IMPACTS OF AIR POLLUTANTS ON VEGETATION IN DEVELOPING COUNTRIES

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Abstract. The predicted increases in emissions of primary pollutants in many rapidly industrializing countries may have severe consequences for the health and productivity of forest trees and agricultural crops. This paper presents a review of air pollution impacts on vegetation in developing countries by summarising information describing the direct impacts to vegetation caused by a number of air pollutants (sulphur dioxide (SO_2), nitrogen oxides (NOx), ozone (O_3) and Suspended Particulate Matter (SPM)). This information has been collected by experts from a number of rapidly industrializing countries in Asia, Latin America and Africa and includes observations of visible injury in the field and the use of transect studies and controlled experimental investigations to ascribe damage to different pollutant concentrations. The ability to synthesise this information to define exposure-response relationships and subsequent air quality guidelines similar to those established in North America and Europe is assessed. In addition, the use of regional and global models describing pollution concentrations is discussed with reference to assessing the extent of adverse impacts and identifying regions likely to be most at risk from air pollution, both for the present day and in the future. The evidence summarised in the paper clearly shows that current pollutant concentrations experienced in many developing countries, particularly Asia, can result in severe damage to vegetation and that without appropriate control measures such damage is likely to worsen in the future as pollutant emissions increase.

Keywords: air pollution, developing country, exposure-response relationships, policy tools, vegetation effects, SO_2, NOx, O_3, SPM.

1. Introduction

Increases in gaseous air pollution over recent decades have been experienced in many industrial and urban centres of Asia, Africa and Latin America primarily as a result of rapid economic growth, industrialization and urbanization with associated increases in energy demands. To date, most attention has focussed on

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the impact of these industrial and urban emissions on human health (Fenger, 1999) whilst little is known about pollutant concentrations and exposure patterns in many suburban and rural areas and associated impacts on the local vegetation. In Europe and North America extensive evidence of the adverse impacts of air pollution on forest trees and agricultural crops has been documented (*e.g.* Fuhrer *et al.,* 1997; Heck *et al.,* 1983). This paper aims to begin to assess the extent of air pollution impacts on vegetation in rapidly industrializing countries and investigate the suitability of tools designed to assess the extent of air pollution damage in Europe and North America to other continents.

Reviews have been commissioned from experts from China, Taiwan, India, Pakistan, Egypt, South Africa, Brazil and Mexico collecting information describing regional emissions, vegetation distributions and local pollutant concentrations. This information is related to observations 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 are described for each of the pollutants SO_2, O_3, NOx and SPM. One of the ultimate aims of collecting this sort of information is to be able to define dose-response relationships or exposure limits for damage. The information collected for SO_2 has been collated and is compared with North American, European and Australian exposure-response relationships in order to investigate the variability in response of different vegetation types to pollutants by region. Regional/global models describing pollutant concentrations can be used to give some indication of the spatial extent of air pollution problems. Results from a global O_3 model are presented here to compare predicted concentrations with the location of field observations of O_3 damage. This information is used to indicate the probable extent of vegetation damage both for the present day and in the future.

2. Regional Air Pollution and Associated Impacts

2.1. Asia

In China, the air pollutants of greatest concern relating to vegetation impacts are SO_2, NOx and SPM. Most SO_2 emissions are associated with the eastern part of China where population density and industrial activity is high. Pollution by NOx is not considered as serious a problem as SO_2 and little attention has been paid to ground level O_3 concentrations. However, the limited monitoring data that do exist show that O_3 is already high enough to cause adverse effects on vegetation in some areas.

The effects of high pollutant concentrations have been observed in Chongquin, the largest industrial city in southwest China. During 1995 the annual daily mean concentration for SO_2 was 340 μg m^{-3}, SPM was 320 μg m^{-3}

and NOx was 67 μg m^{-3} (Jiang and Zhang, 1996). Under such pollution loads trees (predominantly *Facus lacor*) lining the streets have had to be replaced three times since the 1960's. Observed impacts include the development of red and brown necrotic lesions and a thick layers of black dust on the surface of the leaves after several days without precipitation. Other symptoms include delayed sprouting and accelerated senescence. Other tree species such as peach, cherry and citrus have also exhibited signs of air pollution induced injury with inhibited or shortened flowering period, early leaf abscission and premature dropping of fruit (Zheng and Chen, 1991).

