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Natural Minerogenic Dust and Human Health

DUST SOURCES

Atmospheric aerosols include gases and liquids, as well as solid particles. They include material derived from both oceans and landmass, as well as particles that form within the atmosphere, such as sulfates. Solid particles entrained in the atmosphere by detachment from poorly vegetated surfaces (the process of deflation) include, for example, rock and mineral dust, fine mineral aggregates, fibrous minerals, fibrous organic materials, and sea salt. The burning of vegetation (biomass) yields black carbon, which adds to the opacity of the atmosphere. Smoke plumes from fires, both natural and anthropogenic, are often carried thousands of kilometers from their sources, so increasing the air pollution hazard. In addition to the strongly seasonal inputs from the world's drylands, mineral-dust loading of the atmosphere is also enhanced by injection of fine volcanic mineral particles (*tephra*) containing variously toxic minerals.

This paper considers only those dusts that are derived naturally from the land surface, especially in and around the world's drylands. Anthropogenically generated dusts (such as those derived from industries, vehicles, etc.) are not considered here, although mention is made that both inorganic and organic toxic substances may become attached to natural atmospheric dusts, including toxins of human origin.

Atmospheric aerosols also influence the chemistry of the troposphere, including the proportion of ozone. Particle size and chemistry of the dust load affect air temperatures (by varying absorption and scattering of solar radiation). Given the present global warming trend, progressive desertification, and human actions that continue to increase the atmospheric dust loading, the intimate relations between aerosols and the global environment have obvious implications for future climatic change (1), and yet further indirect effects on human health around the world.

Detachment of mineral dust from the ground surface ("deflation"), and its entrainment and transport by the wind is a function of several variables, including wind speed (notably the critical wind speed or threshold velocity required to dislodge particles), the degree of atmospheric instability, the size and shape of the particles, the roughness and moisture content of the land surface, and the degree of particle exposure. The clay-size (<2 μm: Fig. 1) component of soils and sediments is not readily detached from a land surface by the wind as individual particles because of the high interparticle cohesive forces typical of such colloidal materials. Entrainment of these finer particles usually occurs in association with the coarser (silt-sized) grains, as well as in the form of coarse or medium silt-sized aggregates made up of variable mixtures of fine silt and clay-grade particles. Once entrained, however, fine dust particles may travel a thousand or more kilometers before being deposited, some of the finest particles being transported as much as 20 000 km from their source (2). Travel distance is largely a function of particle size and atmospheric conditions, the coarser fractions being deposited much closer to their source. The medium and coarser fractions of such dust (mainly in the silt range: 2–63 μm) may accumulate to form the sediment type known as *loess* (3, 4). Loess is made up of wind-lain geogenic dust, which is subject to varying degrees of postdepositional alteration, particularly by the processes of weathering and soil formation. Loess has been accumulating on the continents, especially Eurasia and the Americas, for millions of years. Its susceptibility to erosion by both wind and water, especially along desert margins and on degraded dryland surfaces, make it a secondary source of wind-blown mineral dust, as mentioned further on.

Dominant dust sources around the world are almost wholly in or adjacent to the great drylands of the northern hemisphere. The greatest of these includes a broad swathe of land across North Africa, the Middle East, northwest India, and central and eastern Asia—from the western Sahara to the Yellow Sea. Other notable sources are found in the Great Basin of the United States and, in the southern hemisphere, east-central Australia, central and northern Argentina, and parts of southern Africa.

In both North Africa and China, dried-out former lake beds are a major source of fine, readily deflated mineral dust (e.g., 5, 6). The Bodélé depression [Chad, North Africa (7)] and the numerous lake depressions in northern China and central Asia are major dust sources of global significance (Figs. 1 and 2).

Saharan dust, driven by the northeast trade winds, takes about a week to cross the Atlantic Ocean, reaching northeastern South America in the (northern) late winter and spring, and the Caribbean, Central America, and the southeastern United States in summer and early autumn (8) (Fig. 2).

