J KAU: Eng. Sci., vol. 3, pp. 115-121 (1411 A.H./1991 A.D.)

A Conceptual Model of Plant and Gaseous Pollutant Interactions

GEOFF RICKS
Department of Landscape Architecture, School of Environmental Design, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia.

ABSTRACT This research paper provides a conceptual model of plant-pollutant interactions with respect to pollutant exposure dose, flux into the plant, and a manifestation of plant damage and injury. The research shows that the response from plants occupies a damage/injury continuum that varies between death at one extreme and recovery at the other.

1. Introduction

The causal link between gaseous air pollution and damage to vegetation is clear[16,24,30,37,41], although their interactions are far from simple. The response from the plant is complex, a function of pollutant exposure, flux into the plant, and the deleterious effects on plant tissues and physiological processes, alleviated by the capacity to counter pollutant action (Fig. 1).

2. Pollutant Exposure Dose

Exposure dose is the amount of pollutant a plant experiences. Traditionally defined in terms of ambient concentration and exposure period[12,39], the importance of successive exposure patterns, especially the magnitude and frequency of changes in concentration and the time interval between polluting episodes, is now recognised[23]: under natural circumstances pollution levels continually fluctuate in response to variations in emission rates and prevailing weather conditions[16]. Moreover, ambient air usually consists of a mixture of pollutants, and assessing the effects of such 'cocktails' is difficult[41,49], especially if results from uniform exposures produced during controlled experimental fumigations are extrapolated to uncontrolled field observations[1,16].

Recently, experimental exposure profiles that mimic simple patterns of ambient air quality have been developed[27,28], but until more representative profiles are gen-

