59215

0114

Rec 1/1/1977

GROWTH REDUCTION IN AMERICAN SYCAMORE (*PLANTANUS OCCIDENTALIS* L.) CAUSED BY Pb-Cd INTERACTION

ROGER W. CARLSON & F. A. BAZZAZ
Department of Botany and Institute of Environmental Studies, University of Illinois, Urbana, Illinois 61801, *USA*

ABSTRACT

Seedlings of American sycamore (Plantanus occidentalis *L.*) *were grown in Drummer silty clay loam soil treated with various concentrations of Pb, Cd, or Pb plus Cd. Plant growth and heavy metal content were measured at the end of* 90 *days. Heavy metal accumulation by plant parts increased with soil treatment levels but was much lower than values previously reported in the literature. Root growth, woody stem diameter increment, new stem growth and foliage growth were found to be synergistically affected by the Pb–Cd treatment. Whilst treatment with Pb or Cd alone caused a reduction in photosynthesis and transpiration, the addition of Cd to Pb-treated plants did not reduce rates of photosynthesis and transpiration below that observed for plants treated with Pb alone. A method is proposed to quantitate the concept of synergism.*

INTRODUCTION

Pb and Cd are two important environmental contaminants which arise from certain mining and manufacturing operations (Buchauer, 1973; Cox, 1974), as well as from the combustion of fossil fuels used in transportation and other energy conversion processes (Cannon & Bowles, 1962; Singer & Hanson, 1969; Chow, 1970; Daines *et al.*, 1970; Lagerwerff & Specht, 1970; Motto *et al.*, 1970; Page *et al.*, 1971; Smith, 1971; MacLean & Langille, 1973; Noller & Smythe, 1974). A wide variety of plants have been shown to be sensitive to contamination with Pb (Lagerwerff, 1971; Bazzaz *et al.*, 1974*a*, 1975; Huang *et al.*, 1974; Rolfe & Bazzaz, 1975) and Cd (Allaway, 1968; Lagerwerff, 1971; John *et al.*, 1972; Lagerwerff & Bierdsdorff, 1972; Page *et al.*, 1972; Haghiri, 1973; John, 1973; Turner, 1973; Bazzaz *et al.*, 1974*a*, *b*; Huang *et al.*, 1974; Carlson *et al.*, 1975).

Environ. Pollut. (12) (1977)—© Applied Science Publishers Ltd, England, 1977
Printed in Great Britain

9225

Pb and Cd are taken up by plants from soil and hydroponic media through th root system (Lagerwerff, 1971; Buchauer, 1973; Rolfe, 1973; Bazzaz *et al.*, 1974, Cutler & Rains, 1974; Carlson *et al.*, 1975; Rolfe & Bazzaz, 1975). In general, the studies demonstrate that Pb movement from the roots to shoots is much less tha that of Cd. The rate of metal accumulation in plants varies between speci (Schroeder & Balassa, 1963; Page *et al.*, 1972; Haghiri, 1973; John, 1973; Rolf 1973; Bazzaz *et al.*, 1974*c*; Carlson *et al.*, 1975; Rolfe & Bazzaz, 1975) and betwee different soils (John *et al.*, 1972; Miller *et al.*, 1974).

Pb uptake by several tree species has been studied by Rolfe (1973). Seedlin were grown in a mixture of either silt loam or sand and vermiculite. The catic exchange capacity of the soils varied from 9 to 21 meq/100 g and pH from 5·2 to 5· After 90 days the Pb was determined for leaves, stems and roots. While there was great deal of variation between the eight species examined in the amount tran located to shoots, all species accumulated significant amounts of Pb ranging fro 40 to 80 μg/g in leaves and 70 to 180 μg/g in stems at a soil treatment level 500 μg/g. Increasing the phosphorus level of the soil tenfold decreased lead uptal by approximately 50%.

Soil contamination with Cd and Zn from a Zn smelter has been found to be ve toxic to growth of red oak (*Quercus rubra* L.) seedlings (Buchauer, 1973). Tl foliage of plants grown in contaminated soil was severely stunted at leaf met contents of 4 to 7 μg/g Cd and 400–500 μg/g Zn. In contrast, foliage of plan grown in uncontaminated soil in an area of heavy aerial fallout from the Zn smelt exhibited no signs of toxicity, although the metal content of washed foliage was to 38 μg/g Cd and 2120 μg/g Zn. It appears that while aerial deposition m contribute to a very large foliage metal content, the effect on plant growth seems derive from soil contaminated with heavy metals.

