioxide), Mexico City (*Phaseolus* bean yield reductions of 5 and 41% due to ozone), and Cairo, Egypt (radish and turnip yield reductions of 23 and 8%, respectively, due to ozone). Contamination with heavy metals affects the quality of crops, sometimes in conflict with the WHO standard (*e.g.* high levels of lead and cadmium were observed in crops grown in suburban areas in Cairo). In the long run sulphur dioxide deposition on soils leads to deplenishment of essential elements due to acidification.

The data presented suggest that air pollution may cause a substantial loss of crop productivity in the developing world. Reported yield losses (up to 40%) were higher than expected on the basis of current knowledge from developed countries. This might be due to factors that modify plant responses to pollution. Environmental conditions often differ between developed and developing countries. High temperature, high light intensity and high relative humidity generally increase plant sensitivity to air pollution. Such conditions prevail in developing countries. Contamination with heavy metals further exacerbates the situation. We speculate that in a radius of 200 km around megacities in developing countries crop production is adversely affected by air pollution. Major crop production areas in developing countries are often found within this sphere of influence.

1. General introduction

Must air pollution be an issue in sustainable food production in the developing world? More specifically, does air pollution adversely affect crop productivity in developing countries, both in terms of quantity and quality? And if so, how large is the impact? These questions will be addressed in this report in the context of DLO programme 306 (Sustainable food production systems and food supply in developing countries).

Air pollution effects on crops around point sources have long been recognised (*e.g.* Heck, 1989). Interest in this topic arose in industrialising Europe in the mid-nineteenth century, when it was noticed that sulphur dioxide and (hydrogen) fluoride gases caused injuries to vegetations. Historically, vegetation injury has been one of the first recognised manifestations of an air pollution problem. In the mid-twentieth century adverse effects of photochemical air pollution on vegetations were demonstrated in Southern California. It is now recognised that photochemical oxidants (primarily ozone) damage crops, both in rural and urban areas. Anthropogenic emissions of trace elements (heavy metals) have also become a point of concern. In Europe, *e.g.*, lead, tin and cadmium aerial concentrations may locally be increased three orders of magnitude compared to mean values, resulting in effects on most-sensitive crops.

Most of the present knowledge on effects of air pollution on crop productivity originated in the United States and Europe. In this report the focus is on pollution in the developing world and on its associated impact on crops. At the regional level, megacities are considered to be the most important sources of air pollution. At the local level, open mining activities may contribute significantly to an air pollution problem. We will report on the air pollution situation in megacities in some developing countries, on emission from the megacities to crop production areas, and on effects of air pollution on crops in those areas. Critical levels and damage models, based on research in developed countries, are used to put our conclusions for the developing world in a broader perspective. Finally, some recommendations are made on how to improve our understanding of the impact of air pollution on crops in developing countries.

2. Frame, definitions and methods

The study presented here can be characterised as a feasibility study. By means of putting together information from literature and from experts in a few weeks time, the potential impact of air pollution on food production in the developing world has been described.
A literature search was done in various abstract journals. Air and soil pollution scientists from AB-DLO provided the expert knowledge. The developing world is considered to include the countries of Asia, apart from Japan, Africa, South America and Central America. Information will be presented on situations in and around megacities in developing countries. Crop production areas in developing countries are often located in the vicinity of megacities.
The information will be presented in a rather general way, with rather generalising conclusions. However, one should keep in mind that there are large differences between countries of the developing world, in terms of their stage of industrial development and air pollution situation. Crops under investigation are crops that are produced for human consumption. Animal-feed and non-food crops are not considered.

An air pollutant is defined as a component of the atmosphere that can have an adverse effect on a plant. Air pollutants can act on plants directly from the atmosphere or indirectly after deposition on soil and water. Megacities are considered to be the most important pollution sources in the developing world. The focus will mainly be on pollutants that are emitted from megacities, and that are deposited both in suburban surroundings as well as in rural crop production areas. Some attention will be paid to point sources in rural areas. Soil pollution will be dealt with as far as it relates to heavy metals. Effects of water pollution are not considered in this study.

The reaction of a plant to air pollution depends on the nature of the component(s), exposure characteristics, the amount of pollutant that is absorbed, plant properties, and external growth factors (Guderian *et al.*, 1985). Heck & Heagle (1985) presented a system (Figure 1) with elements that should be addressed in an assessment of the impact of air pollution on crop productivity. In this study the elements as presented in Figure 1 are addressed as much as possible.

SOURCES

↓

EMISSIONS

↓

DISPERSION AND TRANSFORMATION

↓

AIR QUALITY (Monitoring)

↓

DEPOSITION (Effective Dose)

↓

ASSESSMENT

Figure 1. The air pollution system from source through effect assessment (adapted from Heck & Heagle, 1985)

2.1 Air pollution components

Heck (1989) presented a list of air pollutants and ranked them in order of importance of effects on crop productivity on a global scale. This ranking is, more or less, widely accepted by experts around the world, and probably applies also to the third world situation. For this study we use Table 1 as a starting point. Heck (1989) indicated that several pollutants low on the list have been studied poorly, and may be more important than thought at that time. Almost ten years after its publication the list is still rather up to date. However, one might add polycyclic aromatic hydrocarbons and other volatile organic compounds because there is evidence that these pollutants can adversely affect plants (Tonneijck & Van Dijk, 1993).

In this study most attention will be given to the three highest ranked pollutants of Table 1 and to the group of heavy metals. Ozone, sulphur dioxide and nitrogen oxides (NO_2 and NO) are expected to have the largest impact on crop yields, heavy metals are expected to have the largest impact on crop quality.

Table 1. Phytotoxic air pollutants in order of decreasing importance to cropping systems (adapted from Heck, 1989)

Pollutant	Common name	Form	Primary or Secondary
O_3	Ozone	Gas	Secondary
SO_2	Sulphur dioxide	Gas	Primary
NO_2	Nitrogen dioxide	Gas	Primary/Secondary
HF	Hydrogen fluoride	Gas/Particulate	Primary
$H_2C{=}CH_2$	Ethylene	Gas	Primary
PAN	Peroxyacetyl nitrate	Gas	Secondary
NO	Nitrous oxide	Gas	Primary
Cl_2	Chlorine	Gas	Primary
HCl	Hydrogen chloride	Gas	Primary
Pb, Sn, Cd, Zn, Cu, Hg, As, ...	Heavy metals (treated as one group)	Particulate/Vapour	Primary
NH_3	Ammonia	Gas	Primary
H_2SO_4	Sulphate	Aerosol, rain	Secondary
HNO_3	Nitrate	Aerosol, rain	Secondary
H_2S	Hydrogen sulphide	Gas	Primary
UV-β	Ultra-violet radiation	Radiation	Primary

Note: This list is not meant to be complete but represents the most important air pollutants with respect to terrestrial plant systems. CO_2 is omitted from the original list.

