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Effect of Solid Particulate Matter Deposits on Vegetation – A Review

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ABSTRACT

Very small, or fine, particles are released into the air created by emissions from many natural and man-made sources, including power plants, traffic, agriculture, open fires, and volcanoes. There are hundreds of types and sources for fine particle matter (PM), affecting plants on various ways. Plants suffer from stomatal closure leading to cell/tissue changes, leaves' necrosis, and chlorosis. The first physiological reaction after PM deposition to the vegetation takes place on the leaf with reduced net assimilation efficiency. Long-term depositions change the photochemistry leading to retarded leaf growth. Deposits for many years over plants' surfaces lead to large-scale reductions in the assimilate balance. Additionally, there are few reports on abrasive effects of PM, especially under high wind speed, supporting secondary effects such as an increase in diseases and pest incidence after the protective leaf cuticle were removed physically. Changes in soil chemistry due to PM deposition in the rhizosphere also lead to a change in soil nutritional values. Finally, PM can affect over longer periods natural plant communities due to selective advantage of some species over others.

Keywords: air pollution, fine dusts, fly ash, plant filter, PM_{10}, silica

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INTRODUCTION

Research on the impact of solid particulate matter dates back into the 18th centurary. Sir Percival Pott published 1785 (in Goldberg 1985) an epidemiological study about cancer diseases in chimney sweepers. Since 30 years, human health relating studies are conducted looking into the impact of dust particles on human health (Repace and Lowrey 1980; Spengler *et al.* 1980). However, research on atmospheric pollution and its impact on plants has focused predominantly on phytotoxic elements such as NO_2, O_3, and SO_2 (Farmer 1991a). Recently, public awareness has been raised to CO_2 problems and fine particle matter (PM, fine dust), especially because of increasing traffic and anthropogenic activity in urban areas (Cwiklak *et al.* 2007). As a result, in the last few years the research on the effect of PM on animals, including human being and environment, in Germany and all over the world is increasing. In the meantime, the European Union (EU) raised threshold-safety levels for particulate matter in the air of urban areas of Europe. In January 2005 the EU guideline 1999/30/EG regulating the maximum allowed concentration of fine dust particles smaller or equal to 10 µm (PM_{10}) became legally binding. It has been widely estimated that Germany and other EU countries might not be able to maintain acceptable limits in many places due to ever-increasing pollution and urban sprawl (Umweltbundesamt 2005).

Airborne particle range between 1 nm (0,001 µm) and 100 µm (Graedel and Crutzen 1994). Airborne fine PM can affect negatively human health (Lahl and Steven 2004). The effect of fine dust on human health ranges from temporary impairments to an increase in mortality due to acute respiratory illnesses and cardiac disorders (Hartog *et al.* 2003). Ultrafine particles might cause irritation and allergic response leading to inflammatory changes (Donaldsona *et al.* 1998). As the particles are smaller, they can penetrate into the respiratory system very easily. That particles with a size of more than 10 µm can penetrate into the larynx has been demonstrated (Sarangapani and Wexler 2000). However, only a small fraction of them reaches the smaller bronchi and the alveoli in lung (Pekkanen *et al.* 1997). Particles below 10 µm penetrate these organs/tissues very easily

Received: 20 December, 2007. Accepted: 2 May, 2008.

Invited Mini-Review

Table 1 PM categories based on their.

Category	Property
Very fine particle	Particle < 0.1 µm (= 100 nm)
Fine particle	Particle < 2.5 µm
Raw particle	Particle 2.5–10 µm
PM10	An air pollutant consisting of small particles with an aerodynamic diameter less than or equal to 10 µm.

leading to permanent disability in the system. Ultra fine particles, whose particle size is below 0.1 µm, could even penetrate alveoli and become released into the bloodstream (Borm and Kreyling 2004) leading its distribution throughout the body. Still, correlation studies with different sizes of the dust particles and their biological effect are far from being complete. This might be partly due to diverse and heterogeneous health effects showed by similar dust particles in many different biological model systems as well as by the heterogeneous composition of naturally occurring dusts.

While numerous studies are available in the literature on the effects of fine dusts on human health it must be noted that there are only few studies about their effects on vegetation. Most of these investigations are in urban ecology and related to the research on the air-purifying capacities of urban green (Shao *et al.* 2004). The extent of damage caused by fine dust depositions affecting plants' physiological processes were often not considered. This is surprising considering the fact that long-term adverse effects, including reduced diversity, due to heavy dust depositions on plants is not a new finding (Daily 1997).