Most other studies dealing with heavy metal contamination of tree species ha been concerned with measuring the amount of Pb and Cd accumulated by folia and stems of trees growing along roads and near mining and refining operatio (Smith, 1971, 1973; Noller & Smythe, 1974).

Rates of photosynthesis may be reduced by Pb and Cd as well as other hea metals. Short-term studies with agricultural species have shown an inhibitory effe of both Pb and Cd on photosynthesis for plants of which the roots were excised a the cut stems placed in solutions of heavy metals (Bazzaz *et al.*, 1974*a*, *b*, 197 For whole plants grown hydroponically with heavy metals added to the nutrie solution the rate of photosynthesis is depressed by Cd but not by Pb in short-ter experiments (Carlson *et al.*, 1975). Depressed leaf photosynthesis is highly correlat with the amount of Cd translocated to the foliage of sunflower (*Helianthus annu* L.) and maize (*Zea mays* L.). In the hydroponic studies Pb was not translocated leaves in significant amounts during a 1-week treatment period and photosynthe was not reduced below that of control plants. Thus plant roots seem to be effective barrier to the uptake of Pb under certain growth conditions. However, t

amount of Pb translocated to leaves of maize and soybean plants during a longer treatment period of 2–4 weeks was significant and caused substantial reduction in photosynthesis (Bazzaz *et al.*, 1974*c*) as well as several other metabolic processes (Huang *et al.*, 1974). Pb has also been found to reduce photosynthesis in seedlings of loblolly pine (*Pinus taeda* L.) and autumn olive (*Elaeagnus umbellata* Thunb.) grown for 7 weeks in a Pb-contaminated medium of 1 part soil, 1 part sand and 1 part peat moss (Rolfe & Bazzaz, 1975).

All these studies have dealt with single element effects. However, since Pb and Cd are both frequently found in high concentrations at the same location (Lagerwerff & Specht, 1970; Lagerwerff, 1971; Buchauer, 1973; Natusch *et al.*, 1974), it is necessary to determine the extent of any interaction that might exist between the two heavy metals as it affects plant growth. Furthermore, other environmental contaminants, *e.g.* ozone and sulphur dioxide, have been found to act synergistically in combined treatment (Menser & Heggestad, 1966; Dochinger & Heck, 1969; Dochinger *et al.*, 1970; MacDowall & Cole, 1971; Banfield, 1972; Costonis, 1973). The only examples of a synergistic interaction between heavy metals and plant growth are those published by Miller *et al.* (1974) and Hassett *et al.* (1976), who found root growth to be synergistically reduced by treatment with Pb and Cd.

In this study we examine the effect of Pb and Cd both separately and together on the growth and photosynthesis of American sycamore (*Plantanus occidentalis* L.) seedlings grown for 90 days in a rich agricultural soil. The species is a common urban tree in several areas of the eastern and midwestern United States.

METHODS

Dormant two- to three-year-old saplings of American sycamore were obtained from the Union Tree Nursery in Jonesboro, Illinois, selected for uniformity in size of root system and prepared for experimental use by trimming off terminal and lateral branches to leave a single stem approximately 30 cm long.

Soil was collected from the A-horizon of a Drummer silty clay loam on the University of Illinois experimental farms at Urbana. After being air-dried it was processed with a soil shredder-grinder to break up large clumps and then passed through a 0·96-cm mesh screen. A preweighed amount of heavy metal was added to 2·5-kg portions of a soil mixture containing 1 part 'Perlite' and 6 parts of soil by volume and placed in free-draining 3-litre plastic pots. The addition of heavy metal to soil was done for each pot separately to give treatment levels of 0, 50, 100, 250, 500 and 1000 μg/g Pb as $PbCl_2$, 0, 5, 10, 25, 50 and 100 μg/g Cd as $CdCl_2$ and a combined treatment of 50 + 5, 100 + 10, etc. for Pb + Cd, respectively. After metal addition the pots were wetted to saturation and allowed to air-dry for 6 cycles over the following 3 weeks. The sycamore saplings were transplanted into the pots on 18 July. Over the course of the experiment, glasshouse daytime air temperature

maxima varied from 25 to 35°C with nocturnal minima from 13 to 23°C. Relative humidity varied from 30 to 70% during the day and reached saturation every night except near the end of the 90-day growth period when it was necessary to heat the glasshouse to maintain an average 18°C nocturnal temperature.

