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THE EFFECTS OF DUST ON VEGETATION—A REVIEW

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Abstract

An increase in quarrying, open-cast mining and road traffic suggest that dust deposition onto vegetation may be increasing. This review describes the physical and chemical characters of a range of dust types. The effects of dust on crops, grasslands, heathlands, trees and woodlands, arctic bryophyte and lichen communities are identified. Dust may affect photosynthesis, respiration, transpiration and allow the penetration of phytotoxic gaseous pollutants. Visible injury symptoms may occur and generally there is decreased productivity. Most of the plant communities are affected by dust deposition so that community structure is altered. Epiphytic lichen and Sphagnum *dominated communities are the most sensitive of those studied. However, there have been very few detailed studies on natural and semi-natural systems and some dust types are also very understudied. Recommendations for future research are made in order to overcome this deficiency.*

INTRODUCTION

Research on the effects of dust pollution on plant communities has never received the same level of attention as that given to phytotoxic pollutants such as SO_2, NO_2 and O_3. Results from research that has been undertaken, together with repeated observations of dust deposits on vegetation, suggest that the effects of dust may be important and are worthy of greater research attention.

Dusts consist of solid matter in a minute and fine state of subdivision so that the particles are small enough to be raised and carried by wind. They may originate from many sources. A large range of industrial processes can produce particulate emissions (Fennelly, 1975). Measures to control these have, however, improved dramatically, so that there is now relatively little dust lost from closed processing plants in countries with strict pollution control. The main processes that regularly cause problems, however, are those concerned with mineral extraction. This ranges from the quarrying itself to the various processing operations (e.g. cement manufacture or coal processing). Dust suppression in these operations is more difficult and dust levels can be very high. Mineral extraction is increasing in many countries in order to meet increased construction demand (Harris, 1975; Stanton, 1989). Roads are a further common source of dust. Dusts may be produced from car exhausts, which are more controllable, and from the road surfaces. An increased reliance on road transport today is also evident. In this context, it is increasingly important that we understand the potential impacts that dust deposition may have on vegetation.

This paper provides a comprehensive review of the literature on the effects of dust on plants and their communities. Initially the characteristics of various dust types are described, highlighting those factors that are important in determining the likely impact its deposition may have. The effects of dust are considered according to vegetation type. This is followed by a discussion of the effects of dusts on crop species and on a range of natural and semi-natural vegetation types. Finally, this review concludes with a discussion of recommendations for future research.

CHARACTERISTICS OF DUSTS

A number of characteristics of dust are important in considering its impacts. Dust can have both a physical and a chemical impact. Dust falling onto plants may physically smother the leaves. Thus the absolute level of deposition is important. This is affected by dust emission rates, meteorology and conditions on the leaf surface. Dust can also physically block stomata. Krajickova & Mejstrik (1984) noted that the stomatal diameter was 8–12 μm for a range of crops. Thus particle size is important if dust is to act in this way on stomatal functions. Dusts of diverse origin have very different chemistries. The chemical effect of dust, either on soil or directly on the plant surface, may be more important than any physical effects. Thus before describing effects of dusts themselves it is necessary to consider how these characters vary.

Dusts are of a wide variety of sizes (Fennelly, 1975). Darley (1966) found that cement kiln dust was almost all (80–90%) less than 30 μm in diameter. In contrast, Fairweather *et al.* (1965) found that only dust greater than 30 μm diameter was deposited to urban dust collectors. Particulates from motor vehicles can range from 0·01–5000 μm diameter (Ninomiya *et al.*, 1971), though most urban road dust is in the range of 3–100 μm diameter and that from motor vehicle

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exhausts is 3–30 μm diameter (Thompson *et al.*, 1984). For unpaved roads, Everett (1980) found that there was a rapid decline in particle size in the first 8 m from the road causing a loss of particles greater than 50 μm diameter. At 30 m a further decline took place, this time in particles greater than 20 μm. Similarly Tamm & Troedsson (1955) found that beyond 20 m from an unpaved road only fine silts seemed to be deposited. Fly ash dust from power stations ranges from 1–2000 μm diameter, but is mostly evenly distributed in the 1–400 μm diameter range (Krajickova & Mejstrik, 1984). Coal dust itself, however, varies from 3–100 μm diameter (Rao, 1971). Milford & Davidson (1985) noted that many metals occur as small particulates and may form an important part of the smaller fractions of dust particles. Thus, Ninomiya *et al.* (1971) found that particles less than 0·1 μm diameter made up 40% of the mass of emissions from cars run on leaded fuel, but only 10% from unleaded fuel and that there was a 77% overall reduction in particulates from cars run on unleaded fuel.

Levels of deposition vary greatly. For limestone quarries and cement factories, field rates that cause effects are described later. However, it is worth considering deposition from roads in more detail here. Unpaved roads produce higher dust levels than paved roads. Roberts *et al.* (1975) found that an unpaved dry gravel road with an average daily traffic (ADT) of 250 cars produced mean air concentrations of 584 $\mu g\ m^{-3}$, while a paved road with an ADT of 18 000 produced mean concentrations of 463 $\mu g\ m^{-3}$. Everett (1980) undertook a detailed study of an unpaved road in Alaska and found that in the summer about 10 $g\ m^{-2}\ day^{-1}$ was deposited at the roadside and that there was a logarithmic decline in deposition away from the road, with deposition still occurring 1 km away.

A number of factors determine rates of dust deposition. Many of these are similar to those governing deposition of other pollutants. Belot *et al.* (1976) have modelled particulate deposition and show that an increase in surface roughness causes a significant increase in deposition rates. This confirms earlier experimental observations of Chamberlain (1967) who found that this effect was particularly important at high wind speeds and for particles greater than 10 μm diameter, much of it caused by impaction at the higher wind speeds. Chamberlain (1967) also found that wet surfaces cause increased deposition. Thus while rain may partially wash leaves clean of deposited dust, the resulting wet surfaces may then experience higher deposition rates.