DEFINITION OF FINE DUST

Finest dust particles present in the atmospheric aerosol are called "particulate matter" (PM). The term PM classifies a particular type of air pollution that consists of complex and varying mixtures of particles suspended in the air. PMs are present everywhere, but high concentrations and/or specific types of particles present in ecological niche pose serious threat to living organisms (Vincent and Clement 2000; See *et al.* 2006). In general, PM is a combination of fine solids such as dirt, soil dust, pollens, molds, ashes, and soot and refers to the aerosol form present in the atmosphere (Thönnessen 2007). Additionally, gaseous combustion by-products such as volatile organic compounds, sulfur dioxide and nitrogen oxides are part of the PM repertoire (Rizzo and Scheff 2007). A classification method based on the particle size could be as follows (**Table 1**).

SOURCES AND COMPOSITION OF FINE PARTICULATE MATTER

PM pollutions usually arise from multi-various sources. They can derive from anthropogenic activity as well as from natural sources (Schelle-Kreis *et al.* 2007) (**Table 2**). They can be released into the environment as primary or secondary particles. Primary PM develop and are produced directly from the source. While secondary PM are reaction products in the atmosphere. Examples of such reaction products are ammonium sulfates and nitrate of ammonia as well as aldehydes and ketones (Tong *et al.* 2006). These substances adhere to other atmospheric particles easily leading to the formation of nuclei of condensation (Gibson *et al.* 2007). Fine dusts are carried easily by wind. Many industrial processes, especially quarrying causes fine PM production in huge quantities around the world (Fennelly 1975). Other major sources of PMs are traffic and thermal power plants (Brook *et al.* 2007; Gilmour *et al.* 2007). Contribution of different sources towards total dust pollution varies from location to location. Even within traffic, the emissions from car vary a lot (Düring and Lohmeyer 2001). Langner (2007) used for his calculations of PM filter efficacy rates of urban greens a mean PM emission rate per car of 100 mg km^{-1}. It is not easy to transfer empirically based deposition factors to complex urban situations. Still, Litschke and Kuttler (2007) calculated based on a simple modell for a 100 m long street segment with a daily traffic volume of 40,000 cars a potential removal of 8% of the PM emitted by cars. In this study, a velocity of 0.1 cm s^{-1} and a maximum possible green cover were used for the calculation. The chemical composition of traffic PM emissions has been changed through the introduction of three-way catalytic converters and unleaded gasoline. Leaded gasoline in Germany can contain 13 mg l^{-1} lead (Jentsch 1986). In 1991 leaded gasoline held 25% market share and in 1995 the share went down to 6%. Since 1997, only unleaded gasonile is sold. Lead emits in 0.01-0.1 µm aerosol particles. Those particles can agglumerat to 0.3-1 µm size particles (Alloway 1999). Diesel carbon PM derived from traffic is still a very import source for PM in urban areas (Ried *et al.* 1999). For copper diesel PM and PM debris from car break are the biggest sources (Heinrichs and Brumsack 1997).

Due to a heterogeneous composition of different naturally occurring dusts, it is often very difficult to examine the effects of PM on the vegetation in specific experimental settings. In the literature, profound and valid statements about physical effects of PMs are widely distributed, but rarely chemical effects of dusts are considered. Some silica PMs derived from rock in inland settings and from shells or algae in costal areas are relatively inert in nature (Mewis and Ulrichs 2001a, 2001b; Ulrichs *et al.* 2006b). Other PMs like limestone quarry dusts are highly alkaline in nature (Darley 1966; Everett 1980).

We have to distinguish between two types of dusts impact: 1) the sedimentation, which calls the deposit/setting off from particles under the influence of the force of gravity and 2) the compaction, a reduction of volume based on the pressure of above layers. Dust can impact plants directly by covering aboveground parts of the vegetation or indirectly over the soil and the root systems. Apart from the pure size of the dust particle the physical and chemical characteristics of the particles are also important for their effect on plants. Plants differ in their ability to collect PM from the air (Möller 2003; Wolf-Benning 2006) and in their reaction to PM depositions.

Table 2 Composition and size of particle matter depending from its source.