Air pollution impacts have also been reported around industrial complexes in China including power stations, steel plants and cement factories. In the Hunan Province air pollutants from a coal-burning power station resulted in severe impacts on local agriculture causing in some cases 100% losses in yield. Citrus trees growing in the vicinity of the power station showed reductions of about 55 % in average leaf CO_2 assimilation rates and a 50 % reduction in fruit number per tree compared with those growing in a relatively "clean" area (Boa and Zhu, 1997). In China, most agricultural land (including that used for fruit and vegetable production) is located around cities and industrial areas at low elevation. As such, fruit trees and vegetables are considered at the greatest risk from air pollutants.

Programmes to study the effects of acid rain on soil and vegetation in China led to a field based open top chamber (OTC) project to assess the effects of a range of SO_2 concentrations on the growth and yield of several crop plants. Based on this study yield-response relationships were established and yield losses attributed to SO_2 were estimated in 7 Chinese provinces. The results indicated that SO_2, rather than acid rain was the main factor responsible for yield losses in the studies regions of southern China (Feng *et al.,* 1999). The experimental results are discussed further in section 3.

In India, concern has been raised over air pollutant concentrations of SO_2, NOx, and SPM but concern is also growing over the impact of high O_3 concentrations. The annual average SO_2 concentration ranged from 10 to 120 μg m^{-3} across the country (Agrawal *et al.,* 1999). Annual average NO_2 concentrations range from 10 to 90 μg m^{-3} with especially high concentrations centred around metropolitan cities. High concentrations of O_3 have also been reported in many parts of the country. For example, hourly maximum O_3 concentrations of between 10 and 273 ppb have been recorded in Delhi (Varshney and Agrawal, 1992). In general, the northern and western parts of the country experience higher levels of air pollutants compared to south and eastern parts.

Adverse impacts of air pollution on plants around industrial sources and metropolitan cities have been reported for many parts of India. Field studies identified SO_2 as the most important air pollutant contributing to yield reductions of up to 50 % in agricultural species growing in the vicinity of thermal power plants where SO_2 concentrations of 75 to 135 μg m^{-3} were recorded (Agrawal Pers comm.). Studies on three varieties of *Oryza* sativa growing under ambient conditions near a fertilizer plant in Baroda, Gujrat have shown that high concentrations of SO_2 and NO_2 (mean maximum values of 144 and 210 $\mu g\ m^{-3}$ respectively) induced significant injury. Damage included reductions in panicle length, dry weight of filled grain and grain yield compared to a relatively pollution free site (Anbazhagan *et al.*, 1989).

Field transect studies have highlighted adverse plant responses to dust. Purushothamanan *et al.* (1996) found that spatial variation in foliar dust deposition and yield were correlated. They estimated that the average yield loss in paddy attributable to the cement dust polluted environment was approximately 20 %. Singh *et al.* (1990) investigated *Oryza sativa* growing at different locations around Dala cement factory, Uttar Pradesh and found that vegetative and reproductive parts accumulated significantly lower biomass (by 44 and 60 % respectively) at sites 1 km from the factory receiving high dust loads. Finally, field studies with *Cicer arietium, Glycine max* and *Cajanus cajan* showed reductions in plant height, total chlorophyll and fresh dry weight of plants growing at polluted compared to control sites (Varshney *et al.*, 1997).

