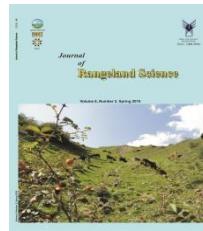Contents available at ISC and SID

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Review and Full Length Article:

Dust Particles and Aerosols: Impact on Biota "A Review" (Part II)

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Abstract. This is the second of series on the impact of dust. It focuses on the physical, chemical and physiological effects of dust particles and aerosols. Plants of all types and classes (from algae to forest trees and everything in between) are adversely affected either directly through abrasion by airborne particles or through interference with plant physiology or indirectly through the impact on soil as particles are deposited in the soil surface with effects on the soil chemistry, soil texture and soil structure. The literature that is reviewed spans decades and the biomes from which examples are drawn cover regions from the Arctic Circle to the equator, from deserts to tropical rainforests. The physiological responses of plants underlie and precede ecological changes at the community level and these changes have implications for such important relationships as predator-prey as shelter food supply and other essential ecosystem services either cease to be provided or are severely curtailed. It was found that all species have maximum dust deposition in the winter season followed by summer and rainy seasons. Chlorophyll content decreased and ascorbic acid content increased with the increase of dust deposition. There was significant negative and positive correlation between dust deposition and chlorophyll and ascorbic acid content, respectively.

Effects of dust particles and aerosols on plants

Deposition of dust on vegetation will be affect by the particle size distribution and the dimensions and density of foliage elements in the dispersion path (Bastan *et al.,* 2013; Mahowald *et al.,* 2014). The effect of size-segregated rather than chemically speciated particulate matter on ecosystem function is mediated by effects on vigour, competitive viability, and reproductive fitness of individual plants. Large-leaved species may provide effective dust barriers close to the source of coarse dusts (e.g. roads or quarries), but less effective barriers against finer dusts that travel greater distances. Dusts effects on vegetation may be connected with the decrease in light available for photosynthetic processes, an increase in leaf temperature due to changed surface optical properties, and interference with the diffusion of gases into and out of leaves (Farmer, 1993; Lokstein *et al.,* 1994; Naidoo & Chirkoot, 2004; Prajapati & Tripathi, 2008e; Prusty *et al.,* 2005; Santosh & Tripathi, 2008). It is clear that dust particle size has important and predictable effects on energy exchange properties of vegetation. Alkaline particulate matter may exert direct effects on leaf surfaces; however, the effects hardly ever reach the ecosystem level because it is difficult to identify a widespread threat to ecosystem function due to un-speciated particulate matter. A wide variety of tree species have been studied in their response to dust (Bohn, 1972; Brandt & Rhoades, 1972; Farmer, 1993; Vardaka *et al.,* 1995). Dust may cause physical injury to tree leaves and bark, reduced fruit setting and a general reduction in growth (Van Gardingen *et al*., 1991). Dusting of stigmatic surfaces completely suppressed fruit production because dust solutions inhibited pollen germination. 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 (Bohn, 1972; Brandt & Rhoades, 1973).

The response by vegetation may be due to the considerable variability in the proportion of dust retained by the leaf and bark and stems. The deposition and retention on to the leaf surface is affected by a number of factors including: particle size and mass, wind velocity, degree of hairiness of leaves, leaf orientation and size and moisture level. Dust abrading leaf surfaces, dust blocking stomata of plants, dust increasing the amount of absorbed incident radiation. These are just a number of different impacts that dust can have on vegetation (Farmer, 1993; Doley, 2006; Prajapati, 2012a). Dust on leaves decreases the photosynthetic rate by shading the leaf surface. The dust of smaller particles had a greater shading effect. Moreover, it was found that the additional absorption of incident radiation by the dust increased the leaf temperature, and consequently changed the photosynthetic rate in accordance with its response curve to leaf temperature. The increase in leaf temperature also increased the transpiration rate (Hirano et al., 1995). Acceptable dust burdens may vary between species and their positions in the plant community.

Ecological effects of airborne particulate matter on plant communities

The focus here is on non-gaseous air-borne pollutants and their interaction with terrestrial vegetation communities. Studies have been done in forests (Brandt & Rhoades, 1972), woodlands (Ricks & Williams, 1974) tundra (Santelmann & Gorham, 1988; Hope *et al.,* 1991) taiga

(Walker & Everett, 1977) wetlands (Gilbert, 1973; Spatt & Miller, 1981). Evidence is that the deposition of dust particulates on plants and soils within these various communities has a lasting impact and the changed conditions may lead to a shift in the botanical composition of the affected area. These effects on plants and soils may lead, in turn, to changes in invertebrates and ultimately to changes in predatory fauna that rely on certain prey species. e.g. leaf eating caterpillars or beetles that are prey for certain birds. Accumulation of dust may affect soil pH (Bohn, 1972) and/or affect permeability of the surface soil either directly or by the interaction with cryptogams (Eldridge, 1993) or other geophytes such as lichens.