	Source	Substance
Anthropogenic	• Power stations, house fire, agriculture, chemical industry, petrochemical chemistry, traffic	• Fly ash, sulfur oxides (SO_2, SO_3), nitrogen oxides (NO, NO_2), ammonia (NH_3), volatile non methyl hydrocarbons, soot particles, abrasion of brakes, exhaust gas of transport
Natural	• Volcano, ocean, forest and shrub fires	• Sea-salt aerosols, dust, pollen, spores, micro organisms, methane, nitrogen dioxide, hydrogen sulfide, nitrates
Fine particle ($PM_{2.5}$)	• Driving automobiles • Burning plants (brush fires and forest fires or yard waste) • Smelting (purifying) and processing metals	• Toxic organic compounds • Heavy metals
Coarse particles (PM_{10})	• Crushing and grinding rocks and soil then blown by wind • Agriculture	• Smoke, dirt and dust from factories, farming, and roads • Mold, spores, and pollen

PM DEPOSITS ON VEGETATION

PM vary widely in sizes (Ninomiya *et al.* 1971; Fennelly 1975) and travel therefore differently in the air. Everett (1980) found that for unpaved roads, there was a rapid decline in particle size in the first 8 m from the road. In a similar study, Tamm and Troedsson (1955) found that beyond 20 m from an unpaved road only fine silts are deposited. Dusts from streets are not necessarily black and might not affect light absorption and leaf temperature as much as other dusts (Sperber 1975).

Generally, coarse particles are filtered by plants at a much higher rate than fine particles (Langner 2007). The amount of PM deposited on plant surfaces varies significantly spatio-temporally. Many of the factors responsible for the PM deposition are similar to those governing deposition of other pollutants. Generally greater surface roughness increases deposition rate (Belot *et al.* 1976). This parameter is especially important at greater wind speeds (Chamberlain 1967). Chamberlain (1967) also describes, that wet surfaces can result in higher deposition rates. The plant reaction differs depending on size of the deposited particles and the percentage of relative humidity. It has been observed that chemical interactions of dusts with the vegetation surface are impaired by the presence of water. For example, fly ash to a great extent is not water soluble and thus the probability of chemical burn only very small. This may not apply to other types of dust. Pilot experiments on PMs which affect plants were conducted by Duggar and Cooley (1914) on commercial crops. They compared charcoal, calcium carbonate, and aluminum hydroxide dusts on *Lycopersicon esculentum*. All three dusts increased transpiration, but charcoal reduced growth parameters while the other dusts increased it. Sree Rangaswami *et al.* (1973) studied in southern India the distribution of plant species around a cement factory that emits PM. Of the 54 species that they found, only nine were able to grow close to the factory. All of those plant species possessed small leaves, resulting in a reduced dust load. Generally, unpaved roads produce higher dust levels than paved roads (Roberts *et al.* 1975). Everett (1980) undertook a detailed study of an unpaved road in Alaska. He 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.

Dusts affect plant physiology at both physically as well as at the chemical and biochemical level. The absolute level of dust deposition might be important for physical effects. Fine dust particles can clog stomatal openings (Oblisami *et al.* 1978; Hirano *et al.* 1995), reduce photosynthesis (Borka 1980), increases leaf temperature (Steinhubel and Halas 1967; Guggenheim *et al.* 1980), and increase transpiration (Eveling 1969).

Reduction of photosynthesis through deposition

The substantial effect of PM deposition on plant leaf surfaces probably lies thereby in a reduction of the photosynthetic product (Auclair 1977; Naidoo and Chirkoot 2004). Krajickova and Mejstrik (1984) confirm this assumption. The authors found that PM from a coal-fired power plant affected photosynthesis of *Calamagrostis epigeios* and *Hypericum perforatum* but the stomata were rarely blocked. They suggested that the dust might act directly on the guard cells, though the mechanisms for this effect remain uncertain until now. After PM deposition on the leaves, *Rhododendron catawbiense* exhibited an increased absorption in the infrared spectrum and a reduced reflection and transmission of radiation (Eller and Brunner 1975).

Deposition of smaller particle sizes leads to stronger reduction of photosynthesis than with coarse particles (Hirano *et al.* 1990). This effect is presumably due to the closer lining of dust particles on leaf surface resulting in a greater shading effect of photosynthetically active radiation (PAR). In experiments, where dusts of different particle sizes were applied electrostatically to *Brassica* plant leaves, no difference in the photosynthetic efficiency of the plant was found. This may be due to uniform particle distribution and a very thin layer of PM deposition (Ulrichs, unpublished data).