2.2 Air pollution effects on plants

To assess the impact of air pollution on vegetation, it has been generally accepted that effect criteria must be chosen that are related to the 'usefulness' of the plant species (Guderian, 1977). So, a distinction has been made between 'injury' and 'damage'. The term 'injury' includes all plant responses as a result of ambient pollution; for example foliar necrosis, physiological alterations and growth reduction. The term 'damage' refers to those effects that reduce the intended use of the plant as determined by economical, aesthetical or ecological values. For crops it is evident that these air pollution-induced effects include reductions in yield and quality. Short-term exposures to high concentrations generally result in acute injury that is visible as necrosis. Chronic exposures to low concentrations can cause physiological alterations that ultimately result in growth and yield reductions. These physiological alterations can occur without visible symptoms.

The two exposure variables, concentration and exposure duration, are basic to an understanding of pollutant effects on vegetation (Larsen & Heck, 1976). The relationships between exposure and effect can be generally characterised by sigmoid curves (Guderian *et al.*, 1985). Below a specific exposure the reactions of exposed plants do not deviate significantly from unexposed controls. This exposure level can be regarded as a threshold value or critical level. When exposures exceed this value, the response of plants increases with increasing exposure and will asymptomatically approach the maximum response level. Depending on plant species or variety, effect criterion and environmental conditions, different response curves for a given pollutant can be found resulting in different threshold values.

Atmospheric deposition of heavy metals contributes to contamination of soils and vegetation. Mosses and lichens are the most sensitive organisms to air pollution by heavy metals. In addition, the quality of agricultural crops may be affected.

In this study most attention will be given to the effect of air pollution on crop yields. Crop quality, which applies to composition or appearance of the crop, will also be addressed, but to a much lesser extent because of less data. Also, some remarks on secondary effects, like predisposition of the crop by exposure to air pollution will be made.

3. Air pollution trends in developing countries

3.1 Human population statistics

During the past 10 years the human population on earth increased annually by 1.6%, to a total of 5.72 billion people in 1995 (FAO, 1996).

The distribution and the increase of the human population over the earth are by far not evenly spread. Approximately 80% of the population lives on the continents of the developing world (Asia, South America, Central America and Africa), 60% on one continent (Asia), and 20% in one country (China). The rate of increase of the population is generally higher in the developing world than in the developed world. For Asia, South America, Central America and Africa the annual increase during the period 1990-1995 was 1.7%, 1.8%, 2.1% and 3.0%, respectively. China was one of the few developing countries that had a smaller-than-average population increase rate (1.1% per year).

Within countries distinct agglomerations of people can be distinguished. Megacities can be defined as agglomerates of more than 5 million people. The number of cities with more than 7 million inhabitants grew from 13 to 35 in the period 1950-1985 (UN, 1989). It is projected that by the year 2000, the population in more than 60 cities will be above 10 million.
A majority of these megacities will be in the developing world (Figure 2). Mexico City, Sao Paolo and Tokyo are projected to be the three biggest cities by 2000, with each over 50 million inhabitants. The human population increase rate in a megacity is generally larger than the national or continental average. People tend to move to cities, especially when the economic perspective in the city looks better. The annual increase of the human population in megacities was between 5 and 10% in the period 1970-1990 (UN, 1989).

Statistics on malnutrition show that in several countries in the developing world, a significant part of the human population does not get enough food according to the WHO-standard (ITM, 1992). Malnutrition is often more severe in rural areas than in urban areas. Trade statistics show that the developing world is becoming more and more an importer of food and cereals, with large differences at the regional and national levels (ITM, 1992). The world food production index of the FAO increased in the period 1988-1995 by 1.6% per year. For Asia, South America, Mexico, and Africa the annual increase was 3.6%, 2.0%, 2.9% and 2.5%, respectively.

3.2 Trends in air pollution in megacities

Air pollution is exacerbated by four specific phenomena that typically occur when countries industrialise: expansion of cities, increase in traffic, rapid economic growth, and higher levels of energy consumption (Yunus *et al.*, 1996). Megacities are often located in river deltas along the coast and surrounded by hills or mountains, which limits the dispersion of pollutants