Impact of dust deposition on photosynthesis

For the majority of mineral dusts, effects on vegetation may be associated with the reduction in light reaching the photosynthetic apparatus of the leaves, an increase in leaf temperature due to changed surface optical properties, and interference with the diffusion of gases into and out of leaves (Farmer, 1993; Doley, 2006; Prajapati, 2012b). But overall, the effect seems to be a reduction in photosynthetic abilities (Hirano *et al.,* 1995; Krishnamurthy & Rajachidambaram, 1986).

The light and energy exchange processes can be predicted with much greater certainty than can the effects of dusts on gas diffusion. Critical dust loads that result in significant alterations in the most sensitive plant functions vary with the particle size distribution and colour of the dust, from about 1 g m^{-2} for carbon black with a median diameter of about 0.15 μm to about 8 g m^{-2} for coarse road or limestone dusts with median diameters greater than about 50 μm. The critical loads vary with the plant function and it has not been possible to predict precisely the nature of one plant response from the knowledge of another. It is clear that dust particle size has important and predictable effects on energy exchange properties of vegetation, and that dust colour may be of secondary concern. In order to make useful predictions of the effects of dusts on plant functions, it is vital that dusts should be described in terms of particle size distributions and that direct evidence should be gathered on the effects of dusts with known physical properties on various environmental processes. Until this is done, it is necessary to apply caution when predicting the impacts of dusts on vegetation.

By incorporating several generalised physiological characteristics of plants it is possible to estimate the likely effects of dust deposition on vegetation and thereby the environmental risks associated with proposed dust-generating activities (Doley and Rossato, 2010).

The effect of dust on photosynthesis in plant canopies was modelled (Lin *et al.*, 1995; Holmes and Morawska, 2006; Doley and Rossato, 2010).

Modelling indicated that the impact of dust deposition on vegetation at the bottom of a plant canopy is greater than on vegetation that is fully exposed to sunlight. Photosynthesis was reduced and this appeared to be due to shading when the upper surfaces of leaves were dusted, and to impeded diffusion when lower surfaces were dusted. These effects were observed with 5 to 10 g dust per m2 leaf surface. These differences mean that acceptable dust burdens may vary between species and their positions in the plant community.

By incorporating several generalised physiological characteristics of plants it is possible to estimate the likely effects of dust deposition on vegetation and thereby the environmental risks associated with any proposed dust-generating activities (Doley and Rossato, 2010).

Potential losses in productivity for various rates of dust deposition

The effects of air-borne pollutants on plants were reviewed by Farmer (1993), and in a report on ecosystem effects, although the coverage of dust effects in the latter is minimal. A much more detailed coverage of the effects of dust on plants is given in a report by the Agricultural Engineering Institute (Prajapati, 2012). McCrea's report gives estimates of the potential losses in crop productivity for various rates of dust deposition. The main focus of the report was on horticultural crops grown alongside unsealed roads, and in this case the losses were shown to be significant within about 200 metres of the source. Grantz *et al.,* 2003 also examine the ecological effects of particulate matter. Kerstiens (1996) showed that coal dusts of uniform mineralogy became visibly darker as the particle size decreased. This means that the heat load on a dusted surface could increase as particle size decreased, without a change in the dust load. Where dusts alter optical properties of snow-covered surfaces, they may lead to vegetation surface temperatures 4 to 11.5°C above those of normal environments (Spatt and Miller, 1981; Spencer and Tinnin 1997), changes in plant community structure and composition (Auerbach *et al.,* 1997, Spencer and Tinnin 1997) and in grazing patterns of ruminant animals (Vardaka *et al.,* 1995).

Atmospheric particulate matter (P_M) is a heterogeneous material. Though designated by various environmental protection agencies as un-speciated mass, it exerts most effects on vegetation and ecosystems by virtue of the mass loading of its chemical constituents. As this varies temporally and spatially, prediction of regional impacts remains difficult. Deposition of P_M to vegetated surfaces depends on the size distribution of the particles and, to a lesser extent, on the chemistry. However, chemical loading of an ecosystem may be determined by the size distribution as different constituents dominate different size fractions. Coating with dust may cause abrasion (see below) and radiative heating, and may reduce the photosynthetically active photon flux reaching the photosynthetic tissues (Lepedus *et al.,* 2003; Lichthenthaler *et al.,* 1982, 1999, 2002; Naidoo & Chirkoot, 2004; Prusty *et al.,* 2005). The transfer of pollutants from the atmosphere to the internal tissues of a leaf may involve several routes and physical processes. Wind and abrasive damage, which are components of weathering, cause changes in leaf surface characteristics and cuticular integrity which influence gaseous diffusion and the uptake of solutes (Kerstiens, 1996).