Initial root weight of experimental plants was estimated by correlation of root weight to stem diameter of saplings not used in the experiment. At the end of 90 days biomass measurements (in gramme oven-dry weight) were made of roots, woody stems, green stems (stems formed after transplanting) and foliage. Root growth was calculated by subtracting the weight estimated at the beginning of the experiment from that measured at 90 days. Stem diameter was measured, with a vernier micrometer, both at the beginning and at the end of the experiment at a position marked on each stem at a height of ~15 cm above the soil surface.

Measurements of apparent CO_2 uptake (hereafter referred to as photosynthesis) and transpiration were begun at 90 days for all surviving seedlings. There was a great deal of variation in the rate of photosynthesis between leaves on the same plant. These rates were highly correlated with leaf age. Therefore the concept of leaf plastichron age (LPA) was used to identify the leaves to be measured on each plant (Larson & Isebrands, 1971). A series of preliminary measurements indicated that the rate of photosynthesis of a leaf with an LPA of 2 (leaf l $\geq$ 50 mm in length) could be reliably estimated by measuring either a leaf with an LPA of $2 \pm 0{\cdot}1$ or by measuring photosynthesis of the two leaves adjacent to LPA = 2 and linearly interpolating between them. This latter method was necessary when the sapling did not have a leaf at LPA = $2 \pm 0{\cdot}1$ at the time of measurement. Photosynthesis and transpiration were measured at 1500 $\mu e\ m^{-2}\ s^{-1}$ (400–700 nm, photosynthetically active radiation), 25°C air temperature, 58–63% relative humidity, $1{\cdot}5\ m\ s^{-1}$ wind speed and 310–320 $\mu l\ l^{-1}$ CO_2 concentration using the method described by Bazzaz & Boyer (1972) with minor modification. Pb and Cd content of plant parts was determined by the Heavy Metals Analytical Laboratory at the University of Illinois using standard atomic absorption methods.

RESULTS

Heavy metal uptake

The amount of Pb in foliage was greater at higher treatment levels for all plants treated with Pb (Fig. 1). This was true also for foliage Cd content of plants treated with Pb and Cd combined. However, for plants treated with Cd alone, foliage Cd content increased with treatment level of 50 μg Cd/g soil but did not increase further at the higher soil concentration. The effect of the combined treatment was to increase foliage metal content for both Pb and Cd over that observed for treatment with each heavy metal alone.

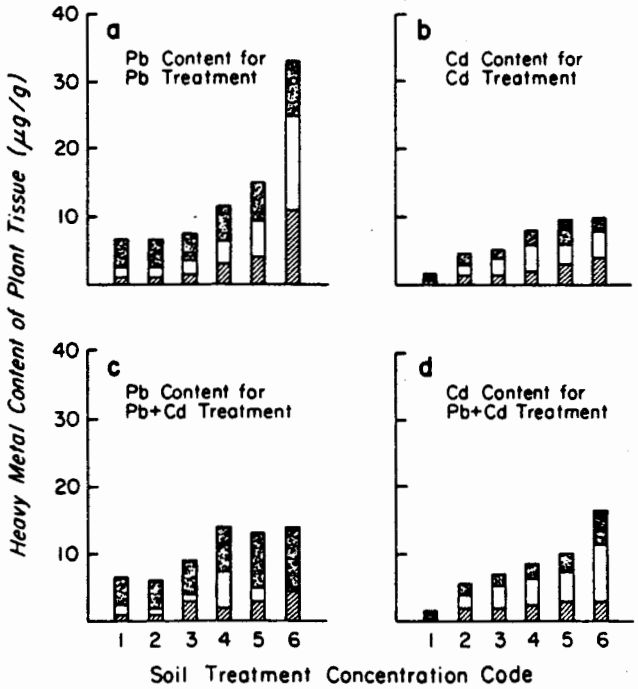

Fig. 1. Heavy metal content of sycamore plants grown in soil treated with various concentrations of Pb, Cd or Pb plus Cd. Soil treatment code 1–6 represents 0, 50, 100, 250, 500 and 1000 μg Pb/g soil respectively for Pb-treated plants (a); 0, 5, 10, 25, 50 and 100 μg Cd/g soil respectively for Cd-treated plants (b); and 0 – 0, 50 – 5, 100 – 10, 250 – 25, 500 – 50 and 1000 + 100 μg Pb + μg Cd/g soil respectively for plants treated with both Pb and Cd (c) and (d). Metal content expressed in units of μg/g of tissue for foliage (shaded), new stems (unshaded) and woody stems (hatched).