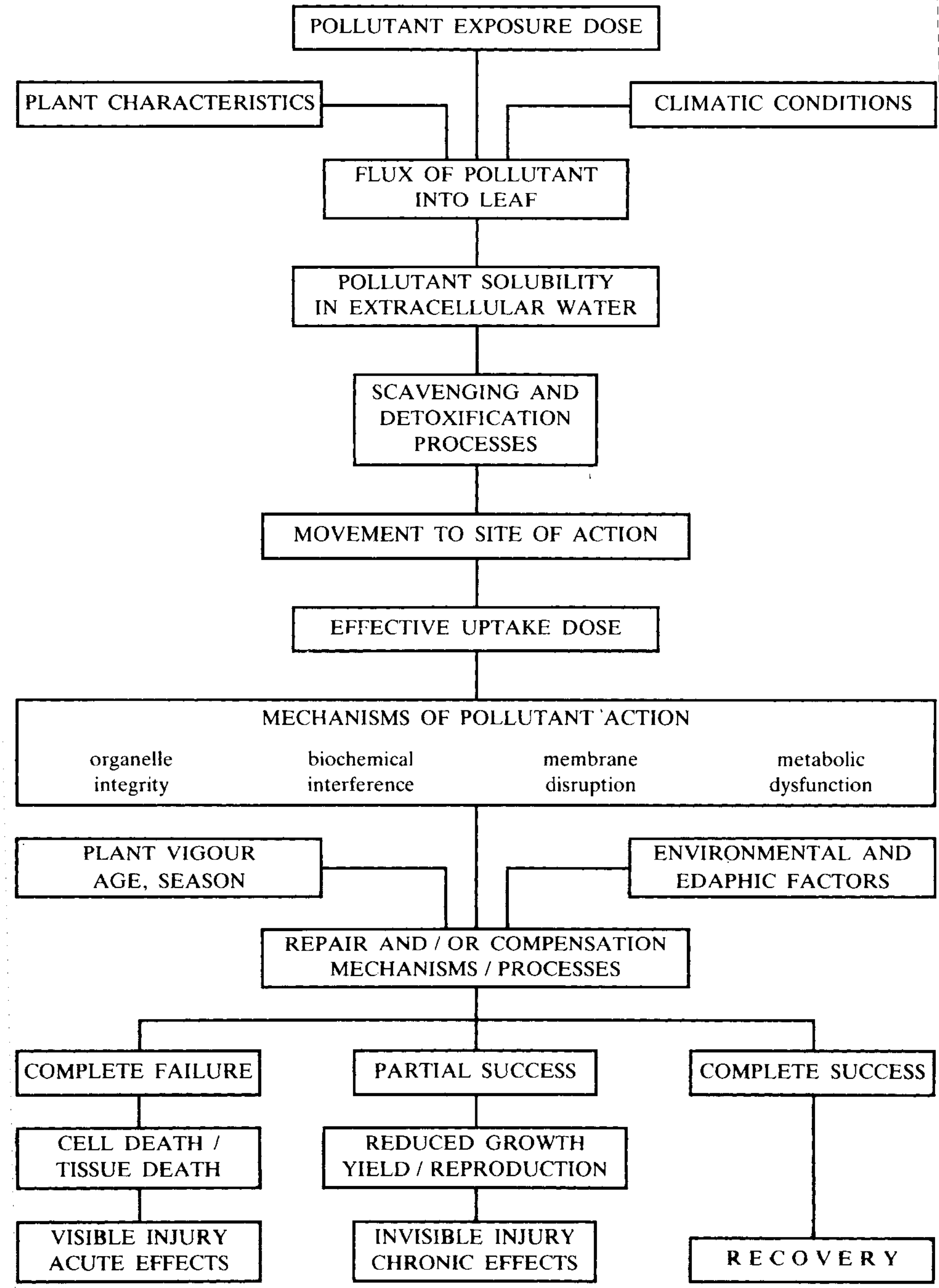

Fig. 1. Conceptual model of plant-pollutant interactions.

erated, the most successful fumigation studies[17-19] will continue to use out-door, open-top chambers[6,13,31,42]. These utilise ambient or filtered air, and facilitate controlled pollutant injection, whilst ensuring realistic micro-climatic conditions[47].

3. Flux into the Plant

Exposure dose and uptake dose (*i.e.*, the amount of pollutant entering the leaves) have often been considered synonomous[15], because particular exposures produced a characteristic plant response. However, examination of unexplained anomalies and apparent contradictions in relation to gas exchange into the leaf, suggests that uptake rates may vary to such an extent that exposure is not always a reliable measure of pollutant flux into the plant[8,33,45,49]. Within the free atmosphere, rapid transport of gases occurs through turbulent (eddy) diffusion, but across the leaf boundary layer and through the stomatal pore and substomatal cavity this changes to molecular diffusion[11,36], dependent upon the concentration gradient between the exterior and interior of the leaf and the diffusion resistances along this pathway. Boundary layer resistance, determined by leaf dimension and windspeed[35], does not vary a great deal in comparison with stomatal resistance, which alters dramatically as the pore opens or closes in response to endogenous metabolic processes[40], leaf water potential[7,34], external environmental factors, including light levels[25,40], and some pollutants[46]. Stomatal resistance has a major influence on pollutant flux into the leaf.

After gases reach the substomatal cavity, they dissolve in the water coating the extracellular surfaces of the peripheral mesophyll cells[26]. Further progress occurs by bulk flow over the exterior of the leaf cells until the pollutant penetrates the cell membranes and cytosol and reaches the cytological and biochemcal targets it normally affects[22].

Thus the flux of pollutant to the leaf surface, its uptake, and the proportion entering the cells may be quite different; what is more, none may reflect the ambient concentration around the plant.

4. Manifestation of Plant Damage

Once a pollutant enters a cell, and disrupts normal cellular ultrastructure, it can interfere in biochemical pathways and processes causing gross cytological damage or major physiological distress[14,22]. However, the picture is complicated by the multiplicity of effects from different pollutants[7,16,22], and the varying response of species and individuals[5,20,43] through their homeostatic capacity to counteract the action of certain pollutants.

Hence, scavenging and detoxification mechanisms act on pollutants during their transport in the extracellular water, reducing amounts reaching the cells[26,44], and the plant's ability to neutralize intracellular pollutant action, through repair or compensation processes[29], decreases internal cellular damage. Repair processes restore a damaged part to its original state, allowing normal function to resume, whereas compensatory mechanisms ignore damaged material, and by additional measures redress the injury or dysfunction. Evidence from long-term experiments[9,21,38] suggests such restorative processes, active during periods of low pollutant exposure, significantly help plants tolerate subsequent higher levels with minimal disruption.