Air pollution in Taiwan has become an important environmental issue. Results over four years from 1994 to 1997 clearly indicate that particulates measured as PM10 (suspended particulate matter < 10 μm) and to a lesser extent O_3 are the most important pollutants (EPA, 1998). The first observation of air pollution impacts to vegetation was recorded in the late 1960s when O_3 induced weather-fleck symptoms were found on the leaves of field growing tobacco plants which were being used as O_3 bio-indicators (Street *et al.*, 1971). Data from the monitoring network around urban areas revealed frequent occurrences of high daily mean O_3 concentrations (> 120 ppb). In association with these high concentrations Sun (1993) observed leaf bleaching injury to field grown leafy sweet potato in the basin area of north Taiwan, Taipei. A field survey performed by Lin and Yang (1996) found that many crops (cucumber, muskmelon, flowers, vegetables, guava and Indian jujube) exhibited O_3 symptoms in south Taiwan.

In Pakistan, Lahore and Karachi are two urban areas that have experienced severe reductions in air quality over recent decades. Monitoring of NO_2 concentrations around Lahore in 1993 to 1994 recorded elevated NO_2 levels, decreasing from city centres (weekly means of 70 $\mu g\ m^{-3}$) to rural areas (weekly means of 10 $\mu g\ m^{-3}$). In contrast, levels of O_3 pollution increased away from the city in peri-urban areas with rural concentration 6 hr weekly means reaching 72 ppb. O_3 bio-monitoring using the Bel-W3 tobacco plant showed that visible leaf injury increased with distance from the city consistent with increasing O_3 concentrations (Kafiat *et al.*, 1994). In Lahore, controlled experimental investigations using OTCs have investigated the impacts of ambient concentrations of O_3 and NOx on the growth of local cultivars of wheat, rice, chickpea, mungbean and soybean crops in comparison with those grown in pollution free air. The damage caused by the exposure of plants to ambient air pollution included reduced numbers of tillers, shoots and leaves; accelerated leaf senescence and yield reductions of between 23 and 47% (Wahid, Pers Comm.). In addition, studies using "EDU"

(N-[2-{2-oxo-1-imidazolidinyl}ethyl]-n2phenylurea) as a chemical protectant to O_3 have shown that seasonal mean O_3 concentrations of 75 ppb for 6 hr per day are sufficient to cause yield reductions of up to 64% to soybean in remote rural areas 30 km from Lahore (Wahid *et al.,* 1997).

2.2. Africa

The increases in air pollution that have occurred around the urban industrial centres of Cairo and Alexandria in Egypt are particularly problematical since these are in the same location as the primary agrarian region, which is limited to the Nile river basin as the primary source of irrigation water. Studies of the effects of air pollution on vegetation have been carried out in the last 20 years in the greater Cairo area and around the main roads within the Nile delta region. Ali (1993) reported instances of visible injury on clover/berseem (*Trifolium repens*) and Egyptian Mallow (*Malva parviflora*) plants growing close to the industrial complex at Shoubra El-Khaima. Mean pollutant concentrations between November 1987 and January 1988 reached 160 $\mu g\ m^{-3}$ SO_2, 88 $\mu g\ m^{-3}$ NOx and 680 $\mu g\ m^{-3}$ of total suspended particulates. Hourly mean O_3 concentrations were also recorded of greater than 100 ppb. Visible injuries included necrosis, red spots and chlorosis with 60 % and 54% of clover and Egyptian Mallow leaves injured respectively.

Hassan *et al.* (1995) assessed the impact of O_3 on the growth and yield of local varieties of radish (*Raphanus sativus* L. cv. Balady) and turnip (*Brassica rapa* L. cv. Sultani) at sub-urban and rural sites in Alexandria using EDU to protect control plants from O_3 effects. At the site mean 6 hr O_3 concentrations over the experimental period were 55 ppb in the suburban site and 67 ppb at the rural site. O_3 impacts included the formation of chlorotic spots on the upper leaf surface and reductions in plant biomass. These effects were recorded for radish at the both sites and for turnip only at the rural site. The study proved that levels of ambient O_3 in Egypt are high enough to have significant impacts on the growth and yield of local varieties of vegetable crops, even at a time of year when O_3 levels are relatively low.