The amount of Pb in new stems increased with treatment concentration in plants treated with Pb alone. However, in plants treated with both Pb and Cd, new stem Pb content increased with soil concentration at low treatment levels but declined at higher levels. For plants treated with Cd alone, the Cd content of new stems increased to 4 μg/g at a treatment level of 25 μg Cd/g soil and did not change with higher treatment concentration. A similar trend was observed for the amount of Cd in new stems at the lower concentrations of the combined treatment. However, at the highest treatment level the amount of new stem Cd for the combined treatment was more than twice that of the plants treated with Cd alone.

The Pb content of woody stems was greater at high treatment levels for plants treated with Pb alone than for the combined treatment. Conversely, the relationship between Cd content of woody stems and treatment concentration of plants treated with Cd alone was similar to that of the combined treatment.

Plant growth

The average value for each growth parameter is presented in Table I for untreated control plants. Three of the 10 control plants transplanted at the beginning of the

TABLE I

MEAN ± SD OF EACH GROWTH PARAMETER FOR UNTREATED CONTROL PLANTS (NUMBER OF OBSERVATIONS = 7)

Root growth (g)	3·78 ± 0·63
Diameter increment (mm)	1·20 ± 0·45
New stem growth (g)	1·35 ± 0·47
Foliage biomass (g)	3·75 ± 1·15
Photosynthesis ($mgCO_2\ dm^{-2}\ h^{-1}$)	17·5 ± 0·90
Transpiration ($g\ H_2O\ dm^{-2}\ h^{-1}$)	1·48 ± 0·13