Acidic and alkaline materials may cause leaf surface injury while other materials may be taken up across the cuticle (Kerstiens, 1996). A more likely route for metabolic uptake and soil can influence nutrient cycling, especially that of nitrogen, through its effects on the rhizosphere bacteria and fungi. Alkaline cation and aluminium availability are dependent upon the pH of the soil that may be altered dramatically by deposition of various classes of P_M. A regional effect of P_M on ecosystems is linked to climate change. Increased P_M may reduce radiation interception by plant canopies and may reduce precipitation through a variety of physical effects. At the present time, evidence does not support large regional threats due to un-speciated P_M, though site-specific and constituent-specific effects can be readily identified. Interactions of P_M with other pollutants and with components of climate change remain important areas of research in assessment of challenges to ecosystem stability. As would be expected, cuticular water permeability is very small compared with maximum stomatal conductance, which ranges from 4 to 12 x 10^{-3} m s^{-1} on a projected leaf area basis

(Kerstiens, 1996; Shepherd & Wynne, 2006).

Dust Deposition in relation to plant architecture

Plant architecture is defined as the three-dimensional organisation of the plant body. For the parts of the plant that are above ground, this includes the branching pattern, as well as the size, shape and position of leaves and flower organs (Reinhardt & Kuhlmeier, 2002). Plant architecture is species specific, indicating that it is under strict genetic control. Although it is also influenced by environmental conditions such as light, temperature, humidity and nutrient status. It can respond to dust deposition by exhibiting thymic stress or other manifestations (Rai, 2014). Some plant species are less susceptible to dust deposition because of the way the leaves and other important features are presented. The shapes and sizes of leaves and flower organs are major determinants of plant architecture. Leaves can be either simple, as in *Arabidopsis* and tobacco, or composed of several subunits, the leaflets, as in tomato and pea. A prototypical leaf has three axes: the proximodistal axis (tip–base), the dorsiventral axis (upper side to lower side, or adaxial–abaxial) and the lateral (left–right).

The review by Cleugh *et al.,* (1998) describes those mechanisms by which wind directly affects crop growth rates and hence yields. Wind-induced plant movement is capable of altering growth rates and leaf morphology, although this is unlikely to be a major cause of growth differences between sheltered and unsheltered crops grown outdoors. The wind's force can tear leaves or strip them from the plant. Dense plant canopies may suffer abrasion through intermittent or constant rubbing. Soil particles lifted into suspension by the wind have the potential to abrade and damage plant tissue. The wind's force can physically knock plants

over, making crops difficult to harvest. Each of these mechanisms operates at a particular time of the growing season. Recovery, and hence final yield, depends on the growth stage and soil/plant moisture status when the damage occurred, the particular species and variety as well as the preceding and subsequent weather. The fact that damage effects are so dependent on the crop and the past weather makes modelling and any simple synthesis of direct wind effects difficult. The most common forms of damage likely in agricultural regions are from sandblasting and lodging (see below). These damage events will be intermittent– their frequency depending on the local climate. Leaf tearing is likely in broad-leafed horticultural crops, and growth effects are also likely in any windy location. It is not possible to predict what the impact of this damage, and other direct effects, will be on final yields, Based on the results in the literature, protection from damage offered by windbreaks may have as large an effect on yields as incremental microclimate benefits (Rapauch *et al.*, 2001).

Plant cuticles, Contact angles and wettability

Leaf surface wettability is influenced by the physicochemistry of the cuticular wax (Shepherd & Wynne Griffiths, 2006; Hall & Jones, 1961; Holroyd, Hetherington & Gray, 2002) and, to a lesser extent, leaf turgor. The waxy cuticle covering epidermal leaf cells increases resistance to gases (Shepherd & Wynne Griffiths 2006). However, nitrogen oxides deposited on cuticles may dissociate in the water film and/or react with cuticular wax components, causing damage. Wettability is measured in terms of the Contact Angle (CA), the angle subtended between the leaf surface and the plane of a tangent to the surface of a water droplet originating at the contact point for air, leaf and water. Values of CA vary widely