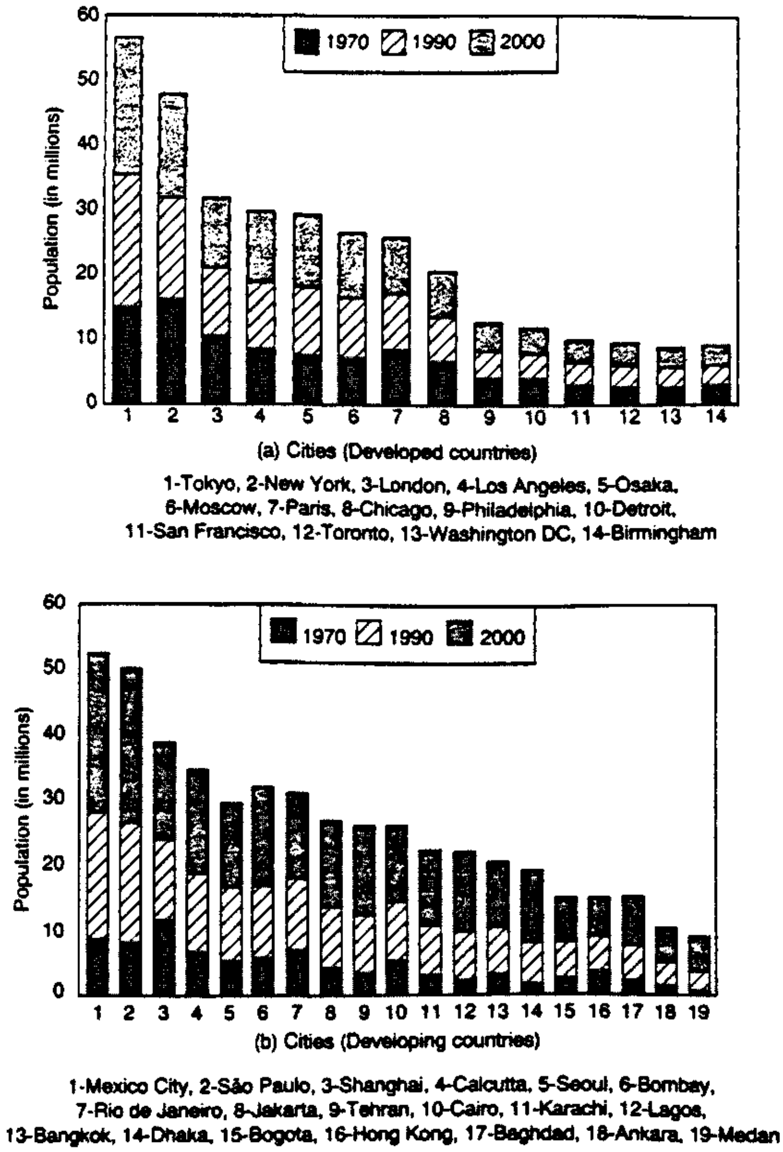

Figure 2. Human population in some cities in the developed (a) and the developing (b) countries (UN, 1989; Yunus et al., 1996)

emitted by the city. In many countries in the developing world industrialisation started in the second half of the twentieth century, and often occurs in the megacities. The fast growth of both industrial and residential areas in megacities in developing countries is often unplanned, unstructured and unzoned. In urban areas the main sources of pollution are power plants, industries, motor vehicles, and domestic sources. Combustion of fossil fuel in stationary and mobile installations, and combustion of waste lead to the production of sulphur dioxide and nitrogen oxides and particulates in the form of fly ash and soot, and several secondary products like ozone, and sulphate and nitrate aerosols. Specific industries such as brick works, chemical factories, metal smelters and mines, and refineries, may contribute additionally by emitting specific components.

Ozone: Troposheric ozone is a secondary pollutant originating from nitrogen oxides and volatile organic compounds. It is quantitatively the most important component of photochemical air pollution. Ozone concentrations vary with season, time of day, and other meteorological conditions. The developing world may be a minor emitter of ozone precursors, but the climate is favourable for its production (Figure 3). Ozone concentrations are higher in periods with high insolation, high temperatures, and air stagnation. In Mexico City, having an exceptionally high level of ozone pollution, the annual mean ozone concentration is around 100 ppbv (*e.g.* De Bauer & Krupa, 1990). During the summer period the ozone concentration in and around Mexico City is higher than in the winter period because of the factors mentioned. The increase in fossil fuel use in industries and automobiles will definitely result in higher levels of ozone. More details on trends and concentrations in megacities can be found in *e.g.* Yunus *et al.* (1996) and WHO/UNEP (1992).

Sulphur dioxide: The annual global emissions of sulphur dioxide currently stand at 294 million tonnes, of which a little more than 160 million tonnes are anthropogenic (UNEP/GEMS, 1991). Man-made emissions are rising by about 4% annually; a rate equivalent to the rise in global energy consumption. Most of the man-made emissions occur in the developed countries in coal-fired power plants (90% of total), but the developing countries will contribute more and more as they develop their industrial base. Sulphur dioxide pollution is becoming particularly evident in countries such as China, Mexico and India (Figure 3). In Beijing the annual mean is quite stable around 40 ppbv; in Mexico City the daily mean is between 30 and 80 ppbv. For comparison, countries in the developed world have annual means of less than 10 ppbv. More details on trends, emissions and concentrations in megacities can be found in *e.g.* Yunus *et al.* (1996) and WHO/UNEP (1992).

Nitrogen oxides: The global emission of nitrogen oxides in 1980 was estimated to be 300 million tonnes per year, of which 150 million tonnes were anthropogenic (UNEP/GEMS, 1991). In the industrial regions of Europe and America, man-made emissions of nitrogen oxides are 5-10 times higher than natural emissions. Here, the main sources are motor vehicles and coal-fired power plants. For the developing countries data are relatively scarce. However, it is becoming evident that problems with nitrogen oxides are occurring in countries like Brazil, Chile, Hong Kong and India (Yunus *et al.*, 1996) (Figure 3). More details on trends and emissions in megacities can be found in *e.g.* Yunus *et al.* (1996) and WHO/UNEP (1992).

Heavy metals: Most air pollution with heavy metals originates from combustion of fossil fuels and waste, and from smelters (iron and non-ferrous). Airborne concentrations may vary considerably. For instance, concentrations of cadmium in Germany may vary between 0.5- 620 ng m^{-3}, and in Japan between 0.5-41 ng m^{-3}. Concentrations of copper may vary in South-America between 30-180, in Central-America between 70-100, and in Japan between 11-200 ng m^{-3}.