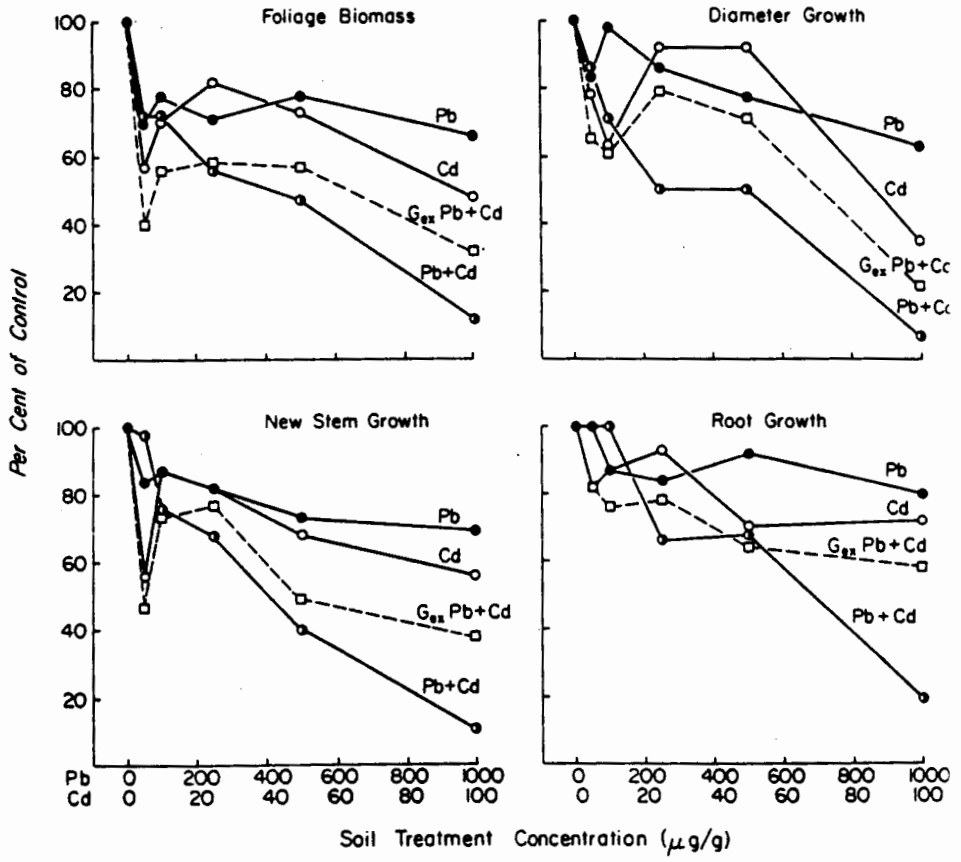

Fig. 2. Relationship between growth and soil concentration for sycamore plants treated with Pb alone (●), Cd alone (○) or Pb plus Cd combined (◑). Values of expected growth for the combined treatment (G_{ex} Pb + Cd) were calculated by multiplication of the reduction in growth due to separate heavy metal treatments and are indicated by the dashed line.

experiment died and were therefore excluded from the data analysis. Standard deviations varied from 17 to 38 % of the mean, indicating a large variability between individual plants. A high degree of variability was also present in the data for plants treated with heavy metals and has, to a certain extent, hampered data interpretation by obscuring some treatment effects.

To enable direct comparison between growth parameters, the growth datum for each observation was expressed as a per cent of the average value obtained for control plants. The data are summarised in Fig. 2, where each point represents the mean of 3 to 5 replications.

Inspection of Fig. 2 reveals a general pattern for all growth parameters in the relationship between treatment concentration and growth reduction. That is, treatment with either Pb or Cd alone caused a reduction in each growth parameter to

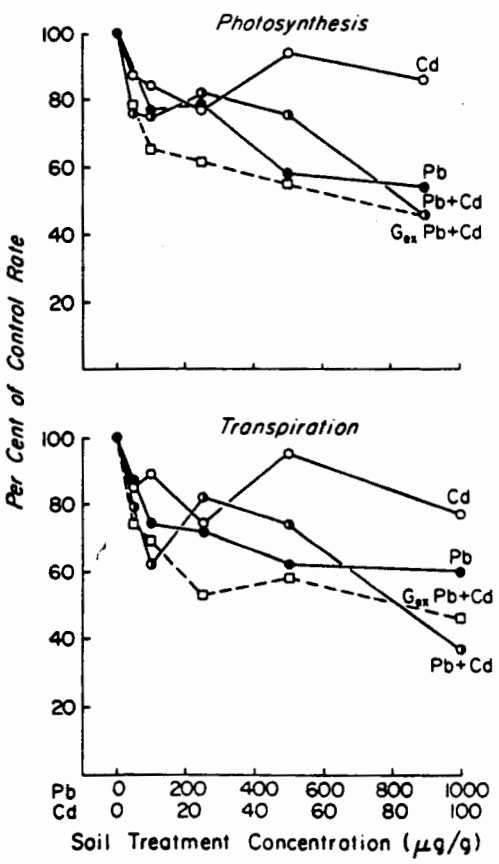

Fig. 3. Relationship between soil heavy metal concentration and gas exchange rates of leaves having a leaf plastichron age (LPA) of 2 (*see* text for discussion of LPA). Treatments are identified and G_{ex} Pb + Cd calculated as for Fig. 2.

between 35 and 80% at the highest treatment concentrations, whilst Pb combined with Cd at their respective single element treatment concentrations caused an additional reduction in growth to between 5 and 20% of the control value.

Photosynthesis and transpiration

The reduction in photosynthesis was greater at high treatment concentrations for both the plants treated with Pb alone and those which received the Pb–Cd combined treatment (Fig. 3). For plants treated with Cd alone, the rate of photosynthesis declined to approximately 80% at low treatment concentrations and increased again to ~90% at higher levels. Variation in the rate of transpiration was closely correlated with variation in the rate of photosynthesis.

DISCUSSION

The amount of Pb translocated to plant shoots in this experiment was much less than that observed in previous studies dealing with tree seedlings (Rolfe, 1973; Rolfe & Bazzaz, 1975). We believe this to be due primarily to the different soil types used in the experiments. The earlier study was carried out using silt loam and sandy soils which have a low sorption capacity for Pb, while, in this study, we used a silt clay loam soil with a high sorption capacity for Pb. Cation exchange capacity, phosphorus level and pH are all factors proportional to the Pb-sorption capacity of soils (Hassett, 1974, 1976; Miller *et al.*, 1974, 1975*a*, *b*) and hence inversely related to metal availability to plants. However, it is important to note that even though only small quantities of Pb and Cd were translocated into the shoots of the sycamore seedlings in this study, significant reduction did occur in all growth parameters.

