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Ecological effect of airborne particulate matter on plants

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Abstract
Atmospheric particulate matter is a mixture of diverse elements. Deposition of particulate matter to vegetated surfaces depends on the size distribution of these particles and, to a lesser extent, on the chemistry. Effects of particulate matter on vegetation may be associated with the reduction in light required for photosynthesis and an increase in leaf temperature due to changed surface optical properties. Changes in energy exchange are more important than the diffusion of gases into and out of leaves which is influenced by dust load, color and particle size. Alkaline dust materials may cause leaf surface injury while other materials may be taken up across the cuticle. A more probable route for metabolic uptake and impact on vegetation and ecosystems is through the rhizosphere. Interception of dusts by vegetation makes an important contribution to the improvement of air quality in the vicinity of vegetation. Although the effect of particulate matter on ecosystem is linked to climate change, there is little threat due to un-speciated particulate matter on a regional scale.

Keywords particulate matter; deposition; alkaline; surface injury; rhizosphere.

1 Introduction

Atmospheric particulate matter (PM) with aerodynamic diameter < 10 µm diameter (PM_{10}) or < 2.5 µm diameter ($PM_{2.5}$) are of great concern for public health due to presence of PAHs (NEPC, 1998, 2003; Prajapati and Tripathi, 2008a-d). Numerous epidemiologic studies highlighted the health implication of fine particles, with aerodynamic diameter smaller than 10 lm (Kunzli et al., 2000; Katsouyanni et al., 2001; Pandey et. al, 2005; Pandey et. al., 2006; Pope et al., 2002; Peng et al., 2005; Prajapati et al., 2006). Characterization of potential PM impacts on ecosystem function, remain important research needs with great potential significance for human welfare (Ayensu et al., 1999; Prajapati and Tripathi, 2008a-d; Telesca and Lovallo, 2011). The total suspended particulate matter (TSPM) in the atmosphere includes particles >10 µm diameter and these larger particles are important in the planning and management of mining, industrial and agricultural operations in order to protect human health (Mulligan, 1996; Manins et al., 2001). Zhang et al. (2011) have studied the consumption of pesticides globally and its implications on the ecosystems.

A number of recent studies observed that in urban atmospheres the concentrations of PM_{10} and $PM_{2.5}$ airborne aerosols show good agreement with traffic-related pollutants and other combustion processes (Prajapati and Tripathi, 2007). Whereas, crustal material, resuspended road dust and long-range transport events are mainly identified as sources of the coarse particles (Park and Kim, 2005; Vallius et al., 2005). Vehicular emissions and agricultural activities generate local dust concentrations close to the source which exceed environmental guideline values (Leys et al., 1998, Manins et al., 2001). 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 (Westman, 1977; Daily, 1997). 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-d).

2 Diversity of Deposition Modes

Rate of transfer of dust from the air to vegetation surfaces which varies greatly with dust properties, and the nature of the receiving environment (Grantz et al., 2003), determines the effect of dust on ecosystem (Table 1). Depositions of atmospheric particle onto vegetation surface have three major routes: (1) wet deposition, (2) dry deposition and (3) occult deposition, obscured from measurements that determine wet and dry deposition, by fog, cloud-water, and mist interception. Factors that influence particle deposition under dry conditions are same that influence the process in the presence of occult precipitation viz. dew, fog and cloud. Precipitation directly determines the magnitude of wet deposition. Precipitation events clean the air, so that dry deposition is eliminated or reduced during subsequent dry periods. Occult deposition depends upon landscape interception of the cloud base (Cape, 1993).

Wet deposition results either from the inclusion of atmospheric particles and gases into cloud droplets by nucleation, and its precipitation (Lovett, 1994). Wet deposition is largely a function of precipitation amount and ambient particulates concentrations and is not affected by surface properties of dusts as much as dry or occult deposition. Wet deposition fluxes during precipitation events exceeded dry deposition fluxes by one to four orders of level (Lindberg and Harriss, 1981). Wet deposition is most efficient for fine particles of atmospheric (secondary) origin and elements such as cadmium, chromium, lead, nickel, and vanadium (Reisinger, 1990; Smith, 1990a, b). However, surface properties of leaves such as wettability, exposure, and roughness strongly influence liquid retention (Neinhuis and Barthlott, 1998). Thickly and tall forested hillsides receive four to six time greater inputs of wet deposition than short vegetation in nearby valleys. This is because of orographic effects (Unsworth and Wilshaw, 1989) and closer aerodynamic coupling to the atmosphere of tall forest canopies than of the shorter canopies in the valleys. This leads to more quickly foliar drying following deposition, reducing the residence time of dissolved particulate matter. At the same time it quickly concentrates the solubilized materials available for cuticular damage or foliar uptake, which depends on concentration (Fowler et al., 1991; Unsworth, 1984; Schonherr and Huber, 1977). The chemical load of the dry-deposited dust material trapped in the canopy is combined with the newly wet-deposited material for transfer to the soil (Lovett and Lindberg, 1984). The concentrations of suspended and dissolved particulates are generally highest at the commencement of precipitation event and decline with its duration (Lindberg and McLaughlin, 1986).

