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EVALUATION OF AIR POLLUTION PHYTOTOXICITY DOWNWIND OF A PHOSPHATE FERTILIZER FACTORY IN INDIA

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Abstract. The effects of air pollution on plants downwind of a fertilizer factory at Udaipur, India, were studied using three woody perennials. Seedlings of these species including a shrub (*Carissa carandas* L.), a leguminous avenue tree (*Cassia fistula* L.) and a fruit tree (*Psidium guajava* L.) were grown in earthen pots at different study sites receiving varying levels of air pollution input. Changes in plant growth, morphological characteristics, photosynthetic pigment, ascorbic acid, N and S contents and in dry matter allocation were considered in relation to the status of ambient air quality. Observations with these parameters have indicated that the ambient air around the factory contained pollutants at phytotoxic levels. Plant height, basal diameter, conopy area, leaf area and chlorophyll, ascorbic acid and foliar-N concentrations decreased with increasing pollution load. However, foliar-S increased slightly at polluted sites. Air pollution load around the factory have also altered the biomass allocation. Root:shoot ratios increased in *C. fistula* and *P. guajava* at polluted sites. In contrast, for *C. carandas* the above ground parts, where foliage assumed predominance showed precedence over the root growth. This species responded characteristically to air pollution stress by allocating more of its photosynthate towards leaf production and shoot growth.

Keywords: air pollution, *Carissa carandas*, *Cassia fistula*, fertilizer factory, phytotoxicity, *Psidium guajava*

1. Introduction

Most of the trees that have limited capacity for vegetative reproduction depend on the successful establishment and survival of seedlings for plantation programmes and for forest regeneration and spread. The seedling stage is a critical phase in the life cycle of all seed plants and it becomes more crucial when planted in stressful environment (Wright and Westoby, 1999). Such seedlings must not only cope with biotic stresses such as herbivory, typical of other areas, but must withstand abiotic stresses including atmospheric contaminants. Atmospheric pollutants have been demonstrated to influence tree seedling growth and survival (Pandey and Agrawal, 1994a).

The problem of air pollution is of global concern. In developing countries like ours, this problem is still growing due to continued population pressure and industrial growth. For instance, due to increasing population pressure, increase in fertilizer use has become unavoidable to achieve maximum agricultural harvest. This has led to rapid growth of fertilizer factories in India. One of the most important discoveries made in the country during mid-sixties has been that of rock phosphate deposits near Udaipur providing a shade of relief as an indigenous source of raw material for fertilizer industry. This has helped development of phosphate fertilizer factories in the region. Phosphate rocks as the source of phosphate fertilizer contain 3.5 tp 4% fluorides, about one half of which is released in manufacture of the fertilizer, primarily as silicon tetrafluoride, which subsequently hydrolyzes to hydrogen fluoride as gas or mist. Further, about 90% of production is acidulated with sulphuric acid to make various forms of soluble phosphates, phosphate fertilizer factories therefore, add sizeable amount of SO_2 alongwith particulate and gaseous emission of fluoride (McCune, 1971).

A number of methods are used to study plant pollutant interactions and to assess the extent of vegetation damage under natural condition. The *in situ* methods are widely used for quantifying the measurable impacts of pollutants on plants growing in their natural habitats. Such experiments have advantage of being performed under natural conditions (Pandey and Pandey, 1994). There exist, however, classes of problems associated with the heterogeneity of the plant material and variations in environmental conditions, and it often becomes difficult to determine unequivocally which environmental factor(s) are the most important in controlling the plant responses. Of the many factors, edaphic (Farley and Fitter, 1999) and biotic (Narayan *et al.*, 1994) controls have particular significance. Transplant studies, in which uniformally sized seedlings of same age group are planted in identical pots and watered identically, offer a more direct approach. The plants are propagated from common stock to ensure genetic uniformity (Chaphekar, 1995). Pot-cultured transplants provide some control over root environment and biotic factors (Chaphekar, 2000). It provides natural exposure to ambient air environment and a better basis for the quantification of atmospheric environmental effects and validity of comparison between sites (Pandey and Agrawal, 1994a; Pandey and Pandey, 1996). Transplant studies can be successfully used for mapping pollution zones (Klumpp *et al.*, 1995; Chaphekhar, 2000). Transplants of lichens and bryophytes have been variously used to monitor the level of air pollution (Gilbert, 1971; LeBlanc *et al.*, 1972). However, in seasonally dry tropical regions where the populations of lichens and mosses are very scarce, such studies can only be performed with species of higher plants commonly found in these areas. This approach was considered for the present study with an objective of quantifying changes in plant morphological characteristics, dry matter allocation, concentrations of chlorophyll, ascorbic acid and nutrients at different pollution zones downwind of a phosphate fertilizer factory using pot-grown seedlings of *Cassia fistula, Psidium guajava* and *Carissa carandas* which could be used as biomonitors of air pollution status in a seasonally dry tropical environment.

2. Material and Methods

2.1. STUDY AREA

The study was conducted during 2000–2001 around Rama Phosphate Fertilizer Factory situated at 17 km SE of city of Udaipur, Rajasthan, India. The study area lies between 24°35′–24°58′N and 72°86′–73°42′E long and between 510 to 580 m above msl. The phosphate factory at Udaipur, established in 1997 with an installed capacity of 14 600 mt per annum, constitutes a very important unit for Rajasthan.

The climate of the area is tropical monsoonal. The year is divisible into a hot and dry summer season (April–June), a rainy season (July–September) and a cold winter season (November–February). October and March are transition months. Mean monthly maximum temperature ranges between 23.2 °C in January and 42.0 °C in May and mean monthly minimum temperature between 5.0 °C in January and 24.8 °C in May. Mean annual rainfall is 760 mm, about 90% of which occurs during rainy season. During the study period however, the annual rainfall remained below this level. Wind direction shifts from predominantly south-westerly during November through March and south-westerly to southerly for most of the remaining months.

The soil of the area is alfisols derived from parent materials high in limestone and $pH > 7$. Soil is medium to heavy textured and soil depth varies from 10 cm along the hill slopes to 6 m in low land. The original vegetation comprises of thin, dry deciduous forests with scattered patches of shrubs and seasonal grasses.