The midlatitude deserts of Asia are a source of substantial airborne dust, especially during spring and early summer. The two major Chinese dust sources (Mongolia and the Tarim Basin–Taklamakan Desert) are of global importance, fine dust from both these regions having been traced to North America, Greenland, and Europe. Driven in the winter half year by large "Siberian High" pressure cells, locally easterly winds flow around the southern flank of the seasonal high pressure cell that

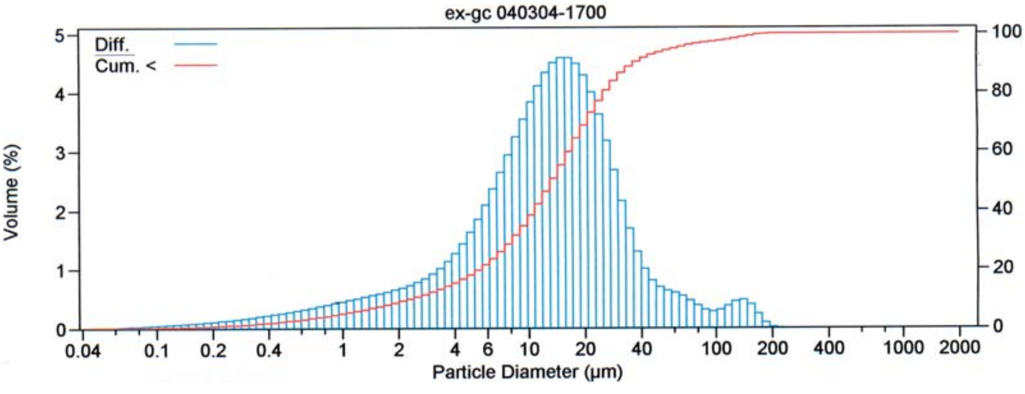

Figure 1. Modal and cumulative percentage volume curves for natural Saharan dust deposited on the island of Gran Canaria in March 2004. The particulate matter (PM) 10 fraction makes up almost 40%, and the PM 2.5 almost 20% of the total volume. (Courtesy of Kenneth Pye.)

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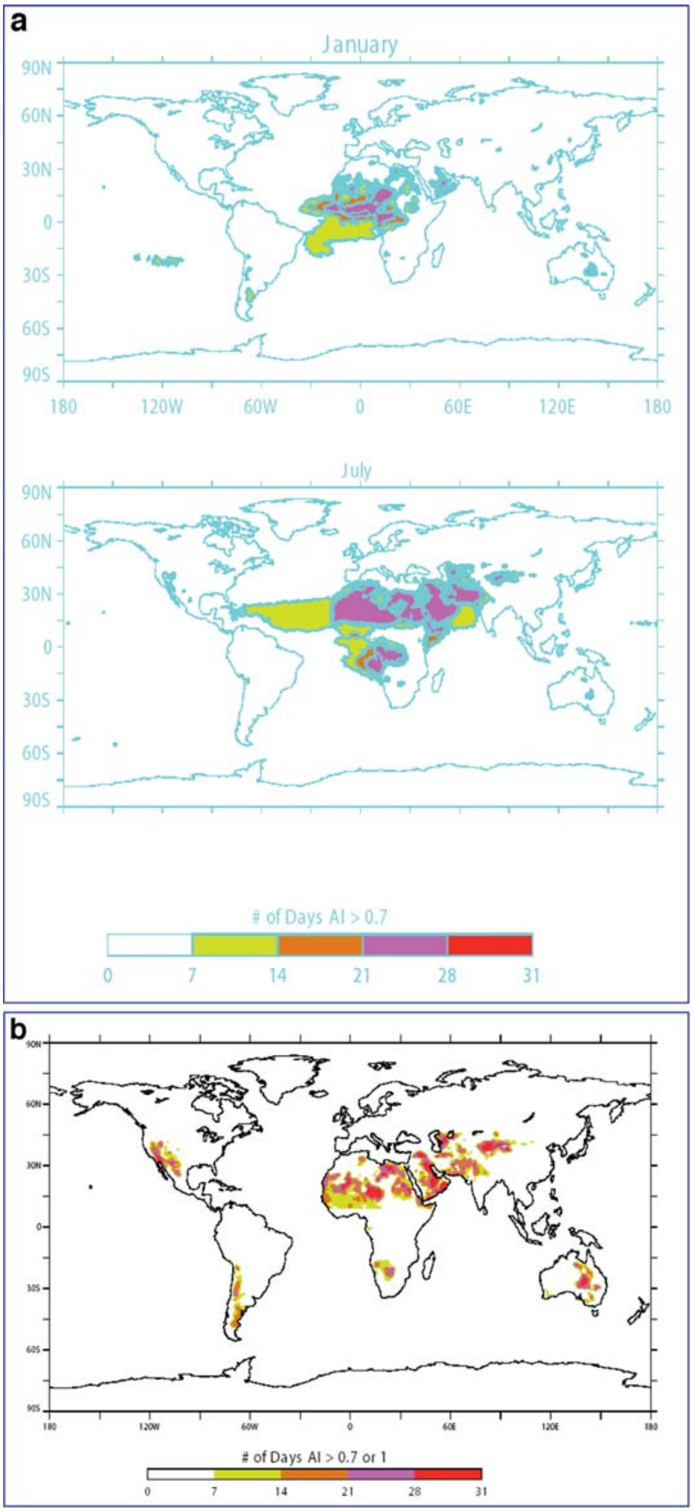