In South Africa there are a number of locations where air pollution is perceived to be a problem. Industrial plants located on the highveld using coal as the primary fuel source result in emissions of SO_2 (Siversten *et al.,* 1995). SPM emissions from household coal and wood burning are also a concern in urban areas. Due to the high SO_2 emissions, the commercial forests located downwind of the highveld have been most extensively studied for air pollution impacts to vegetation in South Africa. Two year old plants of three commercially important forest species (*Pinus patula, Pinus elliotii* and *Eucalyptus grandis*) were exposed to SO_2 at 4 different concentrations: 133, 266, 1300 and 2660 $\mu g\ m^{-3}$ for 1 or 2 hours a day over 26 days (Kelly, 1986). Visual damage to *E. grandis* was evident at short duration exposures to concentrations of 1330 and 2660 $\mu g\ m^{-3}$ whereas *P. patula* was unaffected.

Foliar symptoms on *P. patula* were surveyed in five forestry regions in Mpumalanga and KwaZulu-Natal which corresponded to a gradient of potential pollution impact. Most trees exhibited some type of chlorosis which appeared to be correlated with the potential pollution impact at the site Olbrich (1990).

2.3. Latin America

The most serious air pollution in Mexico occurs in the vicinity of Mexico City associated with high O_3 and SPM concentrations. Other contributors to air pollution problems include the Mexican oil producing areas located in southern Mexico where high SO_2 concentrations along with other pollutants are thought to be causing serious damage to the local tropical vegetation and crop species. However, only very limited research has been conducted to assess pollutant impacts in this part of the country (de Bauer, Pers. Comm.). SPM is an important air pollutant in the Valley of Mexico, as well as in some other parts of the country but to date no research has been performed.

O_3 damage to *Pinus hartwegii, P. leiophylla* and *P. montezumae* var. *lindleyi* was observed in a southern forested area of Mexico City (Krupa and Bauer, 1976). Injury included chlorotic mottling and premature senescence. O_3 damage was most prevalent at the end of spring and the beginning of the summer season. *P. hartwegii* has been identified as one of the most sensitive species to O_3 exposures with damage being more severe than that observed to *P. montezumae* at the end of a two year period (Hernández and Bauer, 1984).

The sudden decline in sacred fir trees (*Abies religiosa*) observed in the "Desierto de los Diones" national park located to the south west of the Mexico valley, is considered to be caused by O_3 pollution due to the occurrence of O_3 visible injury symptoms (Bauer *et al.*, 1985). In addition, significant ring width reduction of scared fir trees has been observed since the beginning of the 1970's. Branches protected from O_3 by charcoal filtered air supply chambers or anti-transpirants did not show symptoms of O_3 injury (Alavarado *et al.*, 1993).

In Brazil, the pollution climate varies significantly across the country. Pollutant concentrations are highest in the southern and south eastern regions of Brazil associated with the location of large urban and industrial areas. The most renowned industrial complex for air pollution is that located at Cubatão in the state of São Paulo. Active and passive bio-monitoring has been performed within the region to try and identify the main damaging pollutants. An increase in foliar concentrations of sulphur was found in *L. multiflorum* and saplings of *T. pulchra* indicating that annual mean concentrations of SO_2 of 26 and 18 $\mu g\ m^{-3}$ measured at two polluted monitoring sites may well be inducing vegetation damage. Maximum annual mean O_3 concentrations of 78 ppb caused severe O_3 injuries to *N. tabacum* especially at the higher elevations although similar phytotoxic O_3 concentrations are experienced over the entire "Serra do Mar" region representing a risk to sensitive species (Klumpp *et al.*, 1996).

In summary, the data collected by each of the regional experts provides evidence that current levels of air pollution experienced at certain locations cause adverse impacts to vegetation. To fully understand the spatial extent of air pollution damage in terms of the area affected and the magnitude of the impacts, tools need to be developed to relate pollutant exposure to vegetation response. In North America and Europe exposure-response relationships for sensitive plant species have been established for different pollutants. These relationships are used in conjunction with maps describing the spatial variability of pollutant concentrations to identify regions where vegetation may be at risk from ambient pollution levels. Emission reductions can then be targeted to reduce ambient pollutant concentrations in these areas.