2.2. PLANT MATERIAL AND PROPAGATION

The factorial design of the whole experiment consisted of three plant species × four levels of pollutants (4 zones) × seven age classes. The plant species chosen for the present study were three tropical woody perennials found in and around the city of Udaipur. These included a leguminous avenue tree (*Cassia fistula* L.) a fruit tree (*Psidium guajava* L.) and a spiny shrub (*Carissa carandas* L.) that bears edible acidic berries which are pickled. Uniformly sized, five month old seedlings of each species were collected from the nursery of Rajasthan College of Agriculture, Udaipur and divided into two groups. For one group, ten seedlings of each species were carefully removed from their containers by slowly flushing the soil from around the root. The shoot was separated from the root, leaf area recorded and then individual plant component dried to constant weight in an oven at 80 °C to provide an initial root:shoot relationships. The second set of seedlings of each species were planted (one per pot) in 30 cm diameter × 35 cm long earthern pots filled with well manured garden soil (pH 7.48, water holding capacity 50.8%, organic-C 1.48%, total-N 0.1%, available-P 0.006%, exchangeable-K 0.1%, cation exchange capacity 15.9 meq 100 g^{-1}). Earliar trials with such species indicated that the pot size used in this experiment did not restrict seedling root growth. These pot-grown seedlings were allowed to stabilize for a period of four weeks and thereafter ten such seedlings of each species were kept at each study site. The edaphic and climatic conditions were similar except the differences in the air environment. In order to maintain a constant soil moisture and an adequate nutrient supply, pots were uniformly watered thrice in a week during dry seasons and were supplied with manure twice in a year at the rate of 250 g per pot. Pots were protected from biotic disturbances and other interference.

2.3. AIR QUALITY MONITORING

Ambient air quality monitoring for HF, SO_2 and total suspended particulates (TSP) were done with high-volume samplers located at 1.5–3.0 m above ground level at each microsite. HF concentrations were monitored by absorbing air into an aqueous solution of 0.1N NaOH, which was later analysed through a selective fluoride ion electrode (Narayan *et al.*, 1994). Sulphur dioxide was scrubbed through impingers containing tetrachloromercurate and analysed colorimetrically (West and Gaeke, 1956). TSP were trapped on glass fibre filter papers attached to the hopper of high volume samplers. The data are presented as 24 hr average and 2 hr peak concentrations, and expressed as μg m^{-3}. The details of the techniques and sampling duration are described in Pandey *et al.* (1992).

2.4. PLANT SAMPLING AND ANALYSIS

Sampling was done at four monthly intervals at plant ages of 10, 14, 18, 22, 26, 30 and 34 months. Initially, morphological parameters such as plant height, number of leaves, basal diameter, canopy area etc were recorded for all individuals. At 26 months of plant age (4 April 2001), owing to the large number of leaves, first sampling was made for the determination of phostosynthetic pigments, ascorbic acid, foliar-N and sulphate-S concentrations. For this purpose, fully expanded leaf samples were collected at the third to fifth positions from the terminal bud of different branches, between 8:00 to 10:00 hr (Pandey and Agrawal, 1994a). These leaves were then pooled together, and samples in triplicate were taken from three replicates of each species at each micro site. At the end of the experiment (4 December 2001) plants were harvested for the determination of above and below ground biomass and relative total biomass.

Leaf area was measured with a portable leaf area meter (LI-COR, U.S.A.). Plant leaves were closely examined for lesions, if any, in terms of necrosis and the injury was quantified as percentage of leaf area injured using a planimeter. Chlorophyll was extracted in 80% acetone and was determined following MacLachlan and Zalik (1963). For ascorbic acid, the method given by Keller and Schwager (1970) was followed.

TABLE I

Annual 24 hr average air pollutant concentrations (μg m^{-3}) in different zones of Rama Phosphate Fertilizer Factory. Values in parenthesis represent 2 hr peak concentrations

Year	Pollutants	Zones			
		I	II	III	IV
2000	Hydrogen fluoride	3.5 (6.7)	3.4 (6.5)	2.5 (3.4)	0.20 (0.29)
	Sulphur dioxide	86 (191)	80 (183)	56 (132)	15 (27)
	TSP[a]	352 (784)	347 (756)	280 (495)	175 (267)
2001	Hydrogen fluoride	3.6 (6.7)	3.5 (6.6)	2.5 (3.2)	0.21 (0.31)
	Sulphur dioxide	89 (201)	84 (196)	49 (119)	16 (27)
	TSP[a]	357 (796)	350 (760)	283 (504)	173 (253)

[a] Total suspended particulates.

For biomass determination, plants were separated into, leaf shoot and root. Samples were thoughly washed and kept in an oven at 80 °C till the constant weight was achieved. The relative total biomass (RTBi) of species was calculated as below:

$$\mathrm{RTBi} = \frac{[\mathrm{TBi}]^p}{[\mathrm{TBi}]^c} \times 100 \, ,$$

where, $[\mathrm{TBi}]^p$ is the mean total biomass of ith species at zones I, II and III in question and $[\mathrm{TBi}]^c$ is the mean total biomass of the same species at reference zone IV. Since all the species accumulated the highest total biomass at zone IV, this ratio expresses the proportional loss in total biomass of a species at a given polluted site. Mean relative growth rates of shoot and root were calculated as described in Hunt (1990). Root:shoot ratio (RSR) was also calculated for each species. Dry leaf samples were powdered and used for the determination of N and $SO_4^{2-}S$ following micro-Kjeldahl technique (Mishra, 1968) and turbiditimetric method (Rossum and Villarruz, 1961), respectively.

2.5. STATISTICAL ANALYSIS

Effects of sites (pollutant concentrations), plant species and their interaction were tested using two-way analysis of variance. Means were separated by Duncan's multiple range test. Data were log transformed when necessary.