The chemistry of dusts is varied. Some dusts are relatively inert in their chemical effects, e.g. those from hard acidic rock quarries. However, limestone quarry dust, cement dust and that from many roads (e.g. Everett, 1980) is highly alkaline. Darley (1966) described solutions of cement kiln dust having a pH of 12·0 and analysis showed that it contained a number of metals and bisulphate, all of which could have a direct toxic effect themselves. A number of mineral elements can be supplied in lime and cement dust. Cawse *et al.* (1989), for example, found that rainfall around a cement plant in south Wales was high in phosphorus and vanadium and had a high pH (>7·0). Occasionally cement production processes may ameliorate the situation, for example Arslan & Boybay (1990) found that solutions of dust from a cement factory in Turkey produced a pH of only 6·5–8·6 and that this may have been due to partial neutralisation by high SO_2 emissions also produced at the plant. Road dust may also contain significant concentrations of metals (Santelmann & Gorham, 1988), while many unpaved roads produce alkaline dusts, which have high calcium levels. The elements in road dust are concentrated in the smaller particles, so that Everett (1980) found that the decline in elemental deposition (excluding calcium) away from a road was not, therefore, as rapid as the decline in the mass of particulate matter. Coal also contains toxic substances, such as fluoride and sulphur compounds. These may be important in affecting vegetation if deposited as dust (Rao, 1971), but this has not yet been determined.

DUST DEPOSITION ONTO VEGETATION

Effects on commercial crop species

Some of the earliest experimental work on commercial crops was done using chemically inert dusts such as silica gel. It was realised that dusts, such as fertilizer or lime, could produce a number of plant responses due to the dust chemistry and that these could be overcome by using chemically inactive dust types. Duggar & Cooley (1914) compared charcoal, calcium carbonate and inert aluminium hydroxide dusts on *Lycopersicon esculentum* and found that all increased transpiration, but that the charcoal reduced growth and the other dusts increased it. Beasley (1942) applied fine inert dusts to *Coleus*. An increased water loss was noticed at night if the dust was applied to the lower leaf surface, with applications of smaller dust particles having the most effect. Eveling (1969) studied excised leaves of *Phaseolus, Coleus* and *Zebrina*. Inert dust applications not only increased water loss, but allowed greater penetration of applications of ammonia. Permeability of the leaves to ammonia was found to increase with increasing concentrations of the dust and with decreasing particle size. The effect lasted up to four weeks after application.

Table 1 presents details of work on crop species with dusts of different types. It can be seen that almost all studies have been with lime/cement dust. These have covered a wide variety of crops, including both temperate and tropical species. The only reports demonstrating no effect of cement kiln dust have been those of Scheffer *et al.* (1961) and Pajenkamp (1961), who were both reporting the same experimental work. This was an extensive study of four crops over two growing seasons, but Czaja (1962) was very critical about the conditions of the study. Table 1 reveals that even quite low application rates of cement dust have been shown to cause effects. These ranged from blocked stomata and leaf injury symptoms to an overall reduction in

Table 1. The effects of dust on different commercial herbaceous and fruit crops. Dust deposition (if studied) is either given as a rate (field determined or experimentally applied) or as a level of deposition covering the leaves

Reference	Crop	Dust type/ source	Deposition rate ($g\ m^{-2}\ d^{-1}$) or level ($mg\ cm^{-2}$)	Effect
Pierce (1909)	*Vitis vinifera*	Cement factory	—	Blocked stomata.
Duggar & Cooley (1914)	*Lycopersicon esculentum*	Charcoal	—	Increased transpiration, reduced fresh weight
		$CaCO_3$ or Inert $Al(OH)_3$	—	Increased transpiration increased fresh weight.
Anderson (1914)	*Rubus idaeus*	Cement factory	—	Inhibition of pollen germination.
Scheffer *et al.* (1961) and Pajenkamp (1961)	*Avena sativa*, *Trifolium repens*, *Beta vulgaris* & *Lolium temulentum*	Cement kiln	Rate = 0·7–1·5	No effects.
Czaja (1961)	*Beta vulgaris*	Cement factory	—	Cell plasmolysis, death, no starch production.
		Limestone factory	—	Some cell plasmolysis, starch still formed.
Darley (1966)	*Phaseolus vulgaris*	Cement kiln	Rate = 0·6	Reduced photosynthesis and increased leaf necrosis
Singh & Rao (1968)	*Triticum aestivum*	Cement	Rate = 7·0	Reduced vegetative and reproductive growth, reduced tissue N, Ca increased P.
Singh & Rao (1981)	*Triticum aestivum*	Cement	Rate = 7·0	Reduced transpiration and growth.
Sree Ramgasamy & Jambulingan (1973)	*Zea mays*	Cement factory	Level = 0·2–1·2	Reduced seed set.
Parsatharathy *et al.* (1975)	*Zea mays*	Cement factory	Rate = 0·2–10·9 Level = 0·2–8·4	Reduced vegetative and reproductive growth.
Taylor *et al.* (1986)	*Beta vulgaris*,	Cement kiln	—	Increase in leaf spotting fungus.
	Medicago sativa	Cement kiln	—	Increased aphid numbers.
Oblisami *et al.* (1978)	*Gossypium hirsutum*	Cement factory	Rate = 0·4	Blocked stomata, increased chlorophyll and tissue cation levels, reduced tissue starch, vegetative and reproductive growth.
Borka (1980)	*Helianthus annus*	Cement kiln	Rate = 0·5, 1·0	Reduced growth, photosynthesis and catalase activity.
Taylor *et al.* (1986)	*Avena sativa*, *Phaseolus vulgaris*	Cement kiln		Acute injury: Yellow leaf spots. Leaf rolling, interveinal necrosis, inhibition of leaf expansion.
	'Grasses'			Leaf curling.
Shukla *et al.* (1990)	*Brassica campestris*	Cement	Rate = 3·0, 5·0, 7·0	Reduced growth.
Hindy *et al.* (1990)	*Triticum aestivum*, *Zea mays*	Cement	—	No uptake of vanadium present in the dust.
Eveling (1969)	*Pisum sativum*	Inert dust		Increased water loss.
Krajickova & Mejstrik (1984)	*Pisum sativum*, *Zea mays*, *Hordeum distichon*	Fly-ash		Decreased diffusive resistance.