Plant reactions due to dust deposition are species dependent. For example, the chlorophyll fluorescence of *Ilex rotunda* and *Ficus microcarpa* grown close by a ceramic plant are less affected than for *Machilus chinensis.* Least changes of the photosystems II have been observed with *I. rotunda* (Wen *et al.* 2004). The chlorophyll fluorescence data of the mangrove, *Avicennia marina*, indicated that leaves coated with dust exhibited significantly lower photosystem II (PS II) quantum yield, lower electron transport rate (ETR) through PSII, and reduced quantum efficiency of PSII (F-v/F-m) (Naidoo and Chirkoot 2004). Nanos and Ilias (2007) are reporting similar results for olive trees exposed to cement dusts. In their study, cement dust decreased leaf total chlorophyll content and chlorophyll a/ chlorophyll b ratio. As a result, photosynthetic rate and quantum yield decreased. Long-term effects include a change in the leave biochemistry and a possible increase in plant pathogen and phytophagous arthropods incidence (Taylor *et al.* 1986). Taylor *et al.* (1986) reported leaf rolling and intervenial necrosis in *Phaseolus vulgaris* after deposition of cement. Sperber (1974) already assumed that plants adapted to low light conditions are less affected by dust depositions than plants adapted to grow directly in the sun.

Interference with stomatal functions

PM deposition can cause blockage of the stomata on the upper surfaces of the vegetation under natural conditions, and to a smaller extent at the lower surfaces. According to Krajickova and Mejstrik (1984), the stomatal diameters of most plants usually range from 8-12 µm. Therefore, PM particle size is an important criterion for a possible leave penetration. Particles with PM_{10} and smaller sizes can theoretically interfere with stomatal functions. Clogging the leaf stomata lowers the rate of transpiration and carbon assimilation, which finally causes a significant reduction in the photosynthesis rate. Dusts affect less plants, which exhibit physical protection structures such as trichomes compared to plants without such physical barriers.

Coal dust significantly reduced carbon dioxide exchange of upper and lower leaf surfaces of the mangrove, *Avicennia marina* by 17-39%, whereby the reduction was generally greater on the lower leaf surface, which has a dense mat of trichomes and salt glands (Naidoo and Chirkoot 2004). Nano and Ilias (2007) describe a decrease of the stomatal conductance to H_2O and CO_2 in *Olea europaea* exposed to cement dusts, resulting in a reduced productivity of olive trees.

Hirano *et al.* (1995) found that dust decreased stomatal conductance of cucumber and kidney beans in the light, but increased it in the dark by plugging the stomata, when the stomata were open during dusting. When dust of smaller size particles was applied to the plants, the effect was greater. However, the effect was negligible by closed stomata during dusting.

Flückiger *et al.* (1979) found, that 1 mg cm^{-2} of silica dust was necessary to cause a decrease in stomatal diffusive resistance in *Populus tremula*, but only 0.5 mg cm^{-2} was necessary to cause an increase in leaf temperature. Metabolic functions in plants operate only in a certain optimal temperature range. If a leaf heats up above 34°C, photosynthetic enzymes begin to denature and the leaf cannot perform its normal function. For example, Jiao and Grodzinski (1996) describe an inhibition of photosynthetic export in *Salvia splendens* above 35°C in both photorespiratory conditions, whereby photosynthesis only under photorespiratory conditions was inhibited. Sucrose and raffinose but not stachyose accumulated in the leaf at 40°C. Plants react in this situation with an increase in transpiration to lower leaf temperatures.

Interaction with the cuticle

Ulrichs *et al.* (2006a) and Majumder *et al.* (2007) used silica dusts applied to *Brassica* leaf surfaces as insecticides. The dusts had strong lipophilicity and weak hydrophobic characteristics. Thereby, the dust got physically absorbed on surface waxes of the leaves causing an irreversible damage resulting in a reduced photosynthetic rate.

Bacic *et al.* (1999) made comparisons between the surfaces of *Pinus halepensis* needles from a site with relatively clean air, and one near to a cement factory in Croatia. Induced changes in the appearance and quantity of surface wax were recorded only for the samples collected near to the cement factory. In particular, crystalline wax in suprastomatal cavities appeared to coalesce, and subsequently additional amorphous wax formed round the rim of the stoma.

However, this effect depends on physico-chemical properties of the PM and environmental conditions. Hofmann and Bomhard (1956) and Ulrichs *et al.* (2005) showed that application of fly ash on leaves did not interact with the leaves in open fields. In open field conditions, small size particles drift easily from the leaf surface via air movement and precipitation. Therefore, dusts impair directly neither leaf surfaces nor photosynthesis significantly.