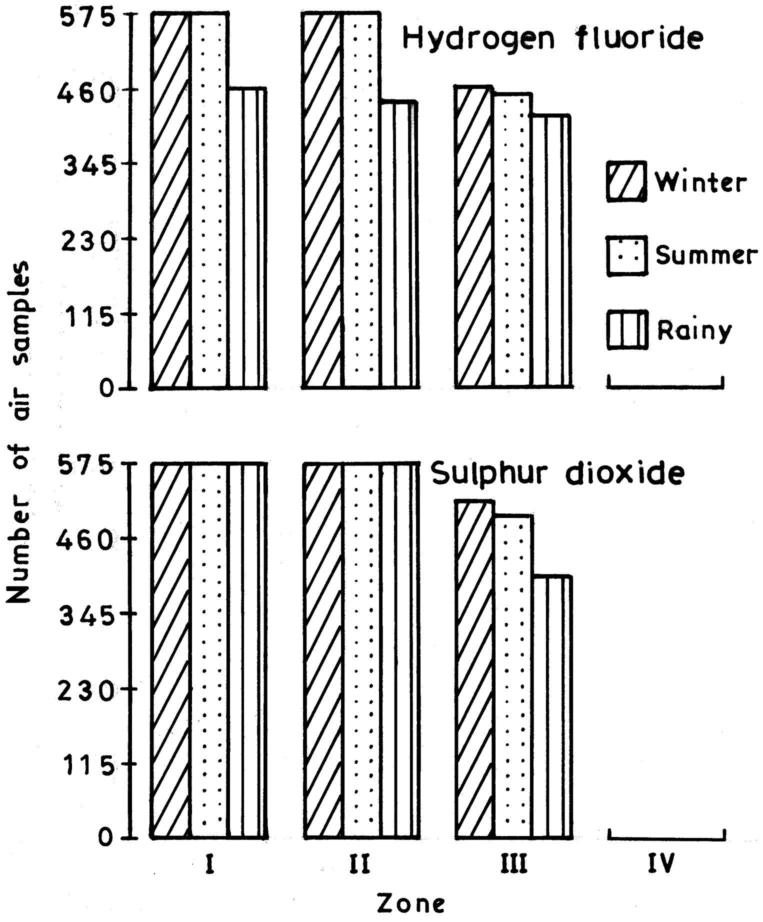

Figure 1. Number of air samples (2 hr average) exceeding 1.0 and 60 μg m^{-3} for HF and SO_2, respectively. (n = 575).

3. Results

Air quality data indicates that the zones selected around Rama Phosphate Fertilizer Factory can be ranked from maximum pollution load to a minimum as I > II > III > IV (Table I and Figure 1). At zone I, dry seasons 2 hr records remained above 1.0 μg m^{-3} (for HF) and 60.0 μg m^{-3} (for SO_2). At zone IV, nones of the 2 hr means concentrations exceeded 1.0 and 60.0 μg m^{-3}, respectively. Since the concentrations of all the pollutants were lowest in zone IV, the data for this zone were used as the reference for comparing changes in plant parameters obtained at other zones.

Heights of all the three species declined in response to the factory emission and the decline was maximum in *C. fistula* follwed by *C. carandas* and then *P. guajava*

TABLE II

Growth performance of plants grown at different zones (I to IV) of Rama Phosphate Fertilizer Factory (All the values are mean of five replicates). There was a marked gradient in pollutants concentration in the order I > II > III > IV

Plant age	*Cassia fistula*				*Psidium guajava*				*Carissa carandas*				ANOVA[a]		
(months)	I	II	III	IV	I	II	III	IV	I	II	III	IV	Sp	S	Int.
	Plant height (cm)														
10	14.6	15.4	21.0	16.3	13.5	12.8	12.6	12.8	14.2	12.9	10.5	10.2	ns	ns	ns
22	23.9	29.9	38.1	62.6	26.0	26.7	29.2	40.0	24.8	26.7	28.9	44.5	*	**	*
34	29.8	35.1	48.2	86.7	39.8	41.9	45.2	67.0	35.7	38.2	46.1	68.4	**	**	**
	Basal diameter (cm)														
10	0.12	0.11	0.12	0.11	0.14	0.14	0.15	0.15	0.16	0.18	0.16	0.15	ns	ns	ns
22	0.25	0.30	0.34	0.56	0.24	0.28	0.36	0.46	0.30	0.31	0.36	0.44	*	*	ns
34	0.32	0.43	0.57	0.72	0.37	0.40	0.55	0.76	0.43	0.45	0.59	0.84	**	**	**
	No. of leaves ($plant^{-1}$)														
10	8	8	10	10	10	11	11	9	30	26	33	35	ns	ns	ns
22	22	24	32	42	22	24	29	30	612	605	410	286	*	**	*
34	44	46	62	72	32	36	42	48	1068	1016	812	415	**	**	**
	Canopy area (cm^2)														
10	109	118	124	116	154	143	168	159	60	60	70	65	ns	ns	ns
22	370	408	490	600	472	508	776	812	800	785	780	816	*	*	ns
34	536	605	718	1260	562	665	1200	1470	1460	1328	1205	1596	**	**	*

[a] Sp: species; S: Site; Int: Interaction.

* $P < 0.05$; ** $P < 0.005$; ns: not significant.

TABLE III

Leaf area injury (%) in plants grown at different zones (I to IV) of Rama Phosphate Fertilizer Factory (values are mean of 5 replicates ± SE). There was a marked gradient in pollutants concentration in the order I > II > III > IV

Plant species	Zone	Plant age (months)			
		22	26	30	34
Cassia fistula	I	9.6±0.87	7.4±0.67	6.2±0.54	20.5±2.11
	II	9.5±0.92	7.1±0.48	6.2±0.60	19.6±1.65
	III	6.2±0.55	4.3±0.38	4.1±0.50	14.2±1.34
	IV	–	–	–	–
Psidium guajava	I	9.2±0.90	9.7±0.86	6.5±0.54	18.7±1.65
	II	9.0±0.86	7.1±0.70	6.2±0.52	18.0±2.05
	III	5.4±0.61	3.8±0.33	3.1±0.28	9.8±1.10
	IV	–	–	–	–
Carissa carandas	I	6.9±0.76	7.8±0.65	7.2±0.64	16.8±1.45
	II	7.0±0.55	7.6±0.71	7.1±0.53	16.2±1.56
	III	3.9±0.31	4.0±0.50	3.8±0.30	10.3±1.12
	IV	–	–	–	–

(Table II). At zone I the reductions in plant height were 65.6, 47.8 and 40.6% for *C. fistula, C. carandas* and *P. guajava*, respectively, after 28 months of exposure. A similar trend was also observed for plant basal diameter. In *C. fistula* and *P. guajava* the number of leaves per plant declined at zones I, II and III (Table II). In contrast, in *C. carandas* the number of leaves were high at zones I, II and III. Canopy area was markedly reduced at zone I, the greatest reduction being in *C. fistula* (57.5%) followed by *P. guajava* (54.8%) and *C. carandas* (12.3%). The canopy height also showed a similar trend (Table II).

In all the three species no visible foliar injury symptoms appeared for the first twelve months of exposure. *C. fistula* showed early appearance of foliar injury symptom and more extensive leaf damage than *P. guajava* and *C. carandas*. The maximum percent leaf area damage was observed at zone I after 28 months of exposure, the values being 20.5% in *C. fistula*, 18.7% in *P. guajava* and 16.8% in *C. carandas* (Table III).