Table 1 Types and determinants of particulate deposition and impact to vegetation (Grantz et al., 2003)

Type of deposition	Determinant of deposition	Quantifiable factors
Dry deposition	Ambient concentration	Distance from source, Emission strength
	Atmospheric condition	Wind speed, Stability, Mixing height Temperature, Humidity, Dew formation
	Aerosol properties	Chemical reactivity, Particle solubility Aerodynamic diameter, Biological availability, Hygroscopicity
	Surface roughness	Terrain discontinuity, Leaf pubescence Leaf shape, Plant density, Branch spacing Tissue flexibility
	Vegetation condition	Surface wetness, Salt exudates, Organic exudates, Insect excreta
Wet deposition	Ambient concentration	Distance from source, Emission strength
	Atmospheric condition	Mixing height, Timing of precipitation, Intensity of precipitation, Duration of precipitation
	Aerosol properties	Chemical reactivity, Particle solubility, Biological availability
	Surface roughness	Terrain discontinuity, Leaf pubescence Leaf area index, Nature of exposed, bark and stem
Occult deposition	As above	Combination of above factors

Although the rate of dry deposition of atmospheric particles to plant and soil is a much slower as compared wet or occult deposition, nevertheless it acts nearly continuously and affects all exposed surfaces (Hicks, 1986). Important physical properties of dusts which determine the particle weight and potential transport distance from a source are specific gravity and particle size. Gravitational sedimentation is the main depositional process, for particles >1 µm diameter, whilst for particles < 0.001 µm diameter i.e. respiratory suspended particulate matter inertial properties become increasingly important in determining their impact onto surfaces (Chamberlain, 1986; Fowler et al., 1989; Wesely and Hicks, 2000; Raupach et al., 2001). Dry deposition of organic materials (e.g., dioxins, dibenzofurans, and polycyclic aromatics) to vegetated surfaces is often dominated by coarse PM, even though mass loading in this size fraction may be small (Lin et al., 1993) relative to fine PM. Leaf orientation, age, roughness and wettability of the leaf surface influences dust interception and thus retention (Neinhuis and Barthlott, 1998; Beckett et al., 2000).The strength and constancy of wind, the porosity of the vegetation with respect to air movement also affect dust retention (Raupach et al., 2001). It is difficult to estimate the rate of loss of dust from vegetation surfaces under dry conditions. Krishnamurthy and Rajachidambaram (1974) reported similar cement dust load and its deposition rate (3.7 g m^{-2} d^{-1}) on coconut and tamarind leaves. Deposition velocities for fine particles to forest surfaces have been reported in the range of 1–15 cm s^{-1} (Smith, 1990a). The rates of decrease in surface dust load with increasing distance from Highways were exponential (Walker and Everett, 1987). Keller and Lamprecht (1995) reported that dust levels near the Dalton Highway in Alaska were relatively invariable over much of the summer growing season and that over 85% of the dust falling on vegetation surfaces may be removed.

Gaseous pollutant species may dissolve in the suspended water droplets of fog and clouds. Aqueous condensation may occur onto preexisting fine particles and such particles may coalesce or dissolve in fog or cloud droplets. Fog formation influences both the total atmospheric burden and deposition of particulate matter (Pandis and Seinfeld, 1989) by accreting and removing particles from the air, by helping particle growth through aqueous oxidation reactions, and by increasing deposition. Low altitude radiation fogs have unlike formation and deposition characteristics than high elevation clouds or coastal fogs. Substantially greater concentration of key polluting species (e.g., NO_3^-, SO_4^{2-}, and organics) occurs in smaller than in larger droplets in these fogs (Collett et al., 1999). Clouds can contain high concentrations of acids and other ions, particularly and in decreasing order of concentration, sulfate (SO_4^{2-}), hydrogen (H^+), ammonium (NH_4^+), and nitrate (NO_3^-). Acidic cloud water deposition has been linked with forest decline in industrialized areas (Anderson et al., 1999). Concentrations of particulate derived materials are often many-fold higher in cloud or fog water than in precipitation or ambient air in the same area. Fog and cloud water deliver PM to foliar surfaces in a hydrated and therefore bio-available form.