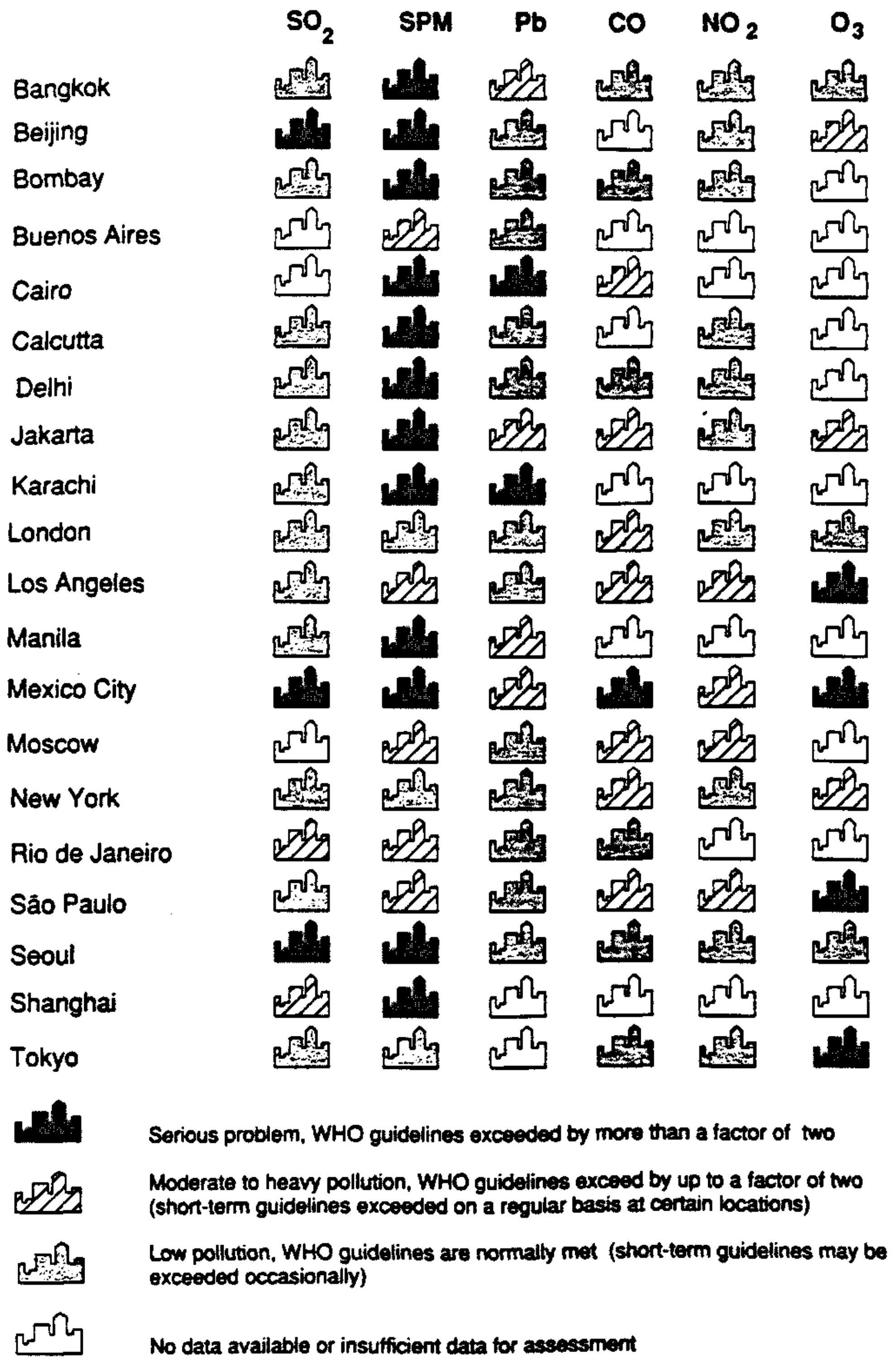

Figure 3. Overview of air quality in 20 megacities based on a subjective assessment of monitoring data and emissions inventory (WHO/UNEP, 1992). SPM means Suspended Particulate Matter.

Concentrations of lead may vary in South-America between 11-334, in Central-America between 0.2-317, and in Japan between 19-1810 ng m^{-3}. The regional contamination of crops occurs mainly in industrialised areas and within or around large cities. Here factories, cars, municipal wastes are among the most common sources of heavy metals. Elements like As, Se, Sb, and Hg may form volatile compounds, and thus may lead to a long aerial transport. Several monitoring programmes in megacities (*e.g.* Buenos Aires (Llosa *et al.*, 1990) and Beijing (Zhou *et al.*, 1989)) revealed that levels of lead, cadmium, zinc, and copper in atmospheres and soils were increased significantly. Regularly, atmospheric concentrations are locally above the WHO guidelines, such as for lead near roadsides (Yunus *et al.*, 1996).

A specific position is taken up by the element mercury, which vaporises quickly when exposed to air. In gold mining, mercury is used to separate the gold from the ore. Large amounts of mercury can evaporate during this process. The estimated emission factor is 0.9 to 1.32 kg mercury per kg gold (Lacerda *et al.*, 1995). Gold mining with large emissions of mercury are carried out in the Amazon region, Phillippines, Thailand, and Tanzania.

3.3 Trends in air pollution in crop production areas

Urban and industrial areas of (mega)cities are likely to be the main sources of air pollution in rural crop production areas in developing countries. Local industries such as brick works, chemical plants, metal smelters and mines, refineries, and biomass burnings may also contribute significantly to an air pollution problem, but probably more at a local scale.

Concentrations of air pollutants in crop production areas depend on many factors such as air pollutant component, source, distance, climatic conditions, elevation and geology. The complex nature of the emission of air pollutants to crop production areas makes that general statements on this subject may differ considerably from an specific local situation. Based on expert judgement, we make the following general statements on immission of air pollutants to crop production areas: Ozone levels in rural area will be affected by a megacity within a radius of approximately 200 km. For sulphur dioxide and nitrogen oxides a diameter of 50 km is estimated; for trace elements/heavy metals from local point sources 10 km.

Dispersion models are available for distances up to 50 km from the source which estimate immission concentrations with reasonable accuracy in both flat and mountainous areas (10x10 km grids) if regional climate and topography are well described. Other models have been available for larger scale distribution: a global tropospheric ozone model is available with the Institute of Meteorology and Oceanography in Utrecht, The Netherlands (Van Hove, personal communication). A regional sulphur dioxide model for South East Asia has been developed (*e.g.* Foell *et al.*, 1995).

To obtain accurate information on air pollution concentrations in rural areas on-site monitoring systems are essential. In Europe and the United States extensive systems have been developed to monitor (air) pollution in rural areas. In the developing world, data on air pollution in rural areas is scattered. Some very general data can be found: *e.g.*, a concentration of 50 ppbv ozone above a savanna-type ecosystem in Brazil was reported by Delany *et al.* (1985), and a range of 50-90 ppbv ozone in Northern tropical Africa during the dry seasons was reported by Marenco *et al.* (1990). Site-specific information can be found in field experiments on air pollution effects on crops (see sections 4.2 and 4.3). It is obvious from these reports that air pollution concentrations in rural areas of the developing world can exceed the critical levels for adverse effects on crops, and often are higher than the natural background level.

Gaseous pollutants like sulphur dioxide and nitrogen oxides partly deposit as a gas and partly dissolve in mist or cloud water. In the later case dispersion distances can go up to more than 1000 km before these compounds precipitate in rain. The resulting drop in pH of rain can be a cause of damage, both to plants and building material, but this has not been quantified. For crops, acidification is considered to be of less importance than the impact of gaseous pollutants.