The area of individual leaves and total leaf area per plant were maximum in plants at zone IV (Figure 2). Leaf biomass decreased with increasing pollution load and the decline at zone I was maximum in *P. guajava* (73.5%) followed by *C. fistula* (72.3%) and then in *C. carandas* (38.8%) at 34 months of plant age. Analysis of variance indicated that the variations in leaf area per seedling, average area of individual leaves, number and biomass of leaves and total plant biomass were significant ($p < 0.005$) with respect to plant species, zones and their interactions. Of the total plant biomass, leaves contributed about 27.0% in *C. fistula*, 27.1% in *P. guajava* and 19.7% in *C. carandas* at zone IV at 34 months of plant age (Figure 2). Exposure to factory emission was found significantly ($p < 0.005$) to reduce the rate of root and shoot growth, although the response varied with species (Figure 3). In comparison to other two species, the rate of root growth was markedly reduced in *C. carandas*. The differential effect of atmospheric environment on root and shoot growth of this species was manifested in a significant decrease in root:shoot ratio. Root:shoot ratio (RSR), which was highest in *C. fistula* followed by *P. guajava* and then in *C. carandas*, also showed a decreasing trend with increasing pollution load (Figure 4). The magnitude of reduction in RSR was maximum in *C. carandas* followed by *P. guajava* and then in *C. fistula*. The relative total biomass (RTB) indicated plant biomass losses of 40.0% for *P. guajava*, 34.5% for *C. fistula* and 31.8% for *C. carandas* at zone I after 28 months of exposure to factory emission (Figure 5).

Chlorophyll and ascorbic acid concentrations were highest in zone IV (Figure 5) and varied significantly between species and zones. Greatest reductions in all the three species were seen at zone I. *C. fistula* was most severely affected with 50.0% reduction in chlorophyll and 33.3% reduction in ascorbic acid contents in zone I compared with zone IV at 34 months of plant age. For *C. carandas*, reductions in chlorophyll and ascorbic acid were lowest. Foliar-N also declined with increasing pollution load, while for SO_4^{2-}-S an opposite trend was observed (Figure 5). For foliar-N, the magnitude of reduction was greatest in *P. guajava* followed by *C. carandas* and then in *C. fistula*. The highest foliar-S concentration was observed in *C. carandas* followed by *C. fistula* and then in *P. guajava*. The respective percentage increases in the same order at zone I were 71.4, 31.6 and 26.3 after 28 months of exposure as compared to plants at zone IV.

4. Discussion

The observations on plant performance have indicated that the seedlings of all the three species propagated at zones I, II and III were adversely affected by factory emission. Changes in plant height, basal diameter, canopy area, leaf area, leaf biomass, total plant biomass and chlorophyll, ascorbic acid and nitrogen concentrations indicated the adverse affects of air pollution around the factory. Growth reductions were maximum at zone I receiving maximum pollution load. As the seedlings were grown under similar climatic and edaphic controls, the observed differences in growth performance may be attributed to atmospheric pollution. A number of workers have observed significant reductions in growth and biomass accumulation (Bunce, 1984; Treshow, 1984; Stevens *et al.*, 1998), photosynthetic pigments (Sidhu, 1980; Weinstein and Alscher-Herman, 1982) and yield (Maclean

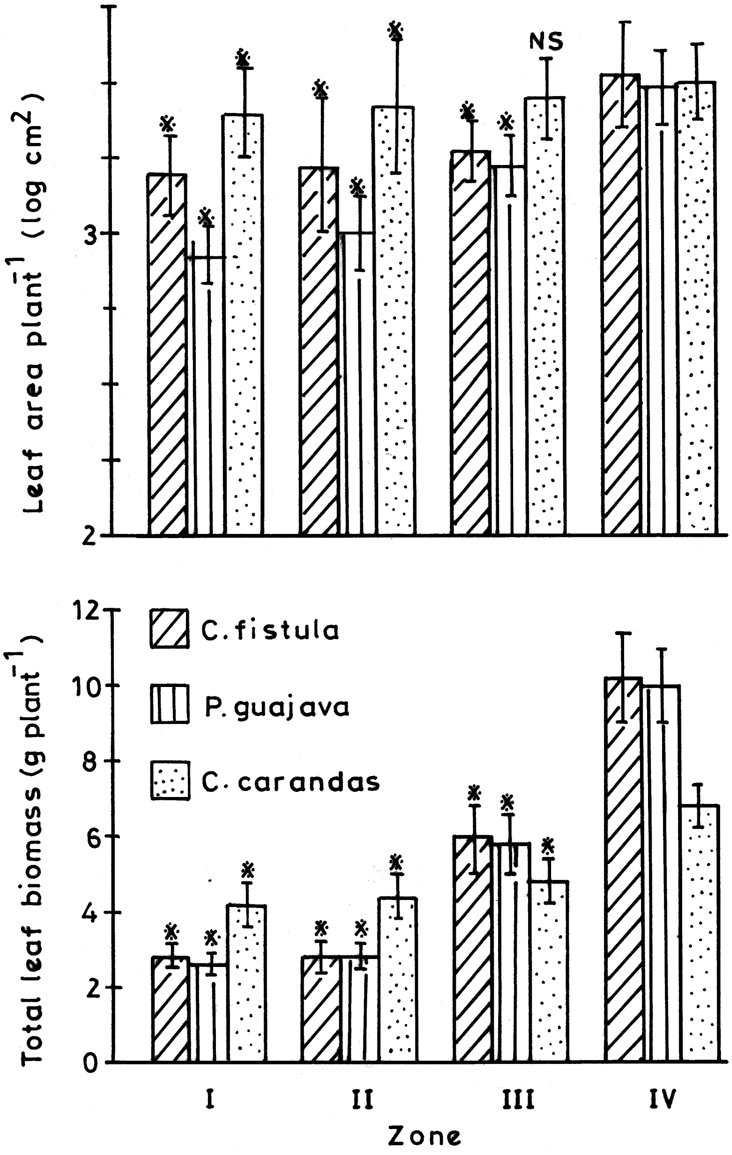

Figure 2. Leaf area per plant, per leaf area, total leaf biomass and total biomass of *Cassia fistula, Psidium guajava* and *Carissa carandas* seedlings grown for 28 months at different zones (I to IV) of the study area. ^{a} Difference significant: $P < 0.005$; NS: not significant. Vertical bars: 1 standard error. There was a marked gradient in pollutants concentration in the order I > II > III > IV.

and Schneider, 1981) in plants exposed to fluoride pollution. In the present study, fluoride appeared the major air pollutant with 2 hr mean concentrations above 1 μg m^{-3} for most sites except the reference zone (Figure 1). The ambient air quality data further indicate that the annual 24 hr concentrations of SO_2 did not exceed