vegetative growth and reproductive structures. Czaja (1961) provided extensive detail of injury to *Beta vulgaris*. The surface pH of the leaves was greatly enhanced (up to pH 10·0). The leaf cells started to plasmolyse 1 week after application of cement dust, with an irregular distribution of chloroplasts and starch no longer being formed. This eventually led to cell death. Czaja (1961) found that application of powered limestone produced much less severe results, with only slight plasmolysis and with starch continuing to be produced. Secondary effects of increased aphid pests and fungal infections were also reported following cement kiln dust treatment (Table 1).

The lowest rates of application of cement/lime observed to cause an effect were those of Darley (1966) and Borka (1980) with 0·6 and 0·5 g m^{-2} d^{-1}, respectively. Lower rates have been reported in the field, but these have occurred only during part of the study period and have been exceeded by high rates during other periods. Apart from early work on inert dusts, the only other study of non-cement/lime dust has been that of Krajickova & Mejstrik (1984) on fly-ash and its effect on stomatal diffusive resistance. There is obviously a need for work on a range of dust types and their effects on crops.

Dust effects on plants may occur via changes in soil chemistry. Indeed, Scheffer *et al.* (1961) considered that this may be most important for long term effects on crops. Liming can have a number of effects on soils (Brady, 1974). Mild liming causes an increase in pH. For example Singh & Rao found the application of cement dust caused soil pH in their open top chambers to rise from 7·3 to 7·8. Liming also causes increased availability of phosphates, calcium and magnesium (Brady, 1974). There is an increase in base saturation and the solubility of iron, aluminium and manganese declines. Potassium may either increase or decrease in availability depending on conditions. Over-liming may lead to deficiencies in iron, manganese, copper and zinc. Phosphate may decrease due to the formation of calcium complexes and its actual uptake by plants may itself be directly affected. Boron uptake and utilization may also be reduced.

Grasslands and heathlands

The earliest reference to dust effects on a natural community are those of Parish (1910) concerning cement dust deposition onto shrub and grassland vegetation in California. On slopes facing the cement factories there were almost pure stands of *Artemisia californica*, with species such as *Encelia farinosa*, *Salvia apiana* and *S. mellifera* having declined or become extinct. The leaves of *A. californica* are narrow and although dusty, did not allow the production of hard surface scales which occurred on the other species. These leaves still become yellow, but generally the species remained resistant.

The most extreme effects of dust on grassland were those found by Krippelova (1982) around a magnesite factory in Czechoslovakia. Here deposition was so great that surface crusts were often formed on the ground and the soil pH was raised to 9·5. Species that usually occur in this region, such as *Lolium perenne*, *Polygonum aviculare* and *Poa annua*, were replaced by *Puccinellia distans*, *Chenopodium glaucum* and *Agropyron repens*. The community here seemed to be responding to the very high ionic levels in the soil as the tolerant species were basically halophiles rather than strictly calcicoles.

Lower rates of deposition also cause changes to grasslands, although the effects are more subtle. Grime (1970) noted changes in acidic grassland at Grange Hill, Derbyshire due to lime quarry dust. The upper soil horizon was found to be less acidic than lower horizons and calcicolous species were more abundant. The invertebrate fauna had also altered, with the occurrence in the dusted grassland of the snail *Cepaea nemoralis*, a species usually restricted to calcareous grassland.

Limestone dust can also have an effect on limestone heath communities. Etherington (1977; 1978) studied Old Castle Down heath in south Wales, subject to limestone quarry dust, and two control heathlands in Somerset. He found that at the control sites the upper soil horizons were leached, allowing the growth of a number of calcifuge plants. At Old Castle Down, however, the dust caused a high pH in the upper soil and there has been a general decline in *Ericaceous species*. Both *Erica tetralix* and *E. cinerea* were also found to exhibit chlorosis typical of that induced by liming. As there had been no significant recent management changes at the site, the vegetational changes were considered to be due directly to the dust deposition.

Topley Pike is a Derbyshire heathland that has been affected by limestone dust deposition (A. C. Warne, unpublished data). The unpolluted heaths have a soil pH of 3–4 and a number of acidophilous species as dominants, including *Calluna vulgaris*, *Vacinium myrtillus* and *Galium saxatile*. The dust-affected areas have a soil pH of 1·5 units higher and are characterised by calcareous species such as *Primula veris*. Tree species, such as *Corylus avelana*, may also have died as the result of the dust. The consequences of this change in the vegetation has been an alteration in the invertebrate communities. The leaf beetles that feed on *G. saxatile*, *Timarcha goettingensis* and *Sermylassa halensis* have declined in abundance. Even species common on calcareous grassland, such as *Cepaea* spp. and *Arianta arbustorum*, have declined due to their food plants being very heavily dusted. As a result of the decline in these herbivores, four insect predators, including *Lampyris noctiluca*, were also of low abundance in the region receiving dust.