4. Air pollution effects on crops

4.1 Plant injury by air pollution and relative sensitivity

A first, relatively simple step in assessing an air pollution problem in a specific area is looking for reports on visible plant injury. The first report on an ozone injury to a crop in a developing country related to potatoes at Jalandhar, India, in 1982 (Bambawale, 1986). Although initially thought to be due to a fungal or bacterial infection, the occurrence of leaf spot on potato was attributed to ozone after demonstrating that protective chemicals (ethylenediurea (EDU) and activated charcoal dust) prevented ozone injury. The report did not relate injury to yield loss, but visible injury is the first sign of a problem in the region. There are a few more solid reports on crop injuries due to air pollution in developing countries, such as an overview paper on crop injuries attributed to sulphur dioxide and fluoride in China (Hongfa, 1989).

The term 'relative sensitivity' in air pollution research is used to rank plants on the basis of their sensitivity in terms of visible injury. The relative sensitivity of more than 20 major agricultural crops is presented in Table I.1 of appendix I. The results originated from laboratory experiments in which plants were exposed to a specific pollutant. It can be concluded that most attention has been given to ozone, sulphur dioxide, nitrogen oxides, and fluoride. Table I.1 can be used to make a quick, but limited assessment of where problems may be expected. Cereals and legumes are considered to be sensitive to all main pollutants. Data for rice is mostly lacking, and if available, it originated from a dry land rice production situation. In general, one can conclude that little attention has been given to the response of tropical crops, *e.g.* no information on millet was found. In Table I.1 crops are sometimes ranked both as sensitive and as intermediate. This differential response is mainly due to the testing of different varieties, and shows that varieties can differ in sensitivity.

4.2 Direct effects of air pollution on crop yields and quality

A next step in assessing an air pollution problem is looking for yield loss reports. Such reports are likely to be published after injury reports are published. A few relevant reports on yield losses due to air pollution in developing countries were found. Three of them are detailed research reports from developing countries and one of them is an overview report from China. Additionally, some information from subtropical developed countries is presented.

Rice and wheat/Pakistan: Ten km South of Lahore in the Punjab, Open Top Chamber (OTC) experiments were carried out that show potential yield losses in the area due to air pollution (Wahid *et al.*, 1995). The experimentalists grew local varieties of wheat and rice on potting compost in pots in the OTCs. Wheat was grown in the dry seasons of 1991-1992 and 1992-1993, rice in the wet seasons of 1992 and 1993. The plants were exposed to ambient air or to charcoal-filtered air. Seasonal 6h mean ozone concentrations were 35 and 52 ppbv for wheat, and 40 and 60 ppbv for rice, respectively. The overall ozone filtration efficiency was 86%. Nitrogen dioxide concentrations were rather constant during the experimental period at a level of about 20 ppbv; the overall filtration efficiency was 59%. Large, statistically significant yield reductions were observed in the ambient air treatments compared to the filtered treatments. On average, grain yields were reduced by 40% and 42% for wheat and rice, respectively. It was suggested that the observed yield losses were mainly caused by ozone.

Radish and turnip/Egypt: In the Nile delta near Alexandria and Abbis OTC experiments were carried out in the spring of 1993 (Hassan *et al.*, 1995). The experimentalists grew radish and turnip on field soils. The crops were regularly sprayed with an ozone protectant (EDU) or with water. The seasonal 6h mean ozone concentrations were 67 and 55 ppbv for the Alexandria and Abbis site, respectively. On average, yields (root dry weight for radish, shoot dry weight for turnip) were reduced by 26% and 8% in non EDU-treated radish and turnip, respectively, compared to EDU-treated plants.

Bean/Mexico: In the Valley of Mexico near Mexico City *Phaseolus* beans were grown on an arable field in 1984 (Laguette-Rey *et al.*, 1986). An ozone tolerant and an ozone sensitive variety were planted. The plants were regularly sprayed with EDU or with water. Ambient ozone concentrations were not presented, but are expected to be high (the annual mean concentration of ozone in the Valley of Mexico is around 100 ppbv). The grain yield was reduced by 5 and 41% for the tolerant and sensitive variety, respectively, in non EDU-treated plants compared to EDU treated plants.

Several crops/China: Air pollution in China is characterised as a typical coal-smoke smog (Hongfa, 1989). A monitoring network around 64 cities in China revealed annual mean concentrations of 40 ppb SO_2 and 25 ppbv NO_x. Yield reductions in the range of 5 to 25% were reported for wheat, barley, cotton, *Phaseolus* bean, soybean, potato, cabbage, rice, and maize. Yield reductions were attributed to sulphur dioxide and, to a lesser extent, fluoride. Ozone has been given very little attention in China, but certainly has an additional impact.

Several crops/California, Italy, Japan: Because of the limited number of solid reports on air pollution damage to crops from developing countries, some additional information is presented from developed countries with a subtropical climate. In California, an extensive research programme on effects of ozone on crop yields was carried out (Olszyk *et al.*, 1988). OTC experiments with ambient and charcoal-filtered air are the basis of the data presented. Yield reductions in the range of 0 to 24% were reported for wheat, barley, rice, maize, grape, lemon, lettuce, onions, sorghum, spinach, and tomato. Yield reductions in California were mainly attributed to ozone. A much smaller, but comparable programme was carried out in the Po plain in Italy (Schenone & Lorenzini, 1992). Here, yield reductions in the range of 6 to 23% were observed for wheat, barley, bean, radish, and melon. The reductions were attributed to ozone. In Japan, rice yield reductions of 7 to 8% due to ambient ozone were observed.

There is relatively little information on the effects of air pollution on the chemical quality of agricultural products, heavy metals excepted (see section 4.3). Reported evidence indicates that ozone has the potential to adversely affect both the quantity and the quality of potato tubers. According to Pell & Pearson (1984), ozone can reduce the percentage dry weight of tubers and can induce an increase in the contents of reducing sugars such as fructose and glucose. These authors also found an increase of the content of glycoalkaloids in tubers of ozonated potato plants. Glycoalkaloids are known to induce a bitter taste in tubers and can adversely affect human health. Exposures to sulphur dioxide resulted both in a stimulation and in a reduction of the dry matter percentage and sucrose content in potato tubers depending on exposure level (Pell *et al.*, 1988). De Temmerman *et al.* (1992) reported that the baking quality of grains was better for spring wheat crops grown in ambient air than for spring wheat crops grown in charcoal-filtered air.

Besides primary effects, air pollution components can also cause secondary effects by predisposing plants to drought, frost, and pathogens. Exposure to sulphur dioxide may increase frost sensitivity of plants (Taylor *et al.*, 1987). Biothrophic pathogens are in general adversely affected by air pollution while necrothrophic pathogens may be stimulated (*e.g.* Manning & Tiedeman, 1995).