PM EFFECT OVER THE SOIL

PM drift resulting from agricultural liming and fertilization can have an eutrophication effect on nearby soils. The best-studied PM depositions are for coal fly ash from power plants. Hofmann and Bomhard (1956) estimated a daily hard coal fly ash deposition of 1 g/m^2. For decades, numerous researchers have looked into the possible use of coal fly ash in agriculture (Page *et al.* 1979; Adriano *et al.* 1980; Maiti *et al.* 1990). Hard coal fly ash (CFA) is a smell less, grey, fine-grained and powdery substance, which consists mainly of spherical, glassy particles. Main components of CFA are SiO_2, Al_2O_3 and Fe_2O_3. Both Logan and Harrison (1995) and Wong (1995) described CFA as rich in calcium and magnesium oxide and thus explaining the high pH value observed by others. CFA contains polychlorinate biphenyls (PCB), polycyclic aromatic hydrocarbons, and various metals in the mg per kg range. In various investigations, fly ash as substrate was used and data were interpreted from the viewpoint of plant nutrition (Elseewi *et al.* 1978; Hill and Lamp 1980; Engelke and Marschner 1991; Kalra *et al.* 1998). Generally, changes in soil chemistry after PM depositions may be most important for long-term effects on plants (Scheffer *et al.* 1961).

Soil nutritional value

Plants use inorganic minerals for nutrition. Many factors influence nutrient uptake for plants. Ions can be readily available to roots or could be "tied up" by other elements or the soil itself. Soil too high (alkaline) or too low (acidic) in pH, makes minerals unavailable to plants. The optimal soil pH ranges for most crop plants between 5.5 to 6.2 or slightly acidic. This creates the greatest average level for availability for all essential plant nutrients. Therefore, extreme fluctuations in pH can cause deficiency or toxicity of nutrients. Cawse *et al.* (1989) found that rainfall around a cement plant in south Wales was high in phosphorus and vanadium and had a pH in the alkaline range.

Oats showed germination delay in alkaline soils coupled with reduced yield (Hofmann and Bomhard 1956). Garden cress was relatively insensitive to pH changes (Grantzau 1997; Ulrichs *et al.* 2005). Engelke and Marschner (1991) demonstrated a phytotoxic effect of boron residues in fly ash applications. Leaves contained highest boron concentrations, whereby boron led to drying up of the edges.

Theis and Wirth (1977) found that major components of CFA PM were Al, Fe, and Si with smaller concentrations of Ca, K, Na, Ti, S, and numerous trace elements. Some of those elements like Ca, Fe, Mg, and K are required for plant growth (Kachroo *et al.* 2006; Inam 2007). Some others like Be, Se, and Mo can be toxic. Generally, CFA is not an optimal source for phosphorus since it was found to be inferior to monocalcium phosphate (Martens 1971). However, Ca^{2+} and Mg^{2+} can increase plant growth, as shown for legumes (Adriano *et al.* 1980; Page *et al.* 1979).

Next to the nutritional value, PM can have negative effects on the soil nutritional value. As for example, alarming concentrations of lead were found in dust of densely populated urban areas and in water and land of various areas near the industrial waste disposals (Singh *et al.* 1997). Plants absorb lead and accumulation of this metal is reported for roots, stems, leaves, root nodules, seeds, etc. (Hevesey 1923). Furthermore, lead content of plant tissues increases with the increase of exogenous lead level. Lead affects plant growth and productivity, whereby the magnitude of the effect depends on the plant species. Photosynthesis has been found to be one of the most sensitive plant processes and the effect of the metal is multifacial. Lead also inhibits N fixation and NH_4 assimilation in the root nodules. It appears that the toxic effect of this metal is primarily at physiological level (Singh *et al.* 1997).

Engelke and Marschner (1991) as well as Warambhe *et al.* (1993) had evidences that high CFA depositions result in high soil pH values and phytotoxic boron contents in this areas that disturb plant growth. Only after sufficient precipitation, the phytotoxic characteristics of the substrates with very high CFA content decrease. Other researchers claimed that higher boron contents in CFA have soil-ameliorating characteristics (Wong and Su 1997). Cline *et al.* (2000) showed that yields of soybeans increased up to 35% by CFA applications on sandy and clay soils in south of Ontario. On the yield of corn, CFA had however no effects. Anderson *et al.* (1990) reported an increase of the health-favorable indolyl glucosinolates: Glucobrassicin (3-indolylmethyl glucosinolate) and neoglucobrassicin (1-methoxy-3-indolylmethyl glucosinolate) in yellow turnip upon CFA application.