In southern India, Sree Rangaswami *et al.* (1973) studied the distribution of species around a cement works. Of the 54 species that they found, only nine were able to grow close to the factory. These species all possessed small leaves, which was considered to enable them to reduce their dust loading. The data were not, however, statistically analysed.

Little work has been done on the effects of other dust types. Fly-ash dust from a coal-fired power plant was found to affect *Calamagrostis epigeios* and *Hypericum perforatum* when studied in the field (Krajickova & Mejstrik, 1984). While examination showed that the stomata were rarely blocked, diffusive resistance was increased. It was thus suggested that the dust may act directly on the guard cells, though the mechanisms for this are uncertain.

Trees and woodlands

A wide variety of tree species have been studied in their response to dust and these are listed in Table 2. The earliest work comes from the study of fruit trees in California. Like much subsequent work, the dust studied was from cement works. This dust may cause physical injury to tree leaves and bark, reduced fruit setting and a general reduction in growth. Anderson (1914) found that dusting of stigmatic surfaces completely suppressed fruit production and that dust solutions inhibited pollen germination. Similarly, Rao (1971) found that coal dust prevented pollen germination on stigmatic surfaces, thus reducing fruit set. Czaja (1962) describes in detail the injuries to a range of tree species from cement-kiln dust. The dust forms a hard crystalline crust on the leaf surface, which dissolves releasing solutions of calcium hydroxide into the intercellular spaces. This causes cell plasmolysis and death. Finally, heavy cement/lime dust deposition can lead to growth reduction for many tree species (Bohne, 1963; Brandt & Rhoades, 1973).

The effects of urban road dust have also been extensively investigated (Table 2). The responses studied have been limited to a reduction in photosynthesis and diffusive resistance and an increase in leaf temperature, the latter two effects making the tree more likely to be susceptible to drought. This may be even further exacerbated by the report of Fluckiger *et al.* (1982) that dusted leaves allowed the greater penetration of road salt, which further increases water stress. It is interesting to note that the responses that have been studied to urban road dust have tended to be quite different to those studied for cement dust. The former have concentrated on physiological effects, while the latter have focused on physical injury and growth reduction. This obviously makes a comparison of the relative effects of the two dust types very difficult.

Trees and shrubs are very efficient at filtering road dust. Steubing & Klee (1970) compared *Rhododendron catawbiense* and *Pinus mugo* along roadsides in Frankfurt. *P. mugo* had a higher filtering effect with up to 0·18 mg cm^{-2} of dust on its leaf surface, while *R. catawbiense* retained a maximum of 0·03 mg cm^{-2}. The comparison of broadleaved and conifer species was extended to an experimental study of dust application to *Carprinus betulus* and *Picea abies*. Dust was deposited mostly to the upper branches of *C. betulus*, but to the lower and middle branches of *P. abies*. In contrast, however, Pyatt (1973) found that there was greater deposition onto the lower branches of three broadleaved species in a field examination. The ability of trees to trap dust efficiently has led to their use as screens to prevent dust transport over longer distances, or to protect particularly sensitive sites. Thus Egglesman (1981) recommended tree screens to protect sensitive peatlands. Rao (1971) also suggested that a tree fence of *Pithecolobium dulce*, a Mexican tree, may form a useful barrier against the transport of coal dust. Obviously, trees used for this purpose need to be particularly insensitive to the type of dust deposited.

The amount of dust that affects trees is much more difficult to ascertain than for crops. Only one study (Brandt & Rhoades, 1972) of cement/lime dust measured the deposition rate (Table 2). The rate was high in comparison to many crop studies, but, being a field study of one particular site, it is not possible to give a critical level of deposition that could start to cause the effects described. Many of the studies of other dust types do not give deposition rates. It is also not certain how important some of the physiological responses described are for the long-term health of the trees. In these studies, it is necessary to rely on the levels of dust on the leaf surface. Fluckiger *et al.* (1979) found that, while 1 mg cm^{-2} of dust was necessary to cause a decrease in stomatal diffusive resistance in *Populus tremula*, only 0·5 mg cm^{-2} was necessary to cause an increase in leaf temperature. Thompson *et al.* (1984) were only able to find effects on *Viburnum tinis* with deposition rates of 5 g m^{-2} d^{-1}. However, even the busiest motorway that they studied had dust levels of only 1·6 g m^{-2} on the leaves. This led these workers to doubt whether this species would be affected by urban road dust under real conditions. Finally, Rao (1971) found that coal dust reduced growth and reproduction in two fruit tree species, at rates varying from 0·03–6·3 gm^{-2} d^{-1}.

The only study of the effects of dust on the community structure of a natural woodland has been that of Brandt & Rhoades (1972), who studied limestone dust deposition in Virginia, USA. Comparisons were made between a polluted and control woodland. The basic age structure of the trees in the woodlands were similar, but the dominant trees were different and the total number of stems per ha was reduced from 11 305 to 7595 at the dusted site. At the control site, the dominants were *Quercus prinus*, *Q. rubra* and *Acer rubrum*. At the polluted site they included *Q. alba*, *Q. rubra* and *Liriodendron tulipifera*. The seedling and sapling strata of the polluted site also contained a high number of young individuals of these tolerant species. The limestone dust caused necrosis of the leaves and peeling bark for almost all the species present, except for *L. tulipifera*. The change in community structure at this site was entirely consistent with the growth responses of the species, with only *L. tulipifera* showing improved growth with the increased pollution.