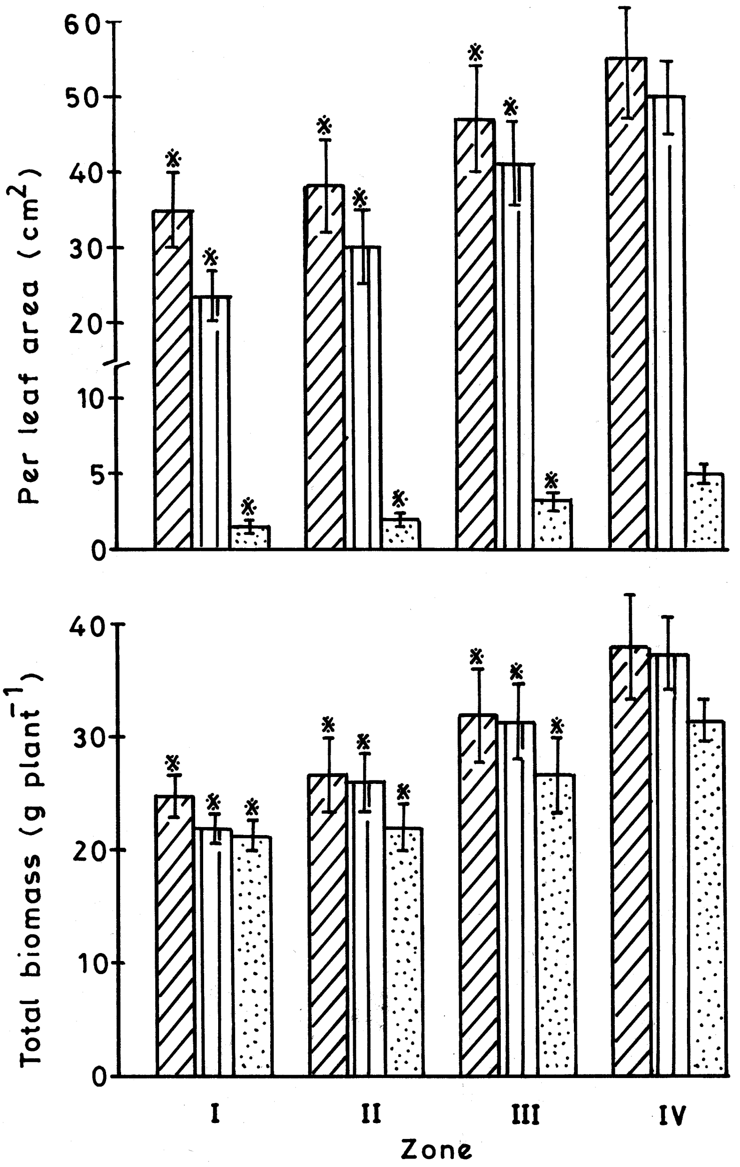

Figure 2. (Continued).

0.03 ppm (134 μg m^{-3}). Fumigation studies have not revealed significant effects at concentrations $\leq$0.03 ppm of SO_2 (Pandey and Agrawal, 1994b). It seems that its peak concentrations and co-occurrence with fluoride could be responsible for causing significant adverse effects observed in the present study. A combination of SO_2 and HF cause injury at concentrations lower than those required for either gas alone (Oleksyn, 1984).

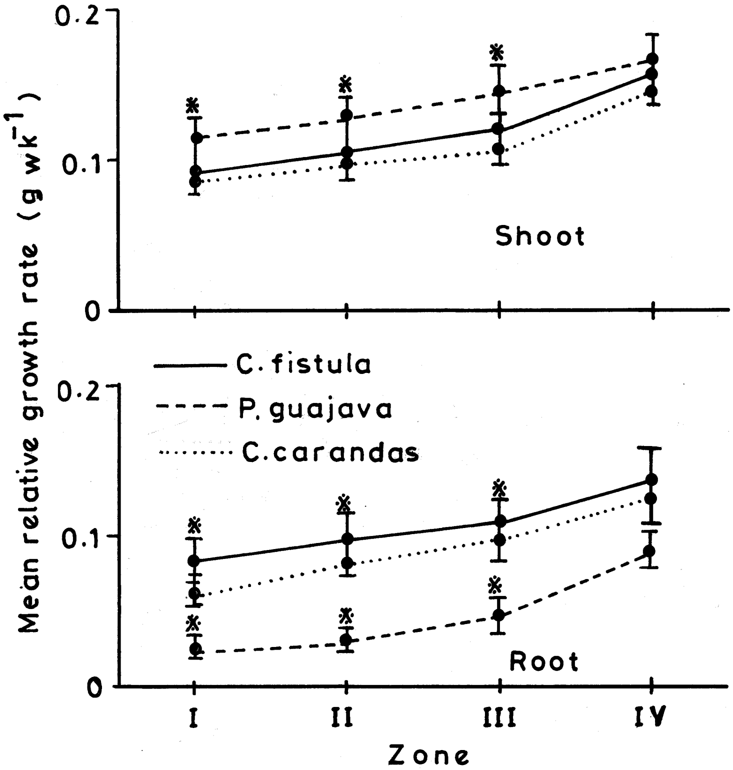

Figure 3. Mean relative growth rate (shoot and root) of *C. fistula, P. guajava* and *C. carandas* seedlings grown at different zones (I to IV) of the study area. [a] Difference significant: $P < 0.005$. Vertical bars: 1 standard error. There was a marked gradient in pollutants concentration in the order I > II > III > IV.

The most important element of plant growth reduction is the decreased photosynthesis due to reductions in leaf area (Smith and Brennan, 1984; Byres *et al.*, 1992), photosynthetic pigments (Pandey and Agrawal, 1994b) and closure of stomata and thereby reduced biochemical fixation of CO_2 (Martin *et al.*, 1988). The present observations indicated significant reductions in total leaf area and chlorophyll concentration. In *C. carandas*, although number of leaves increased significantly at polluted sites, the total leaf area declined due to reduction of individual leaf area. Thus, the reduction in photosynthesis due to loss of leaf area and chlorophyll pigment could lead to reduced seedling growth of *C. fistula*, *P. guajava* and *C. carandas* propagated at polluted zones. Further, air pollution stress is known to increase respiration (Schmidt *et al.*, 1990). Biomass accumulation is the final result of total assimilation after respiration. Since the plants grown at zone IV accumulated the highest total biomass, the relative total biomass (stressed/control) expresses the proportional loss in total biomass of a species at a given polluted site.