from 120° for very hydrophobic *Eucalyptus globulus* to 29° for very hydrophilic *Vicia faba.* At angles < 90° water droplets tend to spread, ultimately forming water films, particularly when leaves are shaken by wind. Conversely, formation of isolated drops is a characteristic of angles > 90°. Contact angles are therefore indicative of water retention capacity, which is significant for surface-colonising insects and microorganisms and for foliar deposition and uptake of nutrients, pollutants and agrochemicals. Droplets on wettable leaves can focus solar radiation up to 20 times, possibly by acting as planoconvex lenses. This may increase the transmission of damaging UV-B to the epidermis and upper mesophyll. Some stress-induced changes in CA and wettability are associated with altered wax composition and morphology (Gardingen *et al.,* 1991). Reductions in CA of up to 30° were correlated with temperature-induced recrystallisation of conifer needle wax, largely composed of (S)-nonacosane-10-ol, from tubular to planar forms, and increased abundance of *br*-alkanes in the wax from *N. tabacum* following exposure to elevated UV-B. Under windy conditions, wax can be removed by fracturing of crystals and abrasion due to aerodynamic loading, impact of raindrops, dust and snow, etc., and by leaf-to-leaf contact. In wind tunnel experiments, wax crystals on the leaves of *Picea stichensis* became flattened and smeared after exposure to airflow at $11 \, ms^{-1}$ for 1 week, and structures within and around the stomatal antechambers of *P.stichensis* and *Pinus sylvestris* were particularly vulnerable (Van Gardingen *et al*., 1991).

Cuticular waxes can reform rapidly after mechanical removal, for example the fine structure of broccoli, *B. oleracea* wax regenerated within 3 days. However, rates of replacement may not be fast enough to maintain normal levels (Hall & Jones, 1961). investigated the relative effects of wind, brushing (thigmic stress) and dehydrating moisture stress conditioning (MSC) on *B. oleracea* as mechanisms for conditioning and hardening glasshouse-grown plants before field planting. After 9 days of treatment, reductions in wax levels due to brushing and wind were similar (31–38%), but that due to MSC was 11%. After 15 days, wax was reduced by 15% due to brushing and 6% due to wind, but had increased by 17% due to MSC, indicative of wax redeposition although the rate of removal by brushing was greater than the rate of renewal. In high concentrations, and under prolonged exposure, acidic and oxidising gases and aerosols can help to degrade cuticular wax and impair stomatal function. This may impose chronic water stress, which can lead to defoliation and death. Various aspects of the interaction between atmospheric pollutants and the leaf cuticle have been reviewed by Heath (1980) and contributors in Prusty *et al*., (2005).

Mechanical stress induced by wind borne dust and aerosols

Wind-induced components of weathering of individual leaves of *Fagus sylvatica* were simulated by the use of a miniature wind tunnel and surface abrasion. The consequence of exposure to wind was widespread disruption of trichomes, and evidence of smoothing of cuticular wax was obtained using low-temperature Scanning Electron Microscopy (SEM). An abrasive treatment also damaged trichomes, created cuticular lesion visible by SEM and significantly increased total surface conductance, to water vapour, on both adaxial (astomatous) and abaxial (stomatous) surfaces. The structural integrity of the cuticle and the spatial distribution of cuticular lesions were investigated by using ruthenium red as a convenient dye tracer. Leaves were found to be most susceptible to abrasive

damage on their abaxial surfaces, where the spatial distribution of lesions was significantly clustered. The occurrence of these lesions may be related to a natural

structural and conductive heterogeneity across the leaf surface. Sites most vulnerable to damage were trichomes and protruding veins (Fig. 1).

Fig. 1. Trichomes (hairs, protruding veins etc) can attract and retain dust but leaf size and leaf angle are important determinants of dust capture and retention

Exposure of *F. sylvatica* leaves to natural weathering processes in an exposed upland site increased uptake of (^{35}S) sulphate from droplets placed on the adaxial cuticle by 30-fold on average compared with leaves grown in a sheltered location at the same altitude. The spatial heterogeneity of sulphate uptake measured at discrete points over a single leaf was also greater in leaves from the exposed site. Consequently, weathering may increase the heterogeneity of gas exchange and the uptake of solutes, by increasing leakiness at localised sites across the leaf surface.

Windblown soil particle abrasion affects millions of hectares of crops annually, and often requires replanting at great expense to farmers (Fryrear, 1986). The resulting injury reduces survival, growth, yield, and quality of both field crops and vegetables (Armbrust, 1968). Major factors that influence the severity of injury caused by soil abrasion include wind speed, soil particle flux density (Fryrear *et al.,* 1973), and the duration of exposure. Sand particle impacts rupture

plant cells, leading to the possibility of short-term, high intensity water stress due to cuticle abrasion and/or impaired stomatal control along with subsequent increases in respiration rate expressed on a live leaf area basis (Armbrust *et al.,* 1974; Fryrear and Downes, 1977; Fryrear *et al.,* 1975; Armbrust, 1972).