Dust deposition has also been found to affect other species in woodlands. Manning (1971) found that leaves of *Vitis vinifera* were a much darker green when exposed to limestone dust, which was probably a direct response to the shading effect of the dust. The growth of *Hedera helix* on trees near the edge of quarries

Table 2. The effects of dust on different tree species. Dust deposition (if studied) is given as a rate (field determined or experimentally applied), level of deposition covering the leaves or concentration of particulates in the atmosphere

Reference	Tree species	Dust type/ source	Deposition rate ($g\ m^{-1}\ d^{-1}$), level ($g\ cm^{-2}$) or concentration ($\mu g\ m^{-3}$)	Effect
Pierce (1909)	'Fruit trees' & *Quercus lobata*	Cement factory	—	Blocked stomata.
Parish (1910) and Pierce (1910)	*Citrus authantium*, *C. limon*	Cement factory & road dust	—	Reduced fruit set, leaf growth, starch production and increased necrosis.
Anderson (1914)	*Prunus avium*, *Malus domestica*, *Pyrus communis*	Cement factory	—	Reduced fruit set.
Czaja (1961)	*Tilia cordata*, *Acer pseudoplatanus*, *Prunus spinosa*, *Corylus avellana*, *Rosa canina*, *Aesculus hippocastanum*, *Salix viminalis*, *Sambucus nigra*	Cement	—	Cell destruction, bark peeling, leaf necrosis.
Czaja (1962)	*Piceae abies*, *Pinus sylvestris*, *Taxus baccata*, *Rosa canina*	Cement	—	Cell destruction.
Bohne (1963)	*Quercus robur*, *Pinus sylvestris*, *Populus alba*	Cement factory Cement factory	—	Leaf injury. Leaf injury, reduced growth.
Manning (1971)	*Tsuga canadenis*	Limestone quarry	Rate = 14·2	Chlorotic needles.
Brant & Rhoades (1972, 1973)	*Acer rubrum*, *Quercus prinus*, *Q. rubra*, *Liriodendron tulipifera*	Limestone quarry Limestone quarry	Rate = 14·2 Rate = 14·2	Reduced growth. Increased growth.
Lal & Ambasht (1982)	*Psidium guayava*	Cement factory	Level = 1·8–47·5	Increased tissue Ca, K, Na and P.
Steinhubel & Halas (1967)	*Populus nigra* & *Prunus laurocerasus*	Building works	—	Increased leaf temperature.
Fluckiger *et al.* (1979)	*Populus tremula*	Inert silica gel	Level = 1·0	Reduced diffusive resistance.
Fluckiger *et al.* (1977)	*Populus tremula*, *Betula pendula*, *Alnus glutinosa*, *Fraxinus excelsior*	Urban road	—	Blocked stomata and reduced diffusive resistance.
Eller (1974, 1977) and Eller & Brunner (1975)	*Rhododendron catawbiense*	Urban road	—	Increased absorption of insolation.
Fluckiger *et al.* (1978)	*Populus tremula*, *Acer campestre*, *Betula pendula*, *Alnus glutinosus*, *Prunus avium*, *Quercus* spp.	Urban road	Level = 1·0–1·5 Conc = 500–1200	Increased leaf temperature.
Fluckiger *et al.* (1982)	*Fraxinus excelsior*	Urban road	—	Reduced diffusive resistance.
Braun & Fluckiger (1987)	*Abies alba*	Urban road	Conc = 25–100	Reduced growth, but compounded by Pb & NO_x.
Guggenheim *et al.* (1980)	*Fraxinus excelsior*	Urban road	—	Increased leaf temperature.

(continued)

Table 2—*contd.*

Reference	Tree species	Dust type/ source	Deposition rate ($g\ m^{-1}\ d^{-1}$), level ($g\ cm^{-2}$) or concentration ($\mu g\ m^{-3}$)	Effect
Thompson *et al.* (1984)	*Viburnum tinis*	Motor vehicle exhaust	level = >0·5	Reduced photosynthesis and diffusive resistance.
Rao (1971)	*Mangifera indica*, *Citrus limon*	Coal dust	Level = 4·5–30·0 Level = 1·5–12·0 Rate = 0·03–6·3	Reduced growth, fruit set and leaf lesions and partial defoliation.
Pyatt (1973)	*Daphne laureola*	Urban area	Level = 2·5–104·4	Blocked stomata.
Ricks & Williams (1974, 1975)	*Quercus petraea*	Smokeless fuel factory	Rate = 0·2–0·6	Blocked stomata and reduced night time diffusive resistence. Promotion of leaf senescence and chlorophyll *a* degradation and enhanced uptake of SO_2.
Havas & Huttunen (1972)	*Pinus sylvestris*	Fertilizer factory	—	Young trees increase growth, old trees decrease growth, leaf injury.

seems to be promoted (e.g. Purvis, 1989). Ivy is a common plant on the rock faces of quarries, so some of its invasion may relate to the close proximity of these trees to such populations. Excessive growth of ivy will adversely affect other epiphytes and so compound the dust effects described below for lichens.

Limestone dust has also been shown to affect the phylloplane flora of woodland species (Manning, 1971). *Sassafras albidium* and *Vitis vulpina* leaves from a dusty area had an increase in the number of fungi and bacteria on their surfaces. There was, however, no observed change in the types of bacteria or fungi found. It is possible that this may have led to the increase in the number of fungal spots seen on these leaves. In conditions of very heavy dusting, however, the phylloplane flora was found to be greatly reduced. The needles of *Tsuga canadensis*, in contrast, had increased fungal and decreased bacterial populations in dusty conditions.