In general, at the higher treatment concentrations each growth parameter was reduced more by the combined treatment than by either heavy metal treatment alone. To determine whether this increased reduction is more than that expected from the reduction caused by each contaminant alone, we calculated the effects in the following manner. The value of each growth parameter for each plant was first expressed as a fraction of the corresponding average value observed for untreated plants. For plants treated with one heavy metal growth was reduced to a specific fraction. This was considered the growth potential for plants exposed to that particular treatment. For the two metals considered together, a term called expected growth (G_{ex}) was calculated as the fractional growth caused by one metal reduced (*i.e.* multiplied) by the fractional growth caused by the second metal. Comparing the experimentally-determined effect of combined treatment with the calculated or expected effect of individual metal treatments then allows determination of the type of interaction between metals. Synergism was indicated if the experimentally-observed effect of combined treatment was greater than, antagonism if less than, and no interaction if equal to, the expected value.

The value of G_{ex} is plotted in Fig. 2 for each growth parameter. Diameter growth, foliage growth and new stem growth of sycamore seem to be synergistically affected by the combined Pb plus Cd treatment at Pb/Cd soil concentrations greater than 250/25. Root growth follows the same trend except for the 500/50 Pb/Cd treatment. A synergistic response of Pb and Cd has been observed by Miller *et al.* (1974) for maize root elongation at much lower soil treatment levels. However, in their study they used a sandy soil having a much lower binding capacity for Pb than the silty clay loam soil used in the present study.

The measured effect of the combined Pb plus Cd treatment on photosynthesis is either less than, or equal to, the expected effect calculated from the effect of each heavy metal alone (Fig. 3). However, photosynthesis of sycamore treated with Pb plus Cd combined is approximately equal at all soil concentrations to the rate of photosynthesis of plants treated with Pb alone. It thus appears that photosynthesis is reduced by Pb treatment to some lower level which is not reduced further by the addition of Cd to the soil. The addition of Cd to Pb-treated plants does, however, synergistically lower biomass accumulation in all plant parts. These results suggest that whilst separate treatments with Pb or Cd alone cause some reduction in both carbon dioxide uptake and growth, the synergistic action of the combined Pb/Cd treatment takes place in biochemical steps converting the assimilated CO_2 into dry matter.

In previous studies we have found a high degree of correlation between the rate of photosynthesis and leaf heavy metal content for both excised leaves (Bazzaz *et al.*, 1974*a*, 1975) and whole plants (Bazzaz *et al.*, 1974*c*, 1975; Carlson *et al.*, 1975). We have found that a linear relationship is adequate to describe this relationship for intact plants. In this study photosynthesis was related to leaf heavy metal content by the following expression:

$$Ps = 17{\cdot}4 - 1{\cdot}59X_1 - 0{\cdot}18X_2 \qquad r = 0{\cdot}806$$

where Ps is in units of mg CO_2 dm^{-2} h^{-1}, X_1 = leaf Pb content in $\mu g/g$ and X_2 = leaf Cd content in $\mu g/g$. Thus only small amounts of Pb or Cd in leaf tissue can result in large reductions in the rate of photosynthesis.

SUMMARY

We have examined the effects of Pb and Cd in individual as well as combined treatment on various aspects of sycamore growth and have found:

(1) That there is a low rate of heavy metal accumulation in shoots even at high treatment levels for silty clay loam soil.

(2) That there is a significant reduction in root growth, diameter increment of new stems, new stem growth, foliage growth and photosynthesis at higher heavy metal concentrations for all treatments.

(3) That a synergistic action of Pb and Cd exists on root growth, diameter growth, new stem growth and foliage growth.

ACKNOWLEDGEMENT

This study was financially supported by grant GI-31605 from NSF-RANN.

REFERENCES

ALLAWAY, W. H. (1968). Agronomic controls over environmental cycling of trace elements. *Adv. Agron.*, **20**, 235–74.

BANFIELD, W. M. (1972). Sulphur dioxide-ozone synergism on eastern white pine. *Phytopathology*, **42**, 493.

BAZZAZ, F. A. & BOYER, J. S. (1972). A compensating method for measuring carbon dioxide exchange, transpiration, and diffusive resistance of plants under controlled environmental conditions. *Ecology*, **53**, 343–9.