Effects of windblown sand on many plants have been investigated since the 1950s, mostly by the use of wind tunnels. The effect of wind abrasion was assessed on crops such winter wheat (*Triticum aestivum*) (Armbrust *et al.,* 1974; Armbrust, 1984); alfalfa (*Medicago sativa*); bean (*Phaseolus vulgaris*) and pea (*Pisum sativum*), cotton (*Gossypium hirsutum*) (Armbrust, 1968; Fryrear, 1971); tomato (*Lycopersicon lycopersicum*) (Armbrust *et al.,* 1969; Greig *et al.,* 1974); soybean (*Glycine max*) (Armbrust, 1972 and 1984; Armbrust and Paulsen, 1973); different vegetable crops (Downes *et al.*, 1977); tobacco (*Nicotiana tabacum*) (Armbrust, 1979); sorghum [*Sorghum bicolor*] (Armbrust, 1982, 1984) and different

grasses (Fryrear *et al.,* 1973). More recent studies include, Cleugh *et al.,* (1998).

Using a wind tunnel, Bohn (1972) blasted seedlings with sand-laden 60 km-per-hour wind. They studied the effects immediately and after two and four weeks. They found that over the first two weeks, the seedlings shifted their growth from root and leaf growth to repair and growth of injured stems. By the fourth week, plant growth had returned to normal, once again balancing growth throughout the plant, down to the roots. Sand abrasive flux density treatments reduced plant biomass and leaf area. While small significant differences in Leaf Area Ratio (LAR) were detected among sand abrasion treatments, Relative Growth Rate (RGR) depended mainly on Net Assimilation Rate (NAR) rather than LAR. Earlier, sought to determine the effects of windblown sand abrasion duration on cotton (*Gossypium hirsutum*) seedlings. Seedlings of three cotton cultivars were exposed to wind velocities of 13.4 m s^{-1} with sand abrasive flux density of 0.42 g cm^{-1} width s^{-1} for six treatment durations ranging from 0 to 40 min. Plants were destructively sampled at the time of the sand abrasion treatment and also at approximately equal to 2 and 4 weeks after exposure. These three sampling dates provided two time intervals for assessing the amount of plant damage and regrowth using classical growth analysis. The effects were dramatic. Cotton seedling shoot growth and leaf area were reduced by increasing sand abrasion duration treatments. It is uncertain whether the physical effects of dust on plant physiology are permanent, because plants seems to recover after rainfall, which may wash dust off leaf surfaces and thus restore photosynthetic capacity.

It is uncertain whether the physical effects of dust on plant physiology are permanent, because plants seems to recover after rainfall, which may wash

dust off leaf surfaces and thus restore photosynthetic capacity. We should be able to estimate dust thresholds which define the amount of acceptable dust loading on plants and other biota (Vardaka *et al.,* 1995). This would help to determine environmentally sustainable dust levels – just as in human health.

Dust deposition and physiological response by plants

Deposition of dust on vegetation will be affected by the particle size distribution and the dimensions and density of foliage elements in the dispersion path (Doley, 2006; Doley & Rossato, 2010; McTainsh & Strong, 2007). The effect of size-segregated rather than chemically speciated particulate matter on ecosystem function is mediated by effects on vigour, competitive viability, and reproductive fitness of individual plants. Large-leaved species may provide effective dust barriers close to the source of coarse dusts (e.g. roads or quarries), but less effective barriers against finer dusts that travel greater distances. Dusts effects on vegetation may be connected with the decrease in light available for photosynthetic processes, an increase in leaf temperature due to changed surface optical properties, and interference with the diffusion of gases into and out of leaves (Farmer, 1993). It is clear that dust particle size has important and predictable effects on energy exchange properties of vegetation (Doley, 2006) Alkaline particulate matter may exert direct effects on leaf surfaces; however, the effects hardly ever reach the ecosystem level because it is difficult to identify a widespread threat to ecosystem function due to un-speciated particulate matter (Prajapati *et al.,* 2012a).

Dust coatings increased leaf temperatures 2 to 4°C, increased the number of bacteria and fungi on the leaves and increased transpiration. Water loss increased with increased concentration and decreased particle size

of applied dust. Total carbohydrate contents were decreased by all treatments when compared to the control. The response by vegetation may be due to the considerable variability in the proportion of dust retained by the leaf and bark and stems. The deposition and retention on to the leaf surface is affected by a number of factors including: particle size and mass, wind velocity, degree of hairiness of leaves, leaf orientation and size and moisture level (Noll & Fang, 1989; Prajapati & Tripathi, 2008e; Prusty *et al.,* 2005).