Arctic communities and other bryophyte dominated ecosystems

The most damaging effects of road dust on any natural community have been found in high arctic systems. This partly reflects the fragility of the vegetation types here as well as the common occurrence of unsurfaced roads. One of the earliest studies was that of Tamm & Troedsson (1955), who were chiefly concerned with nutrient levels supplied in road dust in Sweden. Calcium, potassium, sodium and phosphorus were all found to be in higher concentrations close to a road. Previous studies of the terricolous and epiphytic bryophyte communities (Krusenstjerna, 1945) had suggested a nitrification due to the road dust in this area, although no chemical evidence for the effect could be detected by Tamm & Troedsson (1955). Bryophytes readily trap dust on their rough surfaces (Richardson, 1981) and studies of *Sphagnum* spp. in New Brunswick found a strong correlation between tissue aluminium, chromium, iron, lanthanum, nickel, scandium, samarium and vanadium and distance from a road (Santelmann & Gorham, 1988). Legerwerff & Specht (1970) also found roadside vegetation to be contaminated with cadmium, nickel, lead and zinc.

The most comprehensive studies of the effects of dust on a natural ecosystem have been those concerned with the gravel roads in the Alaskan Tundra. Different vegetation types in the tundra vary in their sensitivity to dust deposition. Tables 3 and 4 present summary lists of effects on different communities and of species sensitivity. The most sensitive systems of all are those dominated by *Sphagnum* spp. Spatt & Miller (1981) found that *Sphagnum lenense* near a road and subject to dust deposition had a decreased photosynthetic rate and chlorophyll *a* content. The species had declined beside the roadside, where deposition was 1·0–2·5 $g\ m^{-2}\ d^{-1}$. However, they could still detect effects of the dust at a distance from the road where the deposition rate was only 0·07 $g\ m^{-2}\ d^{-1}$. This work was further extended by Walker & Everett (1987) who found a decline in a range of acidophilous species, especially *Sphagnum*, close to the road. These were replaced by minerotrophic species, such as *Ceratodon purpureus*, *Bryum* spp. and *Polytrichum juniperinum*. *Sphagnum* was lost up to 20 m from the road and the tolerant mosses provided only partial cover. This resulted in an increase in thawing rates along the road sides. Some vascular plants were also adversely affected by the dust. These included *Cassiope tetragona*, *Ledum palustre* and *Vaccinium uliginosum*. The latter two species being considered tolerant by Everett (1980) (Table 4).

It is interesting that the effects of dust were lessened along stretches of the road that passed over limestone

Table 3. Effects of road dust on different northern Alaskan plant communities after two and ten years. Redrafted from Klinger *et al.* (1983)

Vegetation type	Time period (Yr)	Effect of road dust
Dry prostrate shrub tundra	2	Little or no effect
	10	Mosses and lichens will be smothered near road. Low herbs do less well than sedges and shrubs.
Moist graminoid tundra	2	Possible increase in herbs.
	10	Intolerant species decline or die near road (e.g. *Cassopie tertragona, Tomenthypnum nitens* and *Catascopium nigritum*). Tolerant species include *Dryas integrifolia, Drepanocladus* spp., *Salix* spp., *Campyllum stellatum* and *Carex* spp.
Wet graminoid tundra	2	Increase in algae and possibly in standing crop.
	10	Mosses including *Catascopium nigritum* die near road. Other mosses more tolerant.
Aquatic graminoid tundra	10	No effects except close to road where some aquatic mosses may be smothered.

Table 4. A summary list of the more tolerant and less tolerant taxa to dust fall from gravel roads in the Alaskan Tundra. From Everett (1980)

More tolerant taxa	Less tolerant taxa
Vascular plants	
Alnus viridis spp. *crispa*	*Cassiope tetragona*
Picea spp.	*Lycopodium annotinum*
Betula nana	
Salix planifolia spp. *pulchra*	
Rubus chamaemorus	
Eriophorum angustifolium	
E. vaginatum	
E. russeolum	
Ledum spp.	
Vaccinium ulginosum	
V. vitis-idaea	
Spiraea beauverdiana	
Braya pururascens	
Dryas integrifolia	
Mosses	
Polyrichaceae	*Sphagnum spp.*
Aulacomnium turgidum	*Hylocomium splendens*
A. palustre	*Pleurozium schreberi*
Bryum spp.	*Dicranum* spp.
Drepanocladus brevifolius	*Catascopium nigritum*
Scorpidium scorpioides	*Thuidium abietinella*
Camylium stellatum	*Rhytidium rugosum*
Racomitrium lanuginosum	*Cinclidium* spp.
	Meesia triquetra
	Tomenthypnum nitens
Lichens	
Cladonia pyxidata	*Cladina arbuscula*
C. gracilis	*C. alpestris*
Thamnolia subuliformis	*C. rangiferina*
Cetrarea cucullata	*Pelitgera aphthosa*
C. islandica	*Dactylina arctica*
C. nivalis	*Alectoria* spp. (on trees)
	Usnea spp. (on trees)

substrates, where the naturally occurring species were more tolerant of the increased calcium levels in the dust. The earlier thawing along the roadsides due to the loss of vegetation allowed the early growth and flowering of tolerant plants (such as *Eriophorum vaginatum*) and the congregation of large numbers of birds, caribou and a variety of predators. The long-term effects of the dust on the behavioural ecology of the species are uncertain.

Many other north temperate and boreal ecosystems are dominated by bryophytes. These may form an understory layer in forests, for example, or be the dominant vegetation of wetlands. Czaja (1966) found that cement dust caused cell plasmolysis in *Mnium punctatum*. This occurred rapidly and was used to assess the relative toxicity of different cement dust types. Kortesharju *et al.* (1990) studied the tissue element levels of the terricolous moss *Pleurozium schreberi* along a transect from a cement works on northern Finland. They found that calcium levels close to the factory could reach nearly 10% of the air dry weight and these levels continued to decline up to 16 km from the plant. Potassium levels showed a reverse trend, with lowest tissue concentrations closest to the factory. Bates & Farmer (1990) found that the experimental application of calcium in solution to *P. schreberi* could cause a decline in the growth of plants from calcareous sites and that these plants tended to have low intracellular potassium and magnesium levels in the field. It was suggested that excess calcium may occupy most of the cell wall exchange sites and prevent uptake of other essential nutrient cations. The data of Kortesharju *et al.* (1990) suggest that cement dust may have a similar effect.