BAZZAZ, F. A., CARLSON, R. W. & ROLFE, G. L. (1974*a*). The effect of heavy metals on plants: Part I. Inhibition of gas exchange in sunflower by Pb, Cd, Ni and Tl. *Environ. Pollut.*, **7**, 241–6.

BAZZAZ, F. A., ROLFE, G. L. & CARLSON, R. W. (1974*b*). Effect of Cd on photosynthesis and transpiration of excised leaves of corn and sunflower. *Physiologia Pl.*, **32**, 373–6.

BAZZAZ, F. A., ROLFE, G. L. & WINDLE, P. (1974*c*). Differing sensitivity of corn and soybean photosynthesis and transpiration to lead contamination. *J. environ. Qual.*, **3**, 156–8.

BAZZAZ, F. A., CARLSON, R. W. & ROLFE, G. L. (1975). Inhibition of corn and sunflower photosynthesis by lead. *Physiologia Pl.*, **34**, 326–9.

BUCHAUER, M. J. (1973). Contamination of soil and vegetation near a zinc smelter by zinc, cadmium, copper and lead. *Environ. Sci. & Technol.*, **7**, 131–5.

CANNON, H. L. & BOWLES, J. M. (1962). Contamination of vegetation by tetraethyl lead. *Science, N.Y.*, **137**, 756.

CARLSON, R. W., BAZZAZ, F. A. & ROLFE, G. L. (1975). The effect of heavy metals on plants: Part II. Net photosynthesis and transpiration of whole corn and sunflower plants treated with Pb, Cd, Ni and Tl. *Environ. Res.*, **10**, 113–20.

CHOW, T. J. (1970). Lead accumulation in roadside soil and grass. *Nature, Lond.*, **225**, 295–6.

COSTONIS, A. C. (1973). Injury to eastern white pine by sulphur dioxide and ozone alone and in mixtures. *Eur. J. Forest Pathol.*, **3**, 50–5.

COX, D. B. (1974). Cadmium—a trace element of concern in mining and manufacturing. *J. environ. Hlth*, **36**, 361–3.

CUTLER, J. M. & RAINS, D. W. (1974). Characterization of cadmium uptake by plant tissue. *Pl. Physiol., Lancaster*, **54**, 67–71.

DAINES, R. H., MOTTO, H. & CHILKO, D. M. (1970). Atmospheric lead: Its relationship to traffic volume and proximity to highways. *Environ. Sci. & Technol.*, **4**, 318–22.

DOCHINGER, L. S. & HECK, W. W. (1969). An ozone-sulfur dioxide synergism produces symptoms of chlorotic dwarf of eastern white pine. *Phytopathology*, **59**, 399.

DOCHINGER, L. S., BENDER, F. W., FOX, F. L. & HECK, W. W. (1970). Chlorotic dwarf of eastern white pine caused by an ozone and sulphur dioxide interaction. *Nature, Lond.*, **225**, 476.

HAGHIRI, F. (1973). Cadmium uptake by plants. *J. environ. Qual.*, **2**, 93–6.

HASSETT, J. J. (1974). Capacity of selected soils to remove lead from aqueous solution. *Commun. Soil Sci. & Plant Anal.*, **5**, 499–505.

HASSETT, J. J. (1976). Determination of lead sorption capacities of selected Illinois soils using titration curves. *Commun. Soil Sci. & Plant Anal.*, **7**, 189–95.

HASSETT, J. J., MILLER, J. E. & KOEPPE, D. E. (1976). Interaction of lead and cadmium on corn root growth and uptake of lead and cadmium by roots. *Environ. Pollut.*, **11**, 297–302.

HUANG, C-Y., BAZZAZ, F. A. & VANDERHOEF, L. N. (1974). The inhibition of soybean metabolism by cadmium and lead. *Pl. Physiol., Lancaster*, **54**, 122–4.

JOHN, M. K. (1973). Cadmium uptake by eight food crops as influenced by various soil levels of cadmium. *Environ. Pollut.*, **4**, 7–15.

JOHN, M. K., VANLAERHOVEN, C. J. & CHUAH, H. H. (1972). Factors affecting plant uptake and phytotoxicity of cadmium added to soils. *Environ. Sci. & Technol.*, **6**, 1005–9.