Climatic conditions and plant adaptation influence the degree of stomatal control required for a plant to balance nutrient uptake and transpiration (Shah *et al.,* 1989; Eveling & Bataille, 1984; Fernandez *et al.,* 1997; Hetherington & Woodward, 2003, Mansfield & Majernik, 1970). Closure of the stomata will reduce but not prevent pollutant uptake, as significant amounts of gas penetrate the cuticle (Krajickova & Mejstrik, 1984). As a general rule, a plant resists the effects better under conditions of low light, humidity and nitrogen status, when stomata tend to be closed. In order to enter a plant cell, the gaseous pollutant must pass through the extracellular water contained in the cell wall. Therefore, the solubility of the gas becomes an important factor in plant uptake. Absorption tends to be highest in areas where light intensity and metabolic rates are highest, e.g. near the top of the plant canopy. When concentrations are in excess to the plants ability to cope, problems of toxicity and injury develop. Much work has been done in trying to determine "toxicity thresholds" (Honour *et al.,* 2009) And the development of dose-response curves, all of which is informative, but on a very individually specific level. Damage to plants from high levels is more likely to occur at night than during the day, because the lack of photosynthesis at night results in insufficient adenosine triphosphate and

NADPH2, or energy (Wesely and Hicks, 2000).

Dust may be deposited onto surfaces, including plant leaves, sufficient to harm vegetation by blanketing leaf surfaces. There is more limited evidence available on levels at which dust deposition affects plants. Farmer (1993) brought together numerous sources of evidence for damage to vegetation does to dust accumulation. Impacts vary considerably between species and with different dust types. Broadly, however, the evidence suggests that damage to vegetation due to dust deposition will occur at approximately the same levels as nuisance will occur for people.

Plant damage can occur from a variety of sources. These may be environmental, cultural, mechanical or chemical. Dust deposits can have significant effects on plant life, though mainly at high dust loadings.
This can include:

- Reduced photosynthesis due to reduced light penetration through the leaves. This can cause reduced growth rates and plant vigour. It can be especially important for horticultural crops, through reductions in fruit setting, fruit size and sugar levels.

- Increased incidence of plant pests and diseases. Dust deposits can act as a medium for the growth of fungal diseases. In addition, it appears that sucking and chewing insects are not affected by dust deposits to any great extent, whereas their natural predators are affected (Farmer, 1993; Lovett *et al.,* 2009).

- Reduced effectiveness of pesticide sprays due to reduced penetration because of surface dust.

- Rejection and downgrading of produce. This is a particular issue for horticultural and food crops. Dust storms in the arid regions

that cause severe sand blasting wreak some of the most severe havoc (Wang et al., 2015).

Physical effects of dust on leaf physiology

The physical effects of dust accumulating on leaf surfaces, on leaf physiology, such as photosynthesis, transpiration, stomatal conductance and leaf temperature of many different species of plants were investigated. It was found that dust decreased stomatal conductance in the light, and increased it in the dark by plugging the stomata, when the stomata were open during dusting. When dust of smaller particles was applied, the effect was greater. However, the effect was negligible when the stomata were closed during dusting. The dust decreased the photosynthetic rate by shading the leaf surface. A 21–58% reduction in photosynthesis and a decrease in total shoot length. The dust of smaller particles had a greater shading effect. Moreover, it was found that the additional absorption of incident radiation by the dust increased the leaf temperature, and consequently changed the photosynthetic rate in accordance with its response curve to leaf temperature. The increase in leaf temperature also increased the transpiration rate (Hirano *et al.,* 1995). There is a positive correlation between dust level and leaf temperature (and between leaf temperature and leaf-level and photosynthesis rate (Wijayratne *et al.,* 2009). Sharifi *et al.* (1979, 1997) demonstrated that visibly dusty Mojave Desert perennials proximate to military activities exhibit a 21–58% reduction in photosynthesis and a decrease in total shoot length.

Leaf surface contamination

Tolerance or sensitivity to dust pollution was clearly manifested throughout the photosynthetic activity. The exposure to dust pollution stress provoked important reductions in photosynthesis. Exposure to particulate deposition may alter plant growth without physical damage to the plant. Moreover, accumulation of dust particulates on plant leaves could be a major problem affecting their productivity. The pigments content of the light harvesting complex is an important aspect related to the tolerance of plants to dust pollution (Santosh & Tripathi, 2008). A light-harvesting complex is a complex of subunit proteins is an array of protein and chlorophyll molecules embedded in the thylakoid membrane of plants, which transfer light energy to one chlorophyll *a* molecule at the reaction centre of a photosystem, the functional unit in photosynthesis (Lichthenthaler *et al.,* 1982, Lichthenthaler & Burkart, 1989). It is used by plants to collect more of the incoming light than would be captured by the photosynthetic reaction centre alone (Lokstein, 1994; Caffarri, 2009). The pigments are predominantly chlorophyll *b*, xanthophylls, and carotenoid. Chlorophyll *a* is known as the core pigment. Their absorption spectra are non-overlapping in order to broaden the range of light that can be absorbed in photosynthesis (Lichthenthaler *et al.,* 1982). Prusty *et al.,* (2005) have investigated the seasonal variation in dust accumulation on leaves and leaf pigment content of six plant species of mixed habitats and observed significant difference in dust accumulation among plant species and between seasons. Reduction of total chlorophyll, but also chlorophylls *a* and *b*, has been found in leaves of various annual plants and conifers covered by cement dust (Mandre, 1997; Pandey *et al.,* 1990). Olive (*Olea europaea*) leaves have *stomata* on their lower surface only. *Stomata* are nestled in *peltate* trichomes restricting water loss and protecting against blockage by dust particles (Nanos & Ilias, 2007).