Other factors also modify response. Climatic conditions influence uptake by their effect upon exposure dose and gas exchange. Disease and soil quality are significant in determining plant health and vigour[32]: attack from pathogens or poor growing conditions weaken a plant, impairing its homeostatic ability. Susceptibility can alter with age, stage of development or season[12]: younger leaves appear less sensitive than older ones[16,34], and early damage to specialised organs, *e.g.*, cotyledons, growing points or flower initials, seriously affects further growth and productivity[4]. Evergreens may be particularly sensitive during winter periods, when their restorative capacity is reduced by low metabolic activity, whereas deciduous species are extremely resistant at this time because the absence of leaves prevents pollutant uptake[1].

Pollutant damage is conveniently divided into visible and invisible injury[12]. The former describes acute effects, obvious changes in the plant's appearance, usually to the leaves, where damage is greatest[16]. Invisible injury refers to chronic, more subtle, effects upon plant physiology and metabolism, not evident externally, even though there can be significant reductions in growth and productivity[1,2,3,10,30,41]. Visible injury can be regarded as the outward manifestation of an increase in invisible injury, for each represent the opposite end of a common spectrum, a continuum varying between death at one extreme and recovery at the other (Fig. 1).

Acknowledgement

This paper forms part of the work carried out under Research Contract 02-107, provided by the College of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia.

References

[1] **Bell, J.N.B.**, Sulphur dioxide and the growth of grasses, *in:* **Unsworth, D.P.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture,* London: Butterworths, pp. 225-246 (1982).

[2] **Bell, J.N.B.** and **Clough, W.S.**, Depression of yield of ryegrass exposed to sulphur dioxide, *Nature,* **241:** 47-49 (1973).

[3] **Bleasdale, J.K.A.**, Effects of coal smoke pollution gases on the growth of ryegrass (*Lolium perenne* L.), *Environmental Pollution,* **5:** 275-285 (1973).

[4] **Bonte, J.**, Effects of air pollutants on flowering and fruiting *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture,* London: Butterworths, pp. 207-224 (1982).

[5] **Bradshaw, A.D.**, Pollution and evolution, *in:* **Mansfield, T.A. (ed.)** *Effects of Air Pollutants on Plants,* Cambridge: Cambridge University Press, pp. 135-159 (1976).

[6] **Buckenham, A.H., Parry, M.A., Whittingham C.P.** and **Young, A.T.**, An improved open topped chamber for pollution studies on crop growth, *Environmental Pollution Series B,* **8:** 475-482 (1981).

[7] **Fitter, A.H.** and **Hay, R.K.M.**, *Environmental Physiology of Plants,* London: Acedemic Press (1981).

[8] **Fowler, D.** and **Cape, J.N.**, Air pollution in agriculture and horticulture, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture,* London: Butterworths, pp. 3-26 (1982).

[9] **Garsed, S.G., Mueller, P.W.** and **Rutter, A.J.**, An experimental design for studying the effects of fluctuating concentrations of sulphur dioxide on plants, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture*, London: Butterworths, pp. 455-457 (1982).

[10] **Godzik, S.** and **Krupa, S.V.**, Effects of sulphur dioxide on growth and yield of agricultural crops, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture*, London: Butterworths, pp. 247-266 (1982).

[11] **Grace, J.**, *Plant Response to Wind*. London: Academic Press (1977).

[12] **Guderian, R.**, *Air Pollution*. Berlin: Springer-Verlag (1977).

[13] **Heagle, A.S., Body, D.E.** and **Heck, W.W.**, An open top chamber to assess the impact of a pollutant on plants, *Journal of Environmental Quality*, **2:** 365-368 (1973).

[14] **Heath, R.L.**, Ozone, *in:* **Mudd, J.B.** and **Kozlowski, T.T. (ed.)** *Responses of Plants to Air Pollution*, New York: Academic Press, pp. 23-55 (1975).

[15] **Heck, W.W.**, Future directions in air pollution research, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture*, London: Butterworths, pp. 411-436 (1982).