3. Dose-Response Relationships

In Europe and North America extensive programmes performing controlled experimental investigations have resulted in the establishment of dose-response relationships. These relationships identify suitable indices by which to measure pollutant exposures and relate these to appropriate response parameters for individual species. Similar research programmes are being initiated in some developing countries. To date most research has concentrated on collecting evidence of plant response to SO_2 and O_3. Figure 1 describes SO_2 response data collected from different locations around the world and compares the response, in terms of relative yield, to 8 or 7 hr growing season mean SO_2 concentrations of different species and cultivars local to each region.

The Chinese data were collected from OTC studies assessing the effects of a range of SO_2 concentrations (clean air, 132, 264, 396 and 666 μg m^{-3}; 7 hours per day) on the growth and yield of several crop species from seedling to final

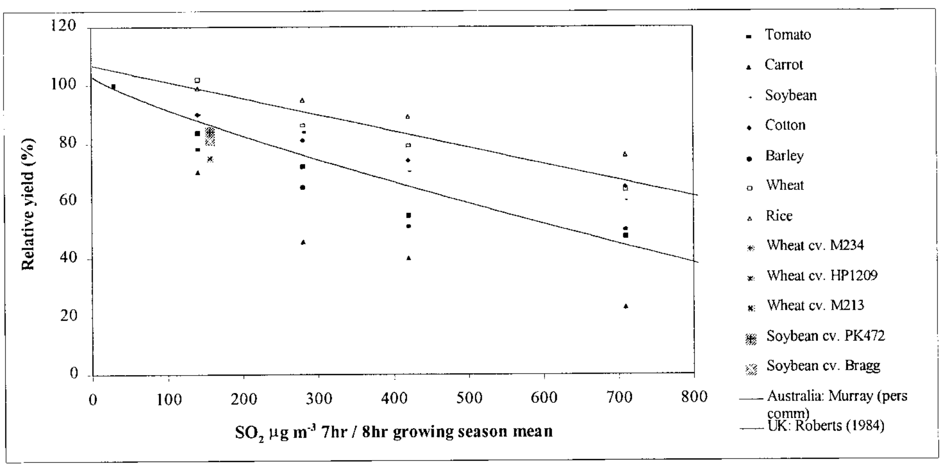

Figure 1. SO_2 dose-response relationship pooling data from China, India, Australia and the UK for differen species and cultivars.

harvest. Similarly, the Indian data were from OTC studies recording relative yield of wheat and soybean cultivars exposed to SO_2 concentrations of 157 $\mu g\ m^{-3}$; 8 hrs day^{-1} for 70 days. The Australian crop species exposure-response relationship is a generalised relationship pooled from experimental data relating mean SO_2 concentrations predicted from continuous exposure, exposure for 8 hr day^{-1}, 4 hr day-1, 2.5 hr day^{-1} and 3 days $week^{-1}$. The bulk of the data came from experiments conducted with an exposure regime of 4 hr day^{-1} over 4 or 5 months. These results are generally similar to results collated from UK experiments by Roberts (1984) for the sensitive *Lolium perenne* (ryegrass) species.

From Figure 1 it is apparent that between species there exist large differences in sensitivity to equivalent SO_2 concentrations. However, the data suggest that the species with higher sensitivities are consistent across regions, for example both Agrawal *et al.* (1991) and Feng *et al.* (1999) identified bean as an especially sensitive genus in India and China respectively. The range of species response to increasing exposures seems broadly consistent between regions indicating a degree of commonality. However, there are a number of regional factors that may modify the response of species to pollutant concentrations such as cultivar type, agronomic practices (irrigation, soil fertilization, use of pesticides) and prevailing climatic conditions. Climate can have a twofold effect by influencing pollutant uptake through the stomata (Emberson *et al.,* 2000), and also by determining the seasonal pattern of air pollution formation of secondary air pollutants like O_3. Vegetation response also varies with exposure to different air pollutant combinations and the air pollutant compositions of developed countries vary by region. This is especially important when considering pollutant interactions, for example studies have shown that plants respond synergistically to SO_2 and NOx (Ashenden and Mansfield, 1978) and similar interactions for other pollutant combinations may exist.