The application of cement dust on olive leaves decreased chlorophyll a and increased chlorophyll b content,

decreased chlorophyll *a*: chlorophyll *b* ratio and slightly decreased total chlorophyll content (Nanos and Ilias, 2007). These changes in the two types of chlorophyll can be attributed to the shading caused by the dust on the leaf or damage to the photosynthetic apparatus due to toxicity or increased water stress. Cement dust also caused a slight decrease in transpiration rate and significant decrease in leaf conductance to H_2O and CO_2 movement via the stomata (by 22 and 18%, respectively). These changes resulted in a small increase of leaf temperature and reduction of water use efficiency by 27%, without changing intercellular CO_2 concentration.

Cellular functions

The many functions of cells are so closely related that description under different headings may detract from the integrated view that is essential to an understanding of pollutant impacts. However, a total understanding cannot be created immediately, and must be assembled from components that have been examined under conditions that allow comparison between studies and species. Darrall and Jager (1988) examined a range of detailed tests that could be applied to air pollutant effects on plants, and concluded that great care had to be exercised if biochemical changes were to indicate pollutant stress responses. In particular, suitable internal or external controls had to be provided, and quantitative tests were generally not available at that time, with the exception of leaf reflectance and stress ethylene evolution. More recently, chlorophyll fluorescence has become a relatively simple non-invasive field of great potential use (Owens, 1994). The variation between species, varieties and technique cultivars in their responses to particular pollutant and other stress combinations requires detailed information to be obtained on each taxon before biochemical techniques can be

applied routinely (Darrall and Jager 1988). Nevertheless, it is important to incorporate some understanding of biochemical and physiological processes in more general indicators of plant responses to pollutants, and the following comments are provided towards this end.

Means of detecting plant physiological responses to air pollution

The study of physiological responses to pollutants may be justified on the grounds that physiological responses are more sensitive to pollutants than is visible injury, and that physiological processes underlie ecological processes. Ultimately, all responses of plants to any environmental stimulus can be described in terms of the genetic constitution of the cells, and the consequent activation or deactivation of enzymes that determine every physiological and morphological response.

Why physiology may be used to detect pollutant effects

Plant responses to air pollution, and to any other environmental factor, can be observed at all levels of organization, from enzymatic, through subcellular organelles, cellular, tissue, organ, organism, community, ecosystem and biome (Darrall and Jager, 1984). The time scales over which assessments at each level can be made vary as much as the spatial scales, so the speed of response to a change in environmental condition can be detected much sooner at the physiological level (which may span the scales of organization from enzyme to organ) than at the ecosystem or biome level, where responses may take years or decades to appear.

Physiological responses are more sensitive than visible injury it has been concluded (Guderian, 1977) that cellular responses to pollutants are more sensitive than responses at the organism level (such as the growth of plants or plant

parts), and that the appearance of injury symptoms is less sensitive than growth. In this context sensitivity implies speed of response as well as the concentration of pollutant at which the smallest significant response can be detected. This proposition is reasonable, and generally applicable, but the relationships between growth and symptom expression are not constant for all species and all pollutants. Part of the inconsistency of the relationships between pollutant effects at different levels of plant organisation arises from the response of the plant to other forms of stress which may be expressed in ways very similar to those resulting from pollutant injury. This applies as much to physiological responses as to visible injury, which is well-documented, for example, oxidative enzyme activity may be used as an expression of response to stress, but the reaction is so general that it cannot always be associated with a pollutant of interest.

Physiological responses underlie and precede ecological changes. This proposition is reasonable, provided the correct responses are measured. Where there is a direct connection between a pollutant effect at the cellular or subcellular level and a response at a much larger level of organisation, physiological responses can provide both a sensitive and early indication of ecological change. For example, as will be discussed later, pollen viability and floral fertilisation involve single cells, and the time scale of effects may be minutes, but the effects influence the total organism which may have a life span of centuries. Where the effects of several or many processes at the smaller scale are confounded as the scale of organisation increases, and applicability of observations at smaller scales of organisation decreases. For this reason, observations on attributes such as some photosynthetic parameters or tissue nutrient relations are not reflected

directly in growth responses of plants or crops. This dilemma confronts not only pollution scientists, but all those who attempt to predict plant community function for any reason on the basis of fine physiological measurements.