3 Effect of Vegetation on Air Quality

Removal of dust particles by vegetation through interception from the atmosphere enhances air quality in urban areas (Beckett et al., 1998, 2000; Freer-Smith et al., 2005), near roadways (Smith, 1971; Freer-Smith et al., 1997). Properties of both particles and the vegetation are important in deciding their interactions, and consequently the effectiveness of particle removal from atmosphere. Leaves, susceptible and highly exposed parts of a plant, may act as persistent absorbers in a polluted environment (Maiti, 1993). Small vegetation elements are more effective in removing small particles from an air stream than are large elements. They act as pollution receptors and decrease dust concentration of the air. The capability of leaves as dust receptors depends upon their surface geometry, phyllotaxy, epidermal and cuticular features, leaf pubescence, and height and canopy of trees (Fowler et al., 1989; Nowak, 1994; Beckett et al., 2000; Raupach et al., 2001). Prajapati and Tripathi (2008a-d) have shown that pollution tolerant tree species can be used for green belt development.

4 Effects of Particulate Matter on Vegetation

Exposure to a given mass concentration of airborne PM may lead to widely differing phytotoxic responses, depending on the particular mixture of deposited particles. Particulate deposition and effects on vegetation unavoidably include (1) nitrate and sulfate and their associations in the form of acidic and acidifying deposition and (2) trace elements and heavy metals, including lead. While size is related to mode and magnitude of deposition, and may be a useful substitute for chemical composition (Whitby, 1978). Mineral dusts in general are less soluble and less reactive than the anthropogenic acid-forming sulfate and nitrate particles (Fowler et al., 1989; Grantz et al., 2003). Dusts with pH values of ≥ 9, may cause direct injury to leaf tissues on which they are deposited (Vardak et al., 1995) or indirectly through alteration of soil pH (Hope et al., 1991; Auerbach et al., 1997) and dusts that carry toxic soluble salts will also have adverse effects on plants (Prajapati and Tripathi, 2008a-d).

Energy exchange between vegetation and atmosphere involves the absorption and conversion of short-wave radiation and the emission of long-wave radiation (Monteith and Unsworth, 1990). Dust deposited on leaf surface alters its optical properties, particularly the surface reflectance in the visible and short wave infrared radiation range (Eller 1977; Hope et al., 1991; Keller and Lamprecht 1995), and the amount of light available for photosynthesis. When dusts alter optical properties of snow-covered surfaces it can lead to vegetation surface temperatures 4 to 11.5 ^{o}C above ambient environments (Spatt and Miller 1981; Spencer and Tinnin, 1997), changes in structure and composition of plant community (Auerbach et al., 1997; Spencer and Tinnin, 1997), and change in grazing patterns of animals (Walker and Everett 1987). In desert environment, road dust loads of 40 g m^{-2} increases leaf temperatures by 2 to 3 ^{o}C (Sharifi et al., 1997).

Dust accumulating on leaf surfaces may interfere with gas diffusion between the leaf and air. Sedimentation of coarse particles affects the upper surfaces of leaves more (Thompson et al., 1984; Kim et al., 2000) while finer particles affects lower surfaces (Ricks and Williams 1974; Krajickova and Mejstrik, 1984;

Fowler et al., 1989; Beckett at al. 2000). In dusty environments species having stomata in grooves, covering of wax on stomata might be affected less than species in which the stomata are located at the outer surface of the leaf.

5 Ecosystem Response to Stress Caused by Particulates

Response against particulates stress begins with changes in the population of sensitive individual organisms at single or multiple trophic levels (Bazzaz, 1996). As a minimum three levels of biological interaction are involved between plants and particulates: (a) the individual plant and its environment, (b) the population and its environment, and (c) the biological community and its environment (Billings, 1978). The response of individual organisms against stress is based on its genotype, stage of growth, existing resources, and microhabitat (Levin, 1998). Competition among individuals and species during ecological succession may improve ecosystem tolerance to the challenge of particulates deposition (Rapport and Whitford, 1999; Guderian, 1985).