4.3 Indirect effects of heavy metals on crops

Several reports are available that describe the accumulation of heavy metals in crops above levels that are toxic to humans and animals. In this section we report on accumulation of heavy metals in crops and associated effects. Fluoride, though not a metal, may cause similar problems. It was decided in this study not to investigate fluoride. We also decided not to address the subject of trace element deficiencies and crop quality. The subject of trace element deficiencies relates to heavy metals and crop quality, and can be quite important in developing countries, but is in essence not an air pollution problem.

Egypt: Soil, weed, vegetation, and dust samples were collected from an agricultural area of Cairo that also has a number of industrial complexes. High levels of Pb, Cd, Ni, Cr, Mn, and Zn were found. The levels are potentially toxic if such products are consumed by animals or humans (Ali *et al.*, 1992). Concentrations of several metals (Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, and Pb) were determined at various depths in alluvial soil profiles from 6 rural areas South and Southwest of Cairo. Metal concentrations in the topsoil are affected by the metal content of airborne dust coming from industrial metal emissions from other areas of the city (Hindy, 1991). Nasralla & Ali (1985) showed that lead can accumulate in vegetables grown near traffic roads at levels that are toxic to humans.

China: Concentrations of seven metals (Cd, Pb, Cu, Zn, Ni, As, and Hg) were measured in rural, agricultural and urban areas impacted by industrialisation during a fifty-year period. A significant change in the surface soil contents of Zn, Pb, Cd, Cu, As, and Hg was demonstrated. An accumulation of metals in plants at levels toxic to humans is expected (Li & Wu, 1991).

Chile: The contents of As, Cd, Cu, Pb, and Zn in 1983 and in 1991 in surface soil samples of an area of Ventanas, Chile, subjected to atmospheric industrial emissions are tabulated. An accumulation of metals in plants at levels toxic to humans is expected. Between 1983 and 1991 the levels in soils increased, and this increase was attributed mainly to the presence of a copper smelter plant (Gonzalez & Ite, 1992).

4.4 Modifying factors

The reaction of a plant to air pollution depends on the nature of the component, exposure characteristics, the amount of pollutant that is absorbed, plant properties, and external growth conditions (Guderian et al., 1985). Differences in genetic constitution form the basis for differential sensitivities of plant species and varieties to a given pollutant. Developmental stage of the plant also influences the type and degree of reaction. External growth factors that include edaphic and climatic conditions, modify plant responses by influencing pollutant uptake and the plant's physiology. Since gaseous air pollutants enter the leaves primarily via the stomata, all factors that influence stomatal opening also exert their effect on pollutant uptake. The presence of other air pollutants than the pollutant in question may also be important. Many experiments have shown that plant responses to pollutant combinations are not simply additive but often more-than-additive (Lefohn & Ormrod, 1984). External and internal factors can interact, thereby modifying the responses of plants to air pollution. In the field, it may therefore be very difficult to relate the response of plants to a specific exposure.

A summary of abiotic and biotic factors that may modify sensitivity of plants to air pollutants is presented in Table II.2 of appendix II. In general one can conclude that factors that stimulate stomata to open will increase sensitivity to air pollution. High relative humidity, high temperatures, and high light intensities stimulate the opening of stomata and increase accumulation of air pollutants in plant tissue. Such conditions often prevail in developing countries. Irrigation also stimulates opening of stomata, and as a result will stimulate air pollution damage. For nutrients in general there is no single trend in how they modify sensitivity (*e.g.* Runeckles & Chevone, 1992); one has to look at a specific nutrient to make a statement (see Table II.2). The same holds for biotic factors such as crop variety, pests, and diseases.

4.5 Critical levels and damage models

Critical levels can be defined as concentrations of pollutants in the atmosphere above which direct adverse effects on receptors may occur according to present knowledge (Ashmore, 1992). Critical levels are defined for the main air pollutants. They are mainly derived from experiments in developed countries.

Ozone: Critical levels for ozone are expressed as cumulative exposures over the threshold concentration of 40 ppbv ozone during daylight hours and are referred to as AOT40. Short-term and long-term critical levels to protect crops against significant effects by ambient ozone have been proposed recently (Kärenlampi & Skärby, 1996). Two short-term critical levels to protect crops against ozone-induced visible injury have been formulated:

- 500 ppb.h over five days when mean vapour deficit exceeds 1.5 kPa, and
- 200 ppb.h over five days when mean vapour deficit is below 1.5 kPa.

The proposed long-term critical level to protect crops against significant yield effects is 3000 ppb.h calculated for a three-month period during the period that the crops are grown. Available information shows that hourly values of ozone in developing countries exceed the threshold level of 40 ppb.

Sulphur dioxide: Fluctuations in the atmospheric concentrations of sulphur dioxide are generally much smaller than those of ozone, which makes defining a critical level easier. A critical level of 10 ppbv sulphur dioxide is presented for agricultural crops (Ashmore, 1992). Agricultural crops are considered to be less sensitive to sulphur dioxide than forests and natural vegetations.

Nitrogen dioxide: The WHO advises a critical level for NO_x (NO and NO_2, added in ppbv and expressed as NO_2 in $\mu g\ m^{-3}$) of 30 $\mu g\ m^{-3}$ (15 ppbv) as an annual mean, and of 75 $\mu g\ m^{-3}$ (22 ppbv) as a 24-hour mean. These critical levels are more protective against crop loss than against adverse effects on natural vegetation.

Heavy metals: Macnicol & Beckett (1985) made an extensive survey of literature to establish critical levels of 30 elements, of which Al, As, Cd, Cu, Li, Mn, Ni, Se and Zn are most predominant. The authors use the term 'upper critical level', which is the lowest concentration at which an element has toxic effects on plants. For 10% yield loss in various crops, presented critical concentrations ranged from 1-20 ppm (on plant dry weight basis) for As, 10-20 ppm for Cd, 20-40 ppm for Co, 1-10 ppm for Cr, 10-30 ppm for Cu, 1-8 ppm for Hg, 10-30 ppm for Ni, and 100-500 ppm for Zn. Kloke *et al.* (1984) presented similar results. They stated that the critical levels for a given element are variable, which reflects the influence of modifying factors.

Although air pollution effects have been observed in the field (see section 4.1), these observations are not directly useful for quantification on a larger temporal and spatial scale. A network with indicator plants is more indicative. Such a system produces a 'warning signal' rather than results that can be translated into crop loss estimates. A model approach is a better option. Crop growth models which simulate biomass production can be used for this purpose.