A number of recent studies observed that in urban atmospheres the concentrations of P_{M10} and $P_{M\,2.5}$ airborne aerosols show good agreement with traffic-related pollutants and other combustion processes (Prajapati and Tripathi, 2007). Whereas, crustal material, re-suspended road dust and long-range transport events are mainly identified as sources of the coarse particles. Vehicular emissions and agricultural activities generate local dust concentrations close to the source which exceed environmental guideline values. Because little attention has been paid to the effects of PM on organisms other than humans or on the processes that underlie ecosystem functioning, it may ultimately prove to be the environmental consequences of reduced biodiversity and the loss of ecosystem goods and services. Direct physical effects of mineral dusts on vegetation became apparent only at relatively high surface loads (e.g. >7 g m^{-2}) (Farmer,1993) whereas the chemical effects of reactive materials such as cement dust which may become evident at 2 g m^{-2} or of particulate sulphates and nitrates having indirect effects on ecosystems (Grantz *et al.,* 2003). It is necessary to identify some principles that may indicate these impacts, and the need for mitigation measures (Prajapati and Tripathi, 2008a). Studies were undertaken to assess the dust interception efficiency of some selected tree species and impact of dust deposition on chlorophyll and ascorbic acid content of leaves (Prajapati & Tripathi, 2008b; Wang *et al.,* 2013; Noor *et al.,* 2014). The plant species selected for the study included *Ficus religiosa, Ficus benghalensis, Ligustrum lucidum, Mangifera indica, Dalbergia sissoo, Psidium guajava and*

Dendrocalamus strictus. Maximum dust interception was achieved by *Dalbergia sisso* and least by *Dendrocalamus strictus.* Thus plants can be used to intercept dust particles which are of potential health hazards to humans (Rai and Panda, 2014).

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مروری بر ریز گردها و آئروسول‌ها: تاثیر روی جانداران (قسمت ۲)

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چکیده. این مقاله، بخش دوم از مجموعه بررسی اثرات گرد و غبار می‌باشد. این بخش روی اثرات فیزیکی، شیمیایی و فیزیولوژیکی ذرات گرد و غبار و معلق در هوا متمرکز شده است. همه انواع و رده‌های گیاهان (از جلبک‌ها تا درختان جنگلی و همه گیاهان حد واسط آن‌ها) از طریق سایش مستقیم توسط ذرات معلق در هوا یا از طریق ایجاد اختلال در فیزیولوژی گیاه و یا غیر مستقیم از طریق تاثیر روی خاک، تحت تاثیر نامطلوب قرار می‌گیرند. زیرا ذرات روی سطح خاک انباشته می‌شوند و روی شیمی، بافت و ساختمان خاک تاثیر می‌گذارند. مقالات مروری شامل مدت‌های طولانی و در مکان‌ها و زیستگاه‌های مختلف می‌باشد. نمونه‌های ذکر شده در این راستا از قطب شمال تا استوا، از صحراها تا جنگل‌های بارانی را در بر می‌گیرد. واکنش‌های فیزیولوژیکی گیاهان و به دنبال آن تغییرات اکولوژیکی در سطح جامعه گیاهی قابل بررسی هستند. این تغییرات دلیلی بر تغییر روابط مهمی به شکل صیاد- صید، به شکل پناهگاه، ذخیره غذایی و دیگر بخش‌های ضروری اکوسیستم هستند. خواه این تغییرات به‌راحتی به دست آمده یا بر اثر حوادث و یا بر اثر شدت زیاد تغییرات نمود کرده باشد. در مجموع می‌توان بیان کرد که اکثر گونه‌های گیاهی بیشترین حجم انباشته کردن ذرات گرد و غبار را در فصل زمستان و نیز در فصولی که هوا بارانی است، دارند. در این هنگام محتوای کلروفیل کاهش و میزان اسید اسکوربیک به واسطه افزایش انباشت گرد و غبار در بافت‌های گیاهی افزایش می‌یابد. در نهایت می‌توان نتیجه گرفت که همبستگی مثبت و منفی معنی‌داری بین انباشت گرد و خاک و میزان اسید اسکوربیک و کلروفیل به ترتیب وجود دارد.

کلمات کلیدی: فیزیولوژی، فتوسنتز، روزنه‌ها، سایش، سمیت، ریزوسفر