[16] **Heck, W.W.** and **Brandt, C.S.**, Effects on vegetation: native, crops, forest, *in:* **Stern, A.C. (ed.)** *Air Pollution*, Volume II, *The Effects of Air Pollution*, 3rd ed., New York: Academic Press, pp. 157-229 (1977).

[17] **Heck, W.W., Taylor, O.C., Adams, R., Bingham, G., Miller, J., Preston, E.** and **Weinstein, L.**, Assessment of crop loss from ozone, *Journal of the Air Pollution Control Association*, **32:** 353-361 (1982).

[18] **Heck, W.W., Adams, R., Cure, W.W., Heagle, A.S., Heggestad, H.E., Kohut, R.J., Kress, L.W., Rawlngs, J.O.** and **Taylor, O.C.**, A reassessment of crop loss from ozone, *Environmental Science and Technology*, **17:** 572-581 (1983).

[19] **Heck, W.W., Cure, W.W., Rawlings, J.O., Zaragoza, L.J., Heagle, A.S., Heggestad, H.E., Kohut, R.J., Kress, L.W.** and **Temple, P.J.**, Assessing impacts of ozone on agricultural crops: II Crop yield functions and alternative exposure statistics, *Journal of the Air Pollution Control Association*, **34:** 810-817 (1984).

[20] **Heggestad, H.E.** and **Menser, H.A.**, Leaf spot sensitive strain Bel-W3, a biological indicator of the air polluttant ozone, *Phytopathology*, **52:** 735 (1962).

[21] **Hogsett, W.E., Tingey, D.T.** and **Holman, S.R.**, A programmable experimental control system for determination of the effects of exposure regimes on plant growth, *Atmospheric Environment*, **19:** 1135-1145 (1985).

[22] **Horsman, D.C.** and **Wellburn, A.R.**, Guide to the metabolic and biochemical effects of air pollutants on higher plants, *in:* **Mansfield, T.A.(ed.)** *Effects of Air Pollutants on Plants*, Cambridge: Cambridge University Press, pp. 185-199 (1976).

[23] **Jacobsen, J.S.**, Ozone and the growth and productivity of agricultural crops, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture*, London: Butterworths, pp. 293-304 (1982).

[24] **Jacobsen, J.S.** and **Hill, A.C.**, *Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas*, Pittsburg: Air Pollution Control Association, (1970).

[25] **Jarvis, P.G.** and **Mansfield, T.A.**, *Stomatal Physiology*. Cambridge: Cambridge University Press, (1981).

[26] **Law, R.M.** and **Mansfield, T.A.**, Oxides of nitrogen and the greenhouse atmosphere, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture*, London: Butterworths, pp. 93-112 (1982).

[27] **Lefohn, A.S.** and **Bendict, H.M.**, Development of a mathematical index that describes ozone concentration, frequency and duration, *Atmospheric Environment*, **16:** 2529-2532 (1982).

[28] **Lefohn, A.S., Hogsett, W.E.** and **Tingey, D.T.**, A method for developing ozone exposures that mimic ambient conditions in agricultural areas, *Atmospheric Environment*, **20:** 361-366 (1986).

[29] **Levitt, J.**, *Responses of Plants to Environmental Stress*, 2nd ed. New York: Academic Press, (1980).

[30] **McLaughlin, S.B.**, Effects of air pollution on forests, *Journal of the Air Pollution Control Association*, **35:** 512-534 (1985).

[31] **Mandl, R.H., Weinstein, R.H., McCune, D.C.** and **Keveny, M.**, A cylindrical open-top chamber for the exposure of plants to air pollutants in the field, *Journal of Environmental Quality*, **2:** 371-376 (1973).

[32] **Manion, P.D.**, *Tree Disease Concepts*, Englewood Cliffs: Prentice-Hall, (1981).

[33] **Mansfield, T.A.**, The role of stomata in determining the responses of plants to air pollutants, *in:* **Smith, A. (ed.)** *Commentries in Plant Science*, London: Pergamon, pp. 13-22 (1976).

[34] **Meidner, H.** and **Mansfield, T.A.**, *The Physiology of Stomata*, London: McGraw-Hill, (1968).