Finally, an important feature of dose-response relationships is that they represent species response to realistic ambient pollutant concentrations. Observations indicate that in the worst case scenarios of urban/industrial air quality, mean annual SO_2 concentrations reach maximum values of about 340 $\mu g\ m^{-3}$ as recorded in heavily polluted Chinese cities (Zheng, Pers comm.). Therefore, there is a need to more clearly define for individual species the exposure-response relationships between 0 to 400 $\mu g\ m^{-3}$ annual/growing season SO_2 concentrations which is currently determined by only two concentration levels at approx. 150 and 280 $\mu g\ m^{-3}$).

Relatively few dose-response studies for O_3 have been conducted outside Europe and North America, thus making a similar analysis difficult. However, in contrast to SO_2, there is some evidence that reductions in yield of local cultivars of crops such as rice and wheat are greater than those which might be predicted from North American dose-relationships for O_3. More data are urgently needed to define the O_3 levels at which significant impacts on the yield of local crops might occur in Asia, Africa and Latin America (Ashmore and Marshall, 1999).

4. Identifying Regional / Global Air Pollution Problems.

This paper has summarised key studies that prove ambient pollutant concentrations occurring at site-specific locations across the developing world are at concentrations high enough to cause significant damage to vegetation. Assessments of the extent of the air pollution problem can be achieved using models describing regional/global pollutant concentrations. Here we focus on O_3 pollution since the regional nature of this pollutant means that even at coarse spatial scales the general spatial distribution pattern can be discerned whilst other pollutants such as SO_2, NOx and SPM tend to exist only at high concentrations close to their respective emission sources.

The 3D STOCHEM model (Collins *et al.,* 1997; Collins *et al.,* 2000) has predicted global O_3 concentrations for both the present day (1990) and the future (2030). Future O_3 concentrations are predicted according to emissions based on the IPCC (1992) "business as usual" scenario. O_3 concentrations are described at a spatial scale of 5° × 5° showing maximum growing season (defined as 3 months) means for each grid square. It should be noted that these O_3 concentrations represent values within the well-mixed planetary boundary layer that extends to approximately 50 m above the surface. As such, concentrations at plant canopy heights will be lower, especially during the night-time period when atmospheric stratification reduces atmospheric mixing.

Figure 2 shows that during 1990 there were five main "hot-spots" in parts of North America, Europe, Asia, sub-Saharan Africa and south America where 3 month mean O_3 concentrations reached levels between 60 and 70 ppb. The leaf symbols identify areas where damage to vegetation has been attributed to O_3.