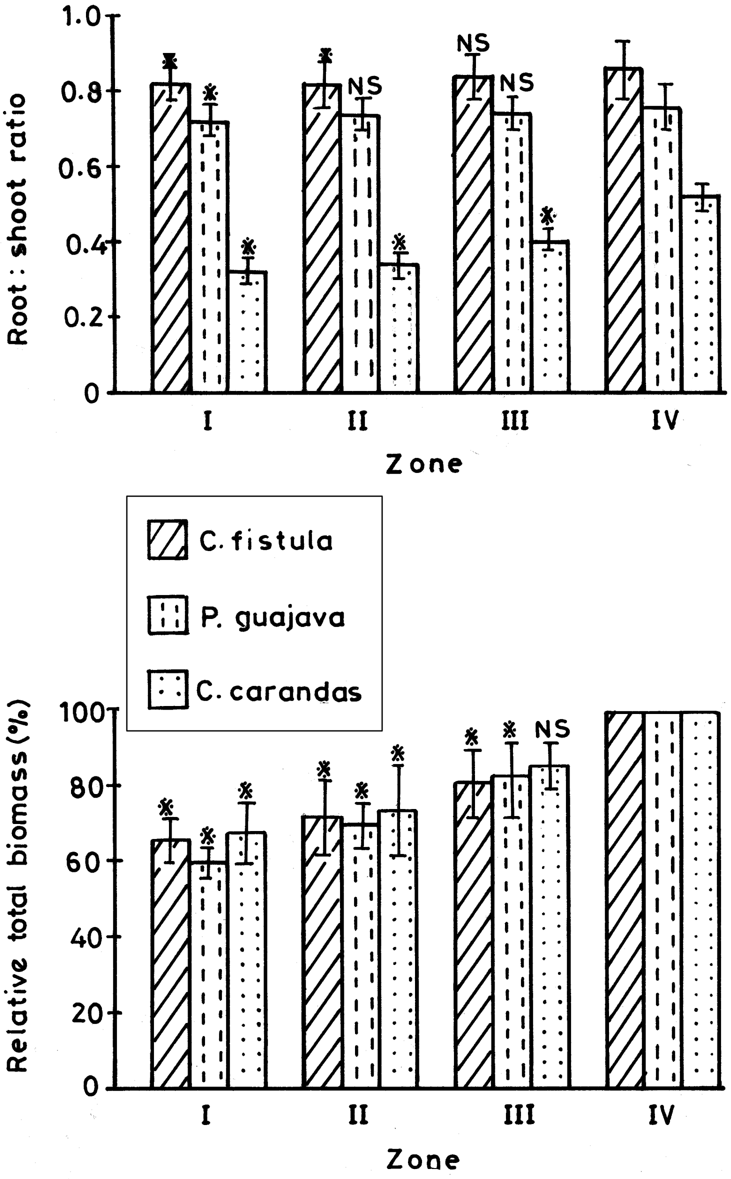

Figure 4. Root:shoot ratio and relative total biomass of *C. fistula, P. guajava* and *C. carandas* seedlings grown for 28 months at different zones (I to IV) of the study area. [a] Difference significant: $P < 0.005$; NS: not significant. Vertical bars: 1 standard error. There was a marked gradient in pollutants concentration in the order I > II > III > IV.

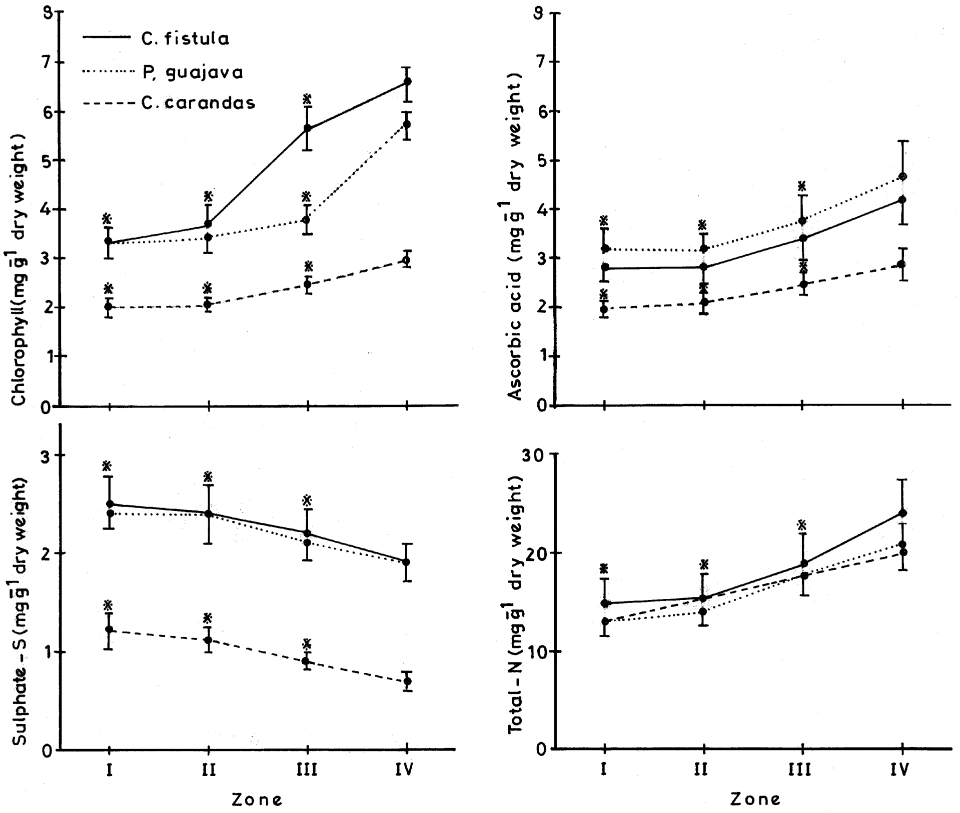

Figure 5. Chlorophyll, ascorbic acid, S and N concentrations in leaves of *C. fistula, P. guajava* and *C. carandas* seedlings grown at different zones (I to IV) of the study area. [a] Difference significant: $P < 0.005$. Vertical bars: 1 standard error. There was a marked gradient in pollutants concentration in the order I > II > III > IV.

Visible injury symptoms appeared in the form of stunted growth and bifacial necrosis towards the tips and margins of the leaf. The tip and marginal necrosis could be due to accumulation of fluoride towards tip and margin of leaves. Simultaneous absorption of SO_2 could enhance the severity of leaf injury. Lack of visible injury at site IV could be due to very low concentrations of pollutants at this site where none of the 2 hr mean concentrations exceeded 1.0 and 60.0 μg m^{-3} for HF and SO_2, respectively.