LAGERWERFF, J. V. (1971). Uptake of cadmium, lead, and zinc by radish from soil and air. *Soil Sci.*, **111**, 129–33.

LAGERWERFF, J. V. & BIERDSDORF, G. T. (1972). Interaction of zinc with uptake of cadmium by radish. *Proc. Ann. Conf. Trace Subst. Environ. Health*, 5th, 515–22. University of Missouri, Columbia, Missouri.

LAGERWERFF, J. V. & SPECHT, A. W. (1970). Contamination of roadside soil and vegetation with cadmium, nickel, lead, and zinc. *Environ. Sci. & Technol.*, **7**, 583–6.

LARSON, P. R. & ISEBRANDS, J. G. (1971). The plastochron index as applied to developmental studies of cottonwood. *Can. J. Forest Res.*, **1**, 1–11.

MACDOWALL, F. D. H. & COLE, A. F. W. (1971). Threshold and synergistic damage to tobacco by ozone and sulfur dioxide. *Atmos. Environ.*, **5**, 553–9.

MACLEAN, K. S. & LANGILLE, W. M. (1973). Heavy metal studies of crops and soils in Nova Scotia. *Commun. Soil Sci. & Plant Anal.*, **4**, 495–505.

MENSER, H. A. & HEGGESTAD, H. E. (1966). Ozone and sulfur dioxide synergism: Injury to tobacco plant. *Science, N.Y.*, **153**, 424–5.

MILLER, J. E., HASSETT, J., KOEPPE, D. E., ROLFE, G. L. & WHEELER, G. L. (1974). Effects of soil properties on Pb uptake by corn and effects of Pb and Cd on corn. *Proc. Ann. NSF Trace Contaminants Conf., Asilomar, California*, 2nd.

MILLER, J. E., HASSETT, J. E. & KOEPPE, D. E. (1975*a*). The effect of soil properties and extractable lead levels on lead uptake by soybeans. *Commun. Soil Sci. & Plant Anal.*, **6**, 339–47.

MILLER, J. E., HASSETT, J. E. & KOEPPE, D. E. (1975*b*). The effect of soil lead sorption capacity on the uptake of lead by corn. *Commun. Soil Sci. & Plant Anal.*, **6**, 349–58.

MOTTO, H. L., DAINES, R. H., CHILKO, D. M. & MOTTO, C. K. (1970). Lead in soils and plants. Its relationship to traffic volume and proximity to highways. *Environ. Sci. & Technol.*, **4**, 231–7.

NATUSCH, D. F. S., WALLACE, J. R. & EVANS, C. A. (1974). Toxic trace elements: Preferential concentration in respirable particles. *Science, N.Y.*, **183**, 202–4.

NOLLER, B. N. & SMYTHE, L. E. (1974). Distribution of lead in vegetation bordering roads in the Sydney Metropolitan area. *Search*, **5**, 108–10.

PAGE, A. L., BINGHAM, F. T. & NELSON, C. (1972). Cadmium absorption and growth of various plant species as influenced by solution cadmium concentration. *J. environ. Qual.*, **1**, 288–91.

PAGE, A. L., GANJE, T. J. & JOSHI, M. S. (1971). Lead quantities in plants, soil, and air near some major highways in southern California. *Hilgardia*, **41**, 1–31.

ROLFE, G. L. (1973). Lead uptake by selected tree seedlings. *J. environ. Qual.*, **2**, 153–7.

ROLFE, G. L. & BAZZAZ, F. A. (1975). Effect of lead contamination on transpiration and photosynthesis of loblolly pine and autumn olive. *Forest Sci.*, **21**, 33–5.

SCHROEDER, H. A. & BALASSA, J. J. (1963). Cadmium: Uptake by vegetables from super phosphate in soil. *Science, N.Y.*, **140**, 819–20.

SINGER, M. J. & HANSON, L. (1969). Lead accumulation in soils near highways in the twin cities metropolitan area. *Proc. Soil Sci. Soc. Am.*, **33**, 152–3.

SMITH, W. H. (1971). Lead contamination of roadside white pine. *Forest Sci.*, **17**, 195–8.

SMITH, W. H. (1973). Metal contamination of urban woody plants. *Environ. Sci. & Technol.*, **7**, 631–6.

TURNER, M. A. (1973). Effect of cadmium treatment on cadmium and zinc uptake by selected vegetable species. *J. environ. Qual.*, **2**, 118–9.