There have been no studies directly concerned with dust deposition onto blanket bog. However, catchment liming to counter the effects of surface water acidification results in the application of limestone powder or pellets to upland vegetation. The effects of such treatments would be very similar to those produced from, for example, limestone dust from quarrying, although the treatments are usually of large infrequently repeated doses. The most comprehensive study of these effects was undertaken by Mackenzie *et al.* (1990). They found that liming killed *Sphagnum* spp., liverworts, lichens and some other moss species, although there was no visible damage to higher plants. Most macro-invertebrates were reduced in number, especially the soil-dwellers e.g. *Collembola* and mites. This emphasis of effects on soil-dwelling invertebrates contrasts with the observations described previously for heathlands.

Epiphytic and terricolous lichens

The most extensive evidence for the effects of dust on plant communities has come from studies on epiphytic lichens. The first comprehensive study was that of Gilbert (1976). He described the effects of limestone dust in Derbyshire, England. Just as epiphytic lichen communities form distinctive zones around sources of sulphur dioxide pollution, Gilbert found zones surrounding a lime dust source. Heavily dusted trees had few lichens, but this was followed by a zone containing lichens that are normally saxicolous together with species typical of hypertrophicated bark. These included *Caloplaca decipiens*, *Catillaria chalybeia*, *Lecanora calcarea*, *L. campestris*, *Lecidella scabra* and some species of *Bacidia* and *Micarea*. Eventually these species declined and were replaced by those typical of acidified bark in a moderately polluted environment, such as *Hypogymnia physodes* and *Parmelia saxatilis*. The dust was found to raise the bark pH of *Fraxinus excelsior* trees from 3·5 to 6·5. A strong positive correlation was found between the species diversity on the trees, bark pH and distance from the dust source. A similar effect was also observed in Northumberland and at Ullapool, Scotland, the latter observations being on saxicolous communities.

In southern Finland, Pihlstrom (1982, 1987) found eutrophication of the bark of *Pinus sylvetris*, with a rise in pH from 4·0 to 8·0, and the occurrence of the *Xanthorion* community where dust was deposited. Of 70 epiphyte species studied, only two algae (*Desmococcus* spp. and *Trentepohlia umbrina*) could be described as highly tolerant of the dust, with the most tolerant lichens being *Physcia tenella*, *P. adscendens*, *Xanthoria parietina*, *Caloplaca holocarpa*, *Lecanora hegenii* and *Hypogymnia physodes*. Cieslinski & Toborowicz (1980), Cieslinski *et al.* (1982) and Cieslinski & Jaworska (1986) have also studied the effects of alkaline dust on *P. sylvestris* epiphytes. Some species are negatively affected by the dust, but others, particularly photophilous species, such as *L. hagenii*, increase. Wittman & Turk (1988) have also shown a complete change in lichen communities with alkaline dust on conifers from the *Pseudovernietum furfuraceae* to the *Physcietum adscendentis*. Cement dust emissions were also found to be important for the epiphytes of *Pinus halepensis* in Algeria (van Haluwyn & Letrouit-Galinou, 1990), although the situation was also complicated by the presence of pollutants from brickworks, Similarly, Steubing *et al.* (1974) found that *H. physodes* had a reduced primary production in the city of Frankfurt, where there was an increase in dust covering of the thalli. However, the cause of this effect was difficult to identify as there were also higher SO_2 levels in the urban area. Terricolous bog lichen species are also adversely affected by the artificial application of lime (MacKenzie *et al.*, 1990). In a dry pine forest area of northern Finland, Kortesharju *et al.* (1990) found that cement dust caused the removal of a number of reindeer lichens (*Cladina* spp.) in a zone around the factory, although *Peltigera canina* was more tolerant as were a number of mosses.

Alkaline dust may increase local diversity in epiphytic floras in tropical regions. Gradstein (1992) concluded that basiphytic epiphytic vegetation is rarer in the tropics than in temperate regions. However, Pocs (1990) in Tanzania and Veneklaas (1990) in the Andes have found that alkaline dust from volcanic eruptions significantly altered bark chemistry, producing locally abundant basiphytic epiphyte floras.

Dust from fertilizer factories can also affect lichens. Kaupii (1980) showed that the application of fertilizer dust to *Hypogymnia physodes* and *Cladonia stellaris* caused a temporary increase in net photosynthesis and an increase in the number of algal cells in the thalli. However, Takala *et al.* (1978) found that fertilizer dust damaged *H. physodes* and *Parmelia sulcata*. Road dust was also found to kill lichens along a dirt road in Alaska (Walker & Everett, 1987). Sensitive terricolous species included *Cladina* spp., *Peltigera* spp., *Cetrarea* spp. and *Stereocaulon* spp. Epiphytes were also affected, with almost no lichens up to 35 m from the road. Affected lichens included *Alectoria* spp., *Usnea* spp., *Ramelina* spp., *Physcia* spp., *Cetraria pinastri* and *Parmelia* spp. Everett (1980) concluded that the most sensitive lichens in the Alaskan ecosystem were those that did not possess a protective outer cortex.

Lichens may either be affected directly by the deposited dust, or there may be an indirect effect via changes in bark chemistry. The diffuse growth form of many lichens is thought to be efficient at trapping dust particles and some epilithic species have been found to incorporate dust into the thalli as they grow (Garty & Delarea, 1987). Direct effects are likely to be most important for terricolous species, which normally receive most of their nutrient input directly from the atmosphere. Dust could either shade the lichens or adversely alter the chemistry of the cell wall exchange sites and so affect nutrient uptake as with the bryophytes discussed above.