Effects of ozone on wheat production are currently modelled by *e.g.* Van Oijen (personal communication). However, the physiological mechanisms of the impact of pollutants on crops is not completely clear. Generally, observed effects are higher than expected on the basis of reduction of photosynthesis and loss of leaf area. This is why currently crop loss estimates must be based on regression equations derived from experiments that are performed under semi-field experiments (generally Open Top Chamber experiments). Such equations have been developed to describe exposure effect relationships for air pollution components and crop yields in developed countries (e.g. Heck *et al.*, 1984; Olszyk & Thompson, 1985; Heck & Heagle, 1985; Olszyk *et al.*, 1988; Van der Eerden *et al.*, 1988; Kobayashi, 1992). These models are relatively simple regression equations that describe a linear or hyperbolic decrease of yield with increasing exposure concentrations. Relationships between ozone exposure and yield loss for some important crops are shown in Figure 4. The regression lines are Weibull crop loss functions (for explanation see Heck *et al.*, 1984). A relationship between exposure to sulphur dioxide and nitrogen dioxide and reduction in biomass of *Poa pratensis* is shown in Figure 5.

The use of regression equations from developed countries in assessing yield reductions in developing countries should be done with caution! The crop response to air pollution in developing countries may differ considerably from the response in developed countries because of the influence of modifying factors (see section 4.3). To illustrate this, the equations of Olszyk & Thompson (1985) would have estimated yield reductions of less than 10% for wheat and rice in Pakistan (see section 4.2) while the observed yield losses were in the order of 40%.

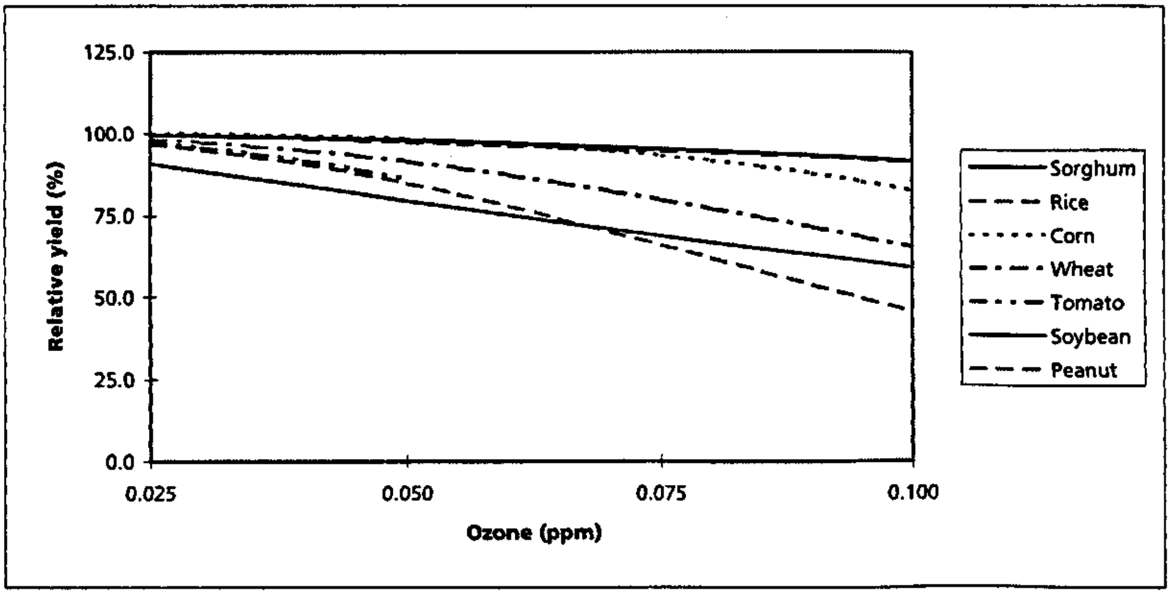

Figure 4. Yield response of major grain and legume crops exposed to ozone. A natural background concentration of 0.025 ppm ozone is applied, and the yield response is related to the response at 0.025 ppm. Seven-hour seasonal mean concentrations are applied apart from rice (5-hour seasonal mean) (adapted from Olszyk & Thompson, 1985).

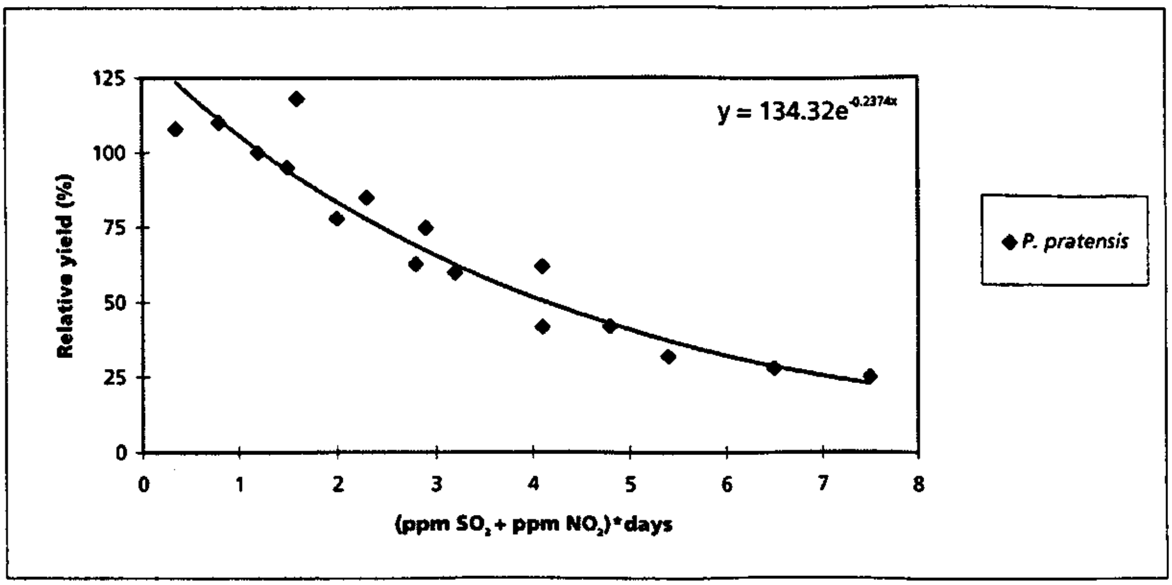

Figure 5. Effect of SO_2 +NO_2 on dry mass production of *Poa pratensis*, relative to control. Data are from several experiments in which the exposure periods and concentrations varied from 20-100 d and 40 to 100 ppb, respectively (Whitmore, 1985).