The results further indicated altered pattern of dry matter allocation at polluted sites. The number of leaves which declined in *C. fistula* and *P. guajava*, increased in *C. carandas*. Reductions in number of leaves in *C. fistula* and *P. guajava* under air pollution stress may be due to decreased leaf production rate and enhanced senescense. The opposite trend in *C. carandas* could be an acclimatory response to air pollution. Changes in number of leaves, leaf biomass and root: shoot ratio indicate the relative importance of dry matter allocation in the plant's ability to acclimatize (Pandey and Pandey, 1996). Under stress condition, many plants show a shift in biomass allocation in order to increase carbon gain or to enhance uptake of water and nutrients. A shift in biomass allocation towards photosynthetic units (leaf) would have the potential advantage of increasing carbon acquisition (Mooney and Winner, 1988). In contrast, a shift from leaf to root mass would increase water uptake with simultaneously reducing its water loss and therefore increasing the effective response of the plant to drought (Chaudhuri *et al.*, 1990). This is a trade-off between the plant's ability to acquire carbon and to increase uptake of water and nutrients (Norby *et al.*, 1992). In the present study, unlike the acclimation to drought, as the plants were sufficiently watered, a shift in biomass allocation towards leaf growth in *C. carandas* could be an acclimation to air pollution by increasing carbon gain. Held *et al.* (1991) reported similar acclimatory response in radish exposed to ozone pollution. Shifts in dry matter allocation towards shoot growth have been reported by Wolfenden and Mansfield (1991) and Balaquer *et al.* (1995). Constantinidou and Kozlowski (1979) observed significant inhibition of leaf expansion and decreased root dry matter accumulation in *Ulmus americana* under pollution stress. Relatively high RSR in *C. fistula* and *P. guajava* plants at polluted zones suggest that these species could allow more dry matter to be allocated towards root.

Reductions in chlorophyll, ascorbic acid and foliar-N contents provide further evidence that the air around Rama phosphate factory contained pollutants at phytotoxic levels. Maximum reduction in chlorophyll was observed at zone I which experienced the greatest pollution load. The reduction in chlorophyll concentration may be ascribed to membrane damage followed by leaching of chlorophyll pigments (Malhotra and Khan, 1980). Some investigators have reported that ascorbic acid, being a natural antioxidant, maintains the stability of plant cell membranes during pollution stress (Dindsa *et al.*, 1982) and scavenges pollution induced free radicals (Mehlhorn *et al.*, 1987; Pandey and Agrawal, 1993). The endogenous level of ascorbic acid is linked with plants ability to tolerate air pollution (Varshney and Varshney, 1984; Lee *et al.*, 1984; Singh *et al.*, 1991). The reduction of ascorbic acid may be due to its consumption during removal of free radicals generated in chain reactions after the penetration of air pollutants into foliar tissue (Wolfenden and Mansfield, 1991). *P. guajava* contained highest level of ascorbic acid of the three species considered in the present study and *C. fistula* showed the greatest reduction in chlorophyll and ascorbic acid concentrations due to air pollution. However, *P. guajava* appeared to be the most sensitive in terms of reduction in nitrogen concentration and biomass accumulation. It seems that for the three species compared here, ascorbic acid concentration was not related to sensitivity to air pollution. Increase in foliar-S contents with increasing ambient SO_2 concentrations, as observed in present study, are reported in other studies (Keller, 1982).

The study suggests that the air environment around Rama Phosphate Fertilizer Factory at Udaipur contained pollutants at phytotoxic levels. Although all the three species considered in the present study showed adverse effects, *C. carandas* responded characteristically to the existing air pollution stress by allocating more of its photosynthate towards leaf production and shoot growth.

References

Balaguer, L., Barnes, J. D., Panicucci, A. and Borland, A. M.: 1995, 'Production and utilization of assimilates in wheat (*Triticum aestivum* L.) leaves exposed to elevated O_3 and/or CO_2', *New Phytol.* **129**, 557–568.

Bunce, H. W. F.: 1984, 'Fluoride emissions and forest survival, growth and regeneration', *Environ. Pollut.* (Ser. A), **35**, 247–251.

Byres, D. P., Dean, T. J. and Johnson, J. D.: 1992, 'Long term effects of Ozone and simulated acid rain on the foliage dynamics of slash pine (*Pinus elliotti* var. *elliotti* Engelm)', *New Phytol.* **120**, 61–67.

Chaphekar, S. B.: 1995, 'Protocol for Phytomonitoring in Industrial Areas in Tropical Monsoonal Region', in M. Munawar, O. Hanninen, S. Roy, N. Munawar, L. Karenlampi and D. Brown (eds), *Bioindicators of Environmental Health*, *Proceedings 7th International Bioindicator Symposium*, Finland SPB Acad. Publ., The Netherlands.

Chaphekhar, S. B.: 2000, 'Phytomonitoring in Industrial Areas', in S. B. Agrawal and M. Agrawal (eds), *Environmental Pollution and Plant Response*, Lewis Publishers, New York, pp. 328–342.

Chaudhuri, U. N., Kirkham, M. B. and Kanesmasu, E. T.: 1990, 'Root growth of winter wheat under elevated carbon dioxide and drought', *Crop Sci.* **30**, 853–861.

Constatinidou, H. A. and Kozlowski, T. T.: 1979, 'Effects of sulphur dioxide and ozone in *Ulmus americana* seedling, I. Visible injury and growth', *Can. J. Bot.* **57**, 170–175.

Dindsa, R. S., Dindsa, P. P. and Thorpe, T. A.: 1982, 'Leaf senescence: Correlated with increased levels of membrane permeability and lipid peroxidation, and decreased levels of superoxide dismutase and catalase', *J. Exp. Bot.* **32**, 93–101.

Farley, R. A. and Fitter, A. H.: 1999, 'Temporal and spatial variation in soil resources in a deciduous woodland', *J. Ecology* **87**, 688–696.

Gilbert, O. L.: 1971, 'The effect of air borne fluorides on lichens', *Lichenologist* **5**, 26–32.

Held, A. A., Mooney, H. A. and Gorham, J. N.: 1991, 'Acclimation to ozone stress in radish: Leaf demography and photosynthesis', *New Phytol.* **118**, 417–423.

Hunt, R.: 1990, *Basic Growth Analysis*, Unwin Hyman, London.

Keller, T. and Schwager, H.: 1970, 'Air pollution and ascorbic acid', *Eur. J. For. Pathol.* **7**, 338–350.

Keller, T.: 1982, 'The S content in forest tree foliage fumigated during summer or winter', *Eur. J. For. Pathal.* **12**, 399–406.

Klumpp, G., Klumpp, A. and Domingos, M.: 1995, '*Hemexocallis* as bioindicator of fluoride pollution in tropical countries', *Environ. Monitor. Assess.* **35**, 27–38.

Le Blanc, F., Rao, D. N. and Comeau, G.: 1972, 'Indices of atmospheric purity and fluoride pollution in Arvida, Quebec', *Can. J. Bot.* **50**, 991–998.