Epiphytic lichens are likely to be mostly affected via changes in the bark. It is well known in studies of acidification that bark pH and calcium content are primary determinants of the lichen flora, due to the ability of the bark to alter the chemistry of tree stemflow (see Farmer *et al.*, 1991). Dust affects both bark pH and calcium content (Lotschert & Kohm, 1977). It is interesting that of the studies on epiphytes listed above only one (Gilbert, 1976) is not concerned with changes on coniferous trees. As these initially have a low bark pH (Barkman, 1958) the change in their chemistry caused by lime would be the most extreme. Broadleaved trees also have low pH bark in areas of high acidic pollutant deposition and would, therefore, also be likely to show considerable changes due to inputs of lime dust. Thus Grodzinska (1971) found a rise in pH for four broadleaved tree species affected by cement dust in southern Poland, where general bark acidification is widespread. This was also the case with Gilbert's (1976) study, in which concern was expressed for the conservation of lichen species in ancient woodlands that could be affected by dust. However, his data were derived from trees already acidified by SO_2. It was possible that the lime-dusted trees provided a refuge for species otherwise lost by the acidification. It is also likely that limestone dust in areas not subjected to other pollutants could have an adverse effect on lichen communities. However, in places receiving acidic pollution, such dust may actually have some conservation benefit. In fact Gilbert (1992) considers that urban trees impregnated with alkaline dust from demolition works, etc., may encourage lichen reinvasion as SO_2 levels fall, by providing suitable substrates for species such as *Lecanora muralis* and *Candelariella vitellina*.

It is evident that more studies have been undertaken on the effects of dust on lichens than on any other vegetation type. While it is obvious from Gilbert's (1976) study that different deposition rates cause different assemblages of lichen species, the only study to have actually measured the deposition rate affecting lichens under study has been that alongside the Alaskan haul road. This means that it is still not possible to predict impacts, even if deposition rates are known. Whilst measuring actual deposition to bark surfaces may be practically very difficult, it would at least be useful to have information on deposition rates to the ground surface.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The physiological responses of crops and trees outlined in this review reveal many different direct routes of action through which dust can affect plants. Dust may also exacerbate secondary stresses, such as drought, insects and pathogens, or allow penetration of toxic metals or phytotoxic gaseous pollutants. Effects of dust on natural communities may alter the competitive balance between species in a community. Substrate (soil or bark) chemistry may be altered, causing changes in the balance between calcicoles and calcifuges. These changes in the vegetation may also affect animal communities, from vertebrate grazers to soil invertebrates. This may, for example, alter cycles of decomposition. Responses of individual species may be negative or positive depending on the particular situation, and only detailed studies may reveal the main reason behind any observed changes. There have, unfortunately, been only a limited number of studies at the community level.

It is evident from this review of the literature that there are many gaps in our knowledge of the effects of dust. Dusts of different types act in different ways. It is not possible, therefore, to extrapolate findings from a study of the effects of limestone dust on heathlands, for instance, to the deposition of coal dust on a heathland. A recent survey was undertaken of regional staff of the Nature Conservancy Council (UK) for observations of dust deposition onto Sites of Special Scientific Interest (SSSIs) (Farmer, 1991). Results indicated that dust deposition occurred throughout the UK onto a wide range of vegetation types and from a wide range of sources. This also illustrated further gaps in our knowledge, e.g. the deposition of limestone dust onto lowland woodland and the effects of neutral/acidic dusts, e.g. coal, on almost any habitat. Drift from agricultural liming and fertilization, which may have a significant eutrophicating effect on nearby hedgerows and woodlands also needs to be investigated. Until research into these areas is undertaken, the ability of those with responsibility for crop protection, or preventing the deterioration of natural and semi-natural habitats, to address developments that may threaten sites will be inadequate. It is important, therefore, that current trends in dust emissions are identified as well as the vegetation types that are likely to be affected by such emissions.

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APPENDIX: ENGLISH NAMES OF CROP AND TREE SPECIES

Acer pseudoplatanus	Sycamore	*Picea abies*	Norway Spruce
Acer rubrum	Maple	*Pinus sylvestris*	Scots Pine
Aesculus hippocastanum	Horse Chestnut	*Pisum sativum*	Pea
Alnus glutinosa	Alder	*Populus alba*	Poplar
Avena sativa	Oats	*Populus nigra*	Black Poplar
Beta vulgaris	Sugar Beet	*Populus tremula*	Aspen
Betual pendula	Birch	*Prunus avium*	Cherry
Brassica campestris	Turnip	*Prunus laurocerasus*	Cherry-Laurel
Carpinus betulus	Hornbeam	*Prunus spinosa*	Blackthorn
Citrus aurantium	Orange	*Pyrus communis*	Pear
Citrus limon	Lemon	*Psidium guayava*	Guava
Corylus avellana	Hazel	*Quercus* spp.	Oak
Daphne laureola	Laurel	*Robinia pseudacacia*	Acacia
Fraxinus excelsior	Ash	*Rosa canina*	Dog Rose
Gossypium spp.	Cotton	*Salix viminalis*	Common Osier
Helianthus annus	Sunflower	*Sambucus nigra*	Elder
Hordeum distichon	Barley	*Tilia cordata*	Lime Tree
Liriodensron tulipifera	Tulip Tree	*Taxus baccata*	Yew
Lolium temulentum	Darnel	*Trifolium repens*	Clover
Lycopersicon esculentum	Tomato	*Triticum aestivum*	Wheat
Malus domestica	Apple	*Tsuga canadensis*	Hemlock
Mangifer indica	Mango	*Vitis vinifera*	Grape vine
Medicago sativa	Lucerne	*Zea mays*	Maize
Phaseolus vulgaris	Beans		