5. General discussion

Information on sources, emissions, dispersion and transformation, air quality monitoring, deposition and uptake, and exposure-effect relationships is needed to understand the air pollution system (*e.g.* Heck & Heagle, 1985). Unfortunately, this information is complete only in part for the developing world. Experts consider megacities to be the most important sources of air pollution in developing countries. Ozone, sulphur dioxide and nitrogen oxides are likely to be the most important gaseous air pollutants in terms of yield losses. Heavy metals are probably the most important particulate air pollutants in terms of loss of crop quality. Investigations show that emissions of air pollutants from megacities are increasing.

Information on dispersion and transformation, and on deposition and uptake are very limited. Information on air quality in crop production areas in developing countries is limited. Biomonitoring and air quality monitoring systems could improve this type of information. Reports on effects of air pollution on crops in developing countries show that there is a problem. Yield losses due to air pollution up to 40% are reported. Accumulation of heavy metals in crops at levels that are toxic to humans sometimes occurs. Exposure-effect relationships for important crops from developing countries are not available.

One of the biggest problems (in this study) is the lack of exact information on immissions of air pollution in crop production areas. This lack of information, combined with the absence of exposure-yield loss relationships for the respective countries, makes it very hard to make an accurate estimate of yield losses due to air pollution in the developing world.

Despite the fact that the information presented in this report is far from complete, there are definitely signs that air pollution can have a serious impact on crop production in developing countries. The yield reductions observed in developing countries that are presented are generally derived with a sound scientific approach. On the other hand, percentages of 25-40% yield reductions exceed expectations, and cannot be explained with the available information on exposure-effect relationships (which are based on experiments performed in Europe and the USA). Hence, the problem may be larger than we thought it would be.

Knowing the limitations of exposure-yield loss relationships, we are restrained to estimate the impact of air pollution on crop productivity in developing countries. A coarse estimate of the yield loss due to ambient air pollution may be in the order of 15-30%. We speculate that in the near future the situation will certainly not improve. Emissions from megacities will probably increase in the future. It is not expected that agricultural production areas will move away from megacities in the developing world in the near future.

6. Conclusions and recommendations

The following conclusions can be drawn from the present study:

- An increase in emissions of air pollution from megacities in the developing world is to be expected knowing present trends in these cities.
- Ozone, sulphur dioxide and nitrogen oxides are likely to be the most important air pollutants in terms of crop productivity in developing countries. Heavy metal accumulation may further decrease crop productivity.
- Serious crop yield reductions due to ambient air pollution in developing countries have been reported. Reductions are as high as 40%, i.e. higher than expected on the basis of existing exposure-effect relationships.
- Information on the air pollution system (sources, emissions, dispersion and transformation, air quality monitoring, deposition and uptake, and exposure-effect) in the developing world is scarce. A further assessment of the impact of air pollution on crop productivity in developing countries requires more information on the air pollution system.

To improve our knowledge on the impact of air pollution on crops in developing countries, we like to make the following recommendations:

- The use of biomonitoring and air quality monitoring systems should be stimulated in developing countries. Especially biomonitoring is recommended. This technique is a very useful tool in assessing air pollution effects on plants, it is relatively cheap, and it is rather convincing towards politicians. It makes people aware of a problem.
- Exposure-effect relationships should be determined for developing country situations. The focus should be on (tropical) crops grown in the vicinity of megacities. Such studies will reveal information on the importance of modifying factors.
- The relative importance of different air pollutants in the developing world should be assessed on the basis of information of the developing world.

7. References

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Appendix I
Relative sensitivity of crops to air pollution

Table I.1. Relative sensitivity of agricultural crops to specific air pollution components under controlled (greenhouse) conditions (sources: Taylor *et al.*, 1987; Jacobsen *et al.*, 1970; Krupa *et al.*, 1997).

Crop	Pollutant									
	O_3	SO_2	NO_x	HF	C=C	PAN	Cl_2	HCl	NH_3	H_2S
Wheat	++ / +	++ / +	+	+		+				
Rice	0									
Maize	++ / +	0	+	++		0	++			
Barley	++	++	++	++ / +		+				
Soybean	++	++ / +		+	+	+	0			++
Sorghum	+			+	0	0				
Millet										
Cotton	0	++ / +		0	++	0				
Bean (*Phaseolus*)	++	++	++	+	++	++	+			++
Oats	++	++ / +	++	+	0	++				
Potato	++	0	+	+						
Peanut	++ / +									
Sugarcane				0						
Rye	++ / +	++	+	+						
Sunflower			++	+			++		++	+ / 0
Rapeseed			+							
Cassave										
Coffee										
Pea (*Pisum*)	++ / +	++	++	+	++					
Grape vine	++			++			+			
Sugar beet	0	++	+	+	0	+		++		

++ = sensitive, + = intermediate, 0 = tolerant.

Appendix II

Modifying factors of air pollution effects

Table II.2. Modifying factors of sensitivity of crops to air pollution components (sources: Taylor et *al.*, 1987; Runeckles & Chevone, 1992).

Crop	Pollutant									
	O_3	SO_2	NO_x	HF	C=C	PAN	Cl_2	HCl	NH_3	H_2S
High relative humidity	+	+	+	+		0		+		
Wet leaves	?	?					0		+	
Drought	-	-	-	-		-	-		-	
Low temperature	-	-		-		-				
High light intensity	+	+				+	+			
Dark	-	-	+			-			+	
Windy conditions	-	+								
Age of plant: young plants	+	+				+	-	-		
Most sensitive tissue	Intermed. leaves	Young leaves	Young leaves	Immature leaves		Young leaves	Indifferent	Young leaves	Indifferent	
High soil salinity	-									
N excess	-	-	-	-						
High P		+		+						
High K	?									
High Ca				-				+		
High S	-	+								
N deficiency	+	-	+	-						
P deficiency		-								
K deficiency	?	+		+						
Ca deficiency		+		-				-		
S deficiency	-	-								
Other air pollutants	+	+	+	+	-	+				
Pests and diseases	+/-	+/-								

+ = increases sensitivity, - = decreases sensitivity, ? = reports are variable, but no general conclusion possible.