Lee, E. H., Jersey, J. A., Gifford, C. and Bennett, J.: 1984, 'Differential ozone tolerance in soybean and snapbeans: Analysis of ascorbic acid in O_3-susceptible and O_3-resistant cultivars by high performance liguid chromatography', *Environ. Exp. Bot.* **24**, 331–341.

MacLachlan, S. and Zalik, S.: 1963, 'Plastid structure, chlorophyll concentration and free amino acid composition of a chlorophyll mutant of barley', *Can. J. Bot.* **41**, 1053–1062.

MacLean, D. C. and Schneider, R. E.: 1981, *Effects of Gaseous Hydrogen Fluoride on the Yield of Field Grown Wheat*, Boyce Thomson Institute at Cornell University, Ithaca, N.Y., **148**, U.S.A.

Malhotra, S. S. and Khan, A. A.: 1980, 'Effects of sulphur dioxide and other air pollutants on acid phosphatase activity in pine seedlings', *Biochem. Physiol. Pflanzen* **175**, 228–236.

Martin, B., Bytnerowicz, A. and Thorstenson, Y. R.: 1988, 'Effects of air pollutants on the composition of stable carbon isotopes $\Delta^{13}C$ of leaves and wood and on leaf injury', *Plant Physiol.* **88**, 218–223.

McCune, D. C.: 1971, 'Problems involved in devising air quality criteria for the effects of fluoride on vegetation', *Am. Ind. Hygiene Assoc. J.* **32**, 697–701.

Mehlhorn, H., Cottam, D. A., Lucas, P. W. and Wellburn, A. R.: 1987, 'Induction of ascorbate peroxidase and glutathione reductase activities by interactions of mixtures of air pollutants', *Free Rad. Res. Comm.* **3**, 193–197.

Mishra, R.: 1968, *Ecology Work Book*, Oxford and IBH Publishing Co., Calcutta, India.

Mooney, H. A. and Winner, W. E.: 1988, 'Carbon Gains, Allocation, and Growth as Affected by Atmospheric Pollutants', in S. Schutle Hostede, N. M. Darral, L. W. Blank and A. R. Wellburn (eds), *Air Pollution and Plant Metabolism*, Elsevier, London, pp. 273–287.

Narayan, D., Agrawal, M., Pandey, J. and Singh, J.: 1994, 'Changes in vegetation characteristics downwind of an aluminium factory in India', *Ann. Bot.* **73**, 557–565.

Norby, R. J., Gunderson, C. A., Wullschleger, S. D., O'Neill, E. G. and McGracken, M. K.: 1992, 'Productivity and compensatory responses of yellow – Poplar trees in elevated CO_2', *Nature* **357**, 322.

Oleksyn, J.: 1994, 'Effects of SO_2, HF and NO_2 on net photosynthetic and dark respiration rates of Scots pine needles of various ages', *Photosynthetica* **18**, 259–262.

Pandey, J., Agrawal, M., Khanam, N., Narayan, D. and Rao, D. N.: 1992, 'Air pollutant concentrations in Varanasi, India', *Atmos. Environ.* **26B**, 91–98.

Pandey, J. and Agrawal, M.: 1993, 'Protection of plants against air pollutants: Role of chemical protectants', *J. Environ. Manage.* **37**, 163–174.

Pandey, J. and Agrawal, M.: 1994a, 'Evaluation of air pollution phytotoxicity in a seasonally dry tropical urban environment using three woody perennials', *New Phytol.* **126**, 53–62.

Pandey, J. and Agrawal, M.: 1994b, 'Growth responses of tomato plants to low concentrations of sulphur dioxide and nitrogen dioxide', *Scientia Hort.* **58**, 67–76.

Pandey, J. and Pandey, U.: 1994, 'Evaluation of air pollution phytotoxicity in a seasonally dry tropical urban environment', *Environ. Monit. Assess.* **33**, 195–213.

Pandey, J. and Pandey, U.: 1996, 'Adaptational strategy of a tropical shrub, *Carissa carandas L.* to urban air pollution', *Environ. Monit. Assess.* **43**, 255–265.

Rossum, J. R. and Villaruz, P.: 1961, 'Suggested methods for turbidimetric determination of sulphate in water', *J. Am. Water Works Assoc.* **53**, 873.

Schmidt, W., Neubauer, C., Kolbowski, J., Schreiber, U. and Urbach, W.: 1990, 'Comparison of effects of air pollutants (SO_2, O_3, NO_2) on intact leaves by measurement of chlorophyll fluorescence and P_{700} absorbance changes', *Photosynthetic Res.* **25**, 214–248.

Sidhu, S. S.: 1980, 'Patterns of fluoride accumulation in boreal forest species under perennial exposure to emissions from a phosphorus plant', *Atmos. Pollut. Stud. Environ Sci.* **8**, 425–432.

Singh, S. K., Rao, D. N., Agrawal, M., Pandey, J. and Narayan, D.: 1991, 'Air pollution tolerance index of plants', *J. Environ. Manage.* **32**, 45–55.

Stevens, D. P., Mc Laughlin, M. J. and Alston, A. M.: 1998, 'Phytotoxicity of hydrogen fluoride and fluoroborate and their uptake from solution culture by *Lycopersicon esculentum* and *Avena sativa*', *Plant Soil* **200**, 175–184.

Treshow, M.: 1984, 'Diagnosis of Air Pollution Effects and Mimicking Symptoms' in M. Treshow, (ed.), *Air Pollution and Plant Life*, John Wiley & Sons, New York.

Varshney, R. K. and Varshney, C. K.: 1994, 'Effects of SO_2 on ascorbic acid in crop plant', *Environ. Pollut.* (Ser. A) **35**, 285–290.

Weinstein, L. H. and Alscher-Herman, R.: 1982, 'Physiological Responses of Plants to Fluorine', in M. H. Unsworth and D. P. Ormrod (eds), *Effects of Gaseous Pollutants in Agriculture and Horticulture*, Butterworths, London, pp. 139–167.

West, P. W. and Gaeke, G. C.: 1956, 'Fixation of SO_2 as sulfitomercurate (II) and subsequent colorimetric estimation', *Anal. Chem.* **28**, 1816–1819.

Wolfenden, J. and Mansfield, T. A.: 1991, 'Physiological disturbances in plants caused by air pollutants', *Proc. Royal Soc. Edinburgh* **97B**, 117–138.

Wright, I. J. and Westoby, M.: 1999, 'Differences in seedling growth behaviour among species: Trait correlations across species, and trait shifts along nutrient compared to rainfall gradients', *J. Ecol.* **87**, 85–97.