Succession in unpolluted (favorable) environment is progressive while, under harsh conditions, due to intermittent natural disturbance, energy is diverted from growth and reproduction to maintenance, and return succession to an earlier stage (Waring and Schlesinger, 1985). Such disturbances disrupt normal physiology and biochemistry of plants, the determinants of energy flow and nutrient cycling, food chain structure, and nutrient inventory (Odum, 1993). These disturbances, nevertheless, sets the stage for revival, which permits the disturbed ecosystem to acclimatize to changing environments. Therefore, these perturbations may yield a temporary setback and recovery can be rapid (Odum, 1969). On the contrary, anthropogenic stresses, such as those due to particulate matter and other anthropogenic deposition, may be more harsh and devastating, with stressed ecosystems recuperating less readily and often undergoing further degradation (Odum, 1969; Rapport and Whitford, 1999), e.g. presence of heavy metal exposure causes tree injury and contributes to forest decline in the northeastern United States (Gawel et al., 1996). Sayyed and Sayadi (2011) have studies the variations in the heavy metal accumulations within the surface soils from the Chitgar industrial area of Tehran.

Effects of particulate matter can result from direct deposition or indirectly by deposition onto the soil. Particulate deposition reduces growth, yield, flowering, and reproduction of plants (Saunders and Godzik, 1986). Tolerant individuals, present in low frequencies in populations when growing in undisturbed areas, have been selected for tolerance at both the seedling and adult stages when exposed to trace metal or nitrate deposition (Ormrod, 1984; U.S. Environmental Protection Agency, 1993). Tolerant individuals within a plant population exhibit a wide range of sensitivity that is the basis for the natural selection of tolerant individuals. The rapid evolution of certain populations of tolerant species, at sites with heavy trace element and nitrate deposition, has been observed (Saunders and Godzik, 1986). Chronic pollutant injury to a forest community may result in the loss of susceptible species, loss of tree canopy, and safeguarding of a residual cover of pollutant-tolerant herbs or shrubs that are recognized as successional species (Smith, 1974; Miller and McBride, 1999).

The effects of dust deposited on plant surfaces are more likely to be linked with their chemistry rather than simply with the mass of deposited particles (Farmer, 1993). Alkaline particles may injure plant surfaces, such as limestone particles (Brandt and Rhoades, 1972, 1973). There has been reduction in growth of the dominant trees owing to crust formation on leaves which reduces photosynthesis and bringing premature leaf fall and destruction of leaf tissues (Brandt and Rhoades, 1973). Alkaline dust containing high levels of MgO deposited on leaf surfaces disrupted the epicuticular waxes (Bermadinger et al., 1988). Cement dust on hydration liberates calcium hydroxide which can raise leaf surface alkalinity in some cases to pH 12. This level of alkalinity can hydrolyze lipid and wax components, penetrate the cuticle, and denature proteins finally plasmolyzing the leaf (Guderian, 1986; Czaja, 1960, 1961, 1962). Limestone dust coating of lichen thallus damaged its photosynthetic apparatus (Arianoutsou et al., 1993). All this leads to change in community structure and function.

It is reported that deposition of particulate matter affects the microbial community living in the phyllosphere. This microbial community plays an important role in decomposition of litter fall (Miller et al., 1982; Jensen, 1974; Millar, 1974). Since fungi are important decompose, changing the fungal community on the needles finally weakens the decomposer community, decrease the rate of litter decomposition. All these processes alter nutrient cycling (Bruhn, 1980). Slowly decomposing litter influences nutrient availability within the ecosystem because of accumulation of carbohydrates and mineral nutrients (Cotrufo et al., 1995). Epiphytic lichens and mosses, because of their nutritional dependence upon and continued contact to particulate deposition, are at risk.

There is various indirect and significant effect of particulate matter on ecosystem. Indirect plant responses of greatest interest are chiefly soil-mediated and depend primarily on the chemical composition of the individual elements present in particulate matter. Changes in the soil may not be observed until accumulation of the pollutant has occurred for 10 or more years, except in the severely polluted areas around industrialized point sources (Saunders and Godzik, 1986). The soil environment is an active site of poorly characterized biological interactions (Wall and Moore, 1999). Rhizosphere organisms play a crucial role in creating chemical and biological transformations, decomposing organic matter and making inorganic minerals available for plant uptake (Wall and Moore, 1999). Indirect effects are usually chronic and occur over time and are difficult to determine because the changes are subtle (Garner, 1994).

6 Conclusions

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. The effect of size-segregated rather than chemically speciated particulate matter on ecosystem function is mediated by effects on vigor, 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, an increase in leaf temperature due to changed surface optical properties, and interference with the diffusion of gases into and out of leaves. 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.

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