[35] **Monteith, J.L.**, Evaporation and environment, *Society for Experimental Biology Symposia*, **19:** 205-234 (1965).

[36] **Monteith, J.L.**, *Principles of Environmental Physics*, London: Arnold, (1973).

[37] **Mudd, J.B.** and **Kozlowski, T.T.**, *Responses of Plants to Air Pollution*, New York: Academic Press, (1975).

[38] **Musselman, R.C., Oshima, R.J.** and **Gallavan, R.R.**, Significance of pollutant concentration distribution in the response of 'red kidney' beans to ozone, *Journal of the American Society of Horticultural Science*, **108:** 347-351 (1983).

[39] **O'Gara, P.J.**, Sulphur dioxide and fume problems and their solutions, *Industrial Engineering and Chemistry*, **14:** 744 (1922).

[40] **Raschke, K.**, Stomatal action, *Annual Review of Plant Physiology*, **26:** 309-340 (1975).

[41] **Roberts, T.M.**, Effects of air pollution on agriculture and forestry, *Atmospheric Environment*, **18:** 629-652 (1984).

[42] **Roberts, T.M., Bell, R.M., Horsman, D.C.** and **Colvill, K.E.**, The use of open-top chambers to study the effects of air pollutants, in particular sulphur dioxide, on the growth of ryegrass, *Lolium perenne* L. Part I – Characteristics of modified open-top chambers used for both air filtration and SO_2 fumigation experiments, *Environmental Pollution Series A*, **31:** 9-33 (1983).

[43] **Roose, M.L., Bradshaw, A.D.** and **Roberts, T.M.**, Evolution of resistance to gaseous air pollutants, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture*, London: Butterworths, pp. 379-410 (1982).

[44] **Tingey, D.T.** and **Tylor, G.E.**, Variation in plant response to ozone; a conceptual model of phsiological events, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture*, London: Butterworths, pp. 113-138 (1982).

[45] **Unsworth, M H.**, Eposure to gaseous pollutants and uptake by plants, *in:* **Unsworth, M.H.** and **Ormrod, D.P. (ed.)** *Effects of Gaseous Air Pollution in Agriculture and Horticulture*, London: Butterworths, pp. 43-63 (1982).

[46] **Unsworth, M.H.** and **Black, V.J.**, Stomatal responses to pollutants, *in:* **Jarvis, P.G.** and **Mansfield, T.A. (ed.)** *Stomatal Physiology*, Cambridge: Cambridge University Press, pp. 187-203 (1981).

[47] **Unsworth, M.H.** and **Mansfield, T.A.**, Critical aspects in the chamber design for fumigation experiments on grasses, *Environmental Pollution Series A*, **23:** 165-177 (1980).

[48] **Unsworth, M.H., Biscoe, P.V.** and **Black, V.J.**, Analysis of gas exchange between plants and polluted atmospheres, *in:* **Mansfield, T.A. (ed.)** *Effects of Air Pollutants on Plants*, Cambridge: Cambridge University Press, pp. 5-16 (1976).

[49] **Williams, R.J.H.** and **Ricks, G.R.**, Effects of combinations of atmospheric pollutants upon vegetation, *in:* **Chadwick, M.J.** and **Goodman, G.T. (ed.)** *The Ecology of Resource Degradation and Renewal*, Oxford: Blackwell Scientific Publications, pp. 127-137 (1975).

نمـــوذج نـــظري للنبـــاتات وتفاعـــلاتها الغازيـــة

جيـــفري ريكس

قسم عمارة البيئة ، مدرسة تصاميم البيئة ، كلية الهندسة ، جامعة الملك عبد العزيز
جـــدة - المملكة العربية السعودية .

المستخلص . يقدم البحث نموذجا نظريا للتفاعلات الملوثة الغازية للنباتات ، من حيث مدى تعرض النباتات للتلوث وسرعة انتشار الملوثات داخل النبات ، ومن ثم الضرر العام لتلك العمليات . كما يتعرض البحث بالتحليل لرد فعل النباتات المتأثرة بالضرر والذي يتراوح مابين القضاء التام على النبات في الحالات القصوى من التلوث والشفاء في الحالات الأخرى .