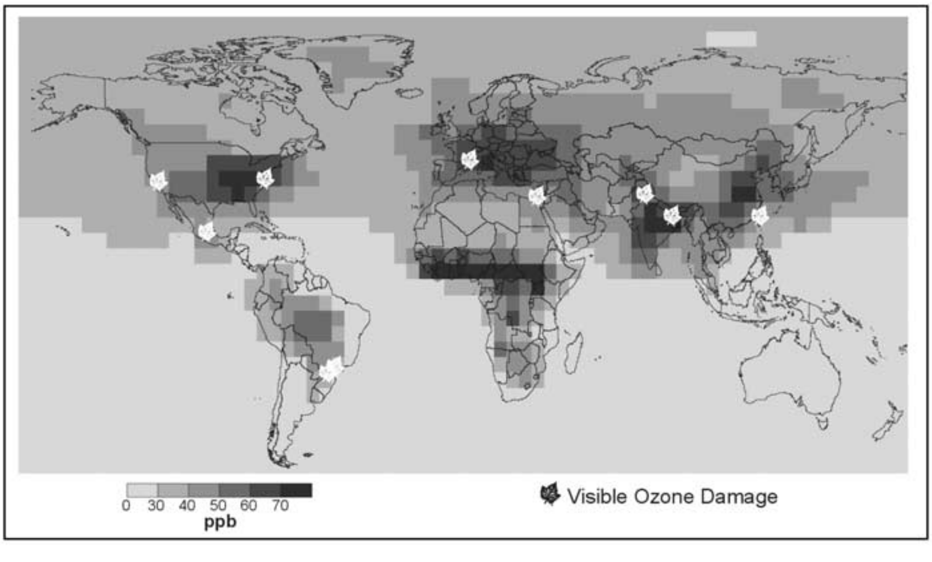

Figure 2. Mean maximum growing season O_3 concentrations for 1990 and areas where site-specific visible O_3 damage to vegetation has been observed.

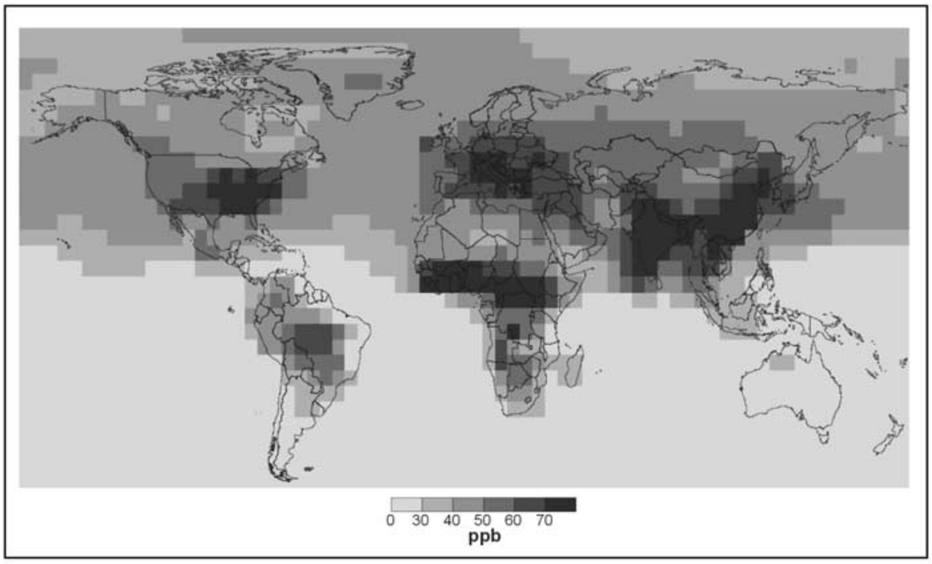

Figure 3. Maximum mean growing season O_3 concentrations for 2030.

These areas largely correlate with model predictions of high O_3 concentrations but in many cases, areas within the same country are experiencing even higher O_3 concentrations. This would suggest that under current day concentrations O_3 pollution is causing significant damage to local vegetation.

Figure 3 shows predicted future global O_3 concentrations assuming a "business as usual" scenario. Elevated O_3 concentrations are still centred around the five main hot-spots but the area covered by concentrations between 60 and 70 ppb is greatly increased. This indicates that if nothing is done to curb O_3 precursor emissions O_3 pollution and associated impacts to vegetation will become a significant problem in the future.

5. Conclusions and Discussion

This paper has summarised key observational and experimental evidence that ambient pollutant concentrations are high enough to cause adverse impacts to vegetation at locations within the rapidly industrializing countries of Asia, Africa and Latin America. SO_2 and O_3 tend to be identified as the pollutants causing most damage to vegetation in terms of the extent of the areas affected and the magnitude of the impacts. Similarly, air pollution impacts to vegetation have been most documented in Asia reflecting the fact that emissions, pollutant concentrations and impacts to vegetation are more widespread and higher than in either Latin America or Africa. The evidence also indicates that research efforts have been biased towards investigating air pollution impacts on agricultural crops rather than forest trees even though severe impacts have been identified for the latter vegetation group. This may reflect the greater importance of crops as a food commodity especially in regions where food shortages and reductions in food quality are a real concern for the population. In addition, agriculture tends to be located close to urban or industrial-residential areas to reduce transport costs and hence is exposed to higher pollution loads.

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