Soil texture and density

Normally, PM deposition makes only a fraction of the topsoil volume. Therefore, a change of the physical structure of the soil is very unlikely. This is of course different if 1) PM are collected and artificially deposited or mixed in soil. For example, soil properties are influenced by CFA application (Grewal *et al.* 2001). 2) Large dust storms occur which carry high loads of PM. Such phenomena occur periodically in all arid and semiarid parts of the world (Péwé 1981). Here the physical and chemical properties of soil vary according to the original properties. Winchell and Miller (1918) collected samples of dust carried by a storm crossing the US Lake States into New England on March 9, 1918. The dust fall was 4.8 g m^{-2} or 48 kg ha^{-1}. The authors estimated that between 1 and 10 million tons were deposited on an area of 480 000 m^2. Such airborne additions of dust are important to horizontal differentiation in many soils (Simonson 1995).

Several researchers described the role of increasing CFA contents in the soil with positive effects on the water holding capacity in sandy (Roberts 1966; Campbell *et al.* 1983) and coarse-grained (Chang *et al.* 1977) soils.

IMPACT OF PM ON PLANT COMMUNITIES

Some of the earliest references regarding to dust influences on plant community structures dates back to 1910. Parish (1910) was interested in the shrub and grassland vegetation in California near cement factories. He found a shift in the vegetation community close to some cement factories. Krippelova (1982) in Czeslowakia has reported extreme effects of PM depositions near a magnesite factory. Here the deposition rate was so high, that surface crusts were formed and the soil pH rose to 9.5, changing the plant communities towards halophiles rather than calcicoles.

For more than 100 years lichens have been recognized as bio-indicators of air pollution. Because lichen species exhibit varying tolerance levels to air pollution it is possible to correlate lichen diversity and air quality (Nimis and Purvis 2002). Lichens intolerant to air pollution, such as *Usnea* species, are rare in urban areas. On the other hand, tolerant lichens, such as *Parmelia* and *Physcia* species, are often in great abundance in urban areas. Road dust can kill lichens along a dirt road in Alaska (Walker and Everett 1987). Epiphytic lichens are most likely affected via changes in the bark (Farmer 1991b). Lotschert and Kohm (1977) reported bark pH and Ca_2 content changes in the bark of trees after long-term dust exposure. In urban areas, dusted leaves of trees allowed a greater penetration of road salts with increasing water stress (Flückiger *et al.* 1982). Since water stress is one of the major urban stressors for trees such findings can help to select plant species and varieties in anthropogenically determined systems.

SUMMARY

Airborne particle matter affects plants on various aspects. Apart from the composition of the PM, kind of the deposition, place of the deposition, climate, plant surface quality, composition of the environment, and soil as well as the quantity of PM deposition are important. Damage ranges from simple reduction of the photosynthetic efficiency of the target plant to stomatal closure leading to cell/tissue changes, leaves' necrosis, chlorosis, etc. The first physiological reaction after PM deposition to the vegetation takes place on the leaf with reduced net assimilation efficiency. Such reactions are immediate and rise to significant level within minutes after PM contact with the leave surface. Long-term depositions change the photochemistry leading to branch thickness, retarded stem, and leaf growth. Deposits for many years over plant surface lead to large-scale reductions in the assimilate balance. Such effects are rampant in the proximity of day mining industry, thereby affecting the vitality of the vegetation nearby and finally productivity of the plants.

So far, there are only few investigations on the possible abrasive characteristics of PM (e.g. silicates) on the vegetation either at the green house or at the field level. This is mainly because for studying such effects friction energy calculations are essential at the micro level and are very difficult under natural conditions. In nature, especially after sand storm such effects can occur with wind turbulences resulting into mechanical damage of the plant surface with varied physiological consequences. Secondary effects such as an increase in diseases and pest incidences after physical removal of the protective leaf cuticle by PMs is not been studied in detail.

Effects of PM on natural plant communities might also be altered due to selective advantage of some species over others. Finally, changes in soil chemistry due to PM deposition in the rhizosphere lead to modification of the equilibrium between different species in a plant community. Till to date, only a limited number of studies were undertaken at the community level and warrants urgent attention.

It is evident that there are many knowledge gaps understanding the impact of PM on plants. Since plants are being increasingly utilized to filter PM from the air in dense populated areas, we can expect here further research.

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