Figure 2. Atmospheric dust monitoring using orbital spectrometry. The Total Ozone Mapping Spectrometer (TOMS) is sensitive to a range of ultraviolet (UV)-absorbing aerosols such as mineral dust, volcanic ash, and black carbon from fossil-fuel combustion sources and biomass burning. The UV surface reflectivity is typically low and nearly constant over both land and water; this allows TOMS to detect aerosols over both continents and oceans. The UV spectral contrast is used in a non-quantitative way as an absorbing aerosol index (AAI).

a. Global distribution of the occurrence frequency of relatively high TOMS AAI values for January and July 1980–1992.

b. Long-term dust storm frequency, showing a distribution of major sources closely similar to other data sources. Sources occur in all continents except Europe and Antarctica (5).

develops over the Taklamakan Desert, and are vigorously uplifted into the upper troposphere westerlies as they come up against the western Kunlun, the Pamir, and the western Tian Shan ranges (all with peaks about 7000 m above sea level). Dust from the Mongolian sources is carried in a more directly west to northwesterly air stream, accounting for the severe late winter and spring dust storms that affect densely populated northeastern China [Fig. 3; see also Fig. 10 in Ref, 9)]. Although airborne dust volumes have increased in the past 30 years or so as a result of increased human settlements and some imprudent farming practices, especially along the southern margins of the northern Chinese deserts (Badain Jarain, Wulanbuhe, Mu-Us, and Onzin-Daq), the process is a natural one with a history going back at least 8 million years. The loess formation, which exceeds 300 m in thickness in several parts of the North China, is impressive evidence of sustained, semicontinuous deposition of the coarser airborne dust fractions (sandy silt and silt) for at least the past 2.6 million years.

The long-term global dust storm frequency closely reflects the distribution of the major dust sources. The annual mean number of "dust days" (defined as reduction in visibility by dust to <1 km) is impressive; e.g., 80 in southwest Asia; more than 30 in the Tarim Basin (Taklamakan Desert), the Hexi Corridor, and the Loess Plateau of China; about 30 in parts of North Africa; and about 20 in the northwest Indian subcontinent (10). Dust storm frequency may be set to increase in some parts of the world if current trends in climate and other environmental changes continue.

Dust palls, rich in very fine mineral dust, occur at both regional and continental scales. Although measurable palls occur throughout the year in some regions, including Middle Asia, Ladakh (NW India), and all of North China (where the exposed population has been estimated at 24 million), there remains much to be learned about the physical, mineralogical, and geochemical characteristics of ambient mineral dust in the context of assessing the disease burden upon exposed human communities. Determination of natural dust sources and concentrations on a regular basis is needed to establish background levels that can serve as a datum for detailed assessment of human and animal exposure levels. Quantitative information on naturally occurring background levels of potentially toxic aerosols is generally sparse, underlying the need for much more detailed physical, chemical, and mineralogical characterization of atmospheric dust.

PATHOLOGICAL EFFECTS OF INHALED MINERAL DUST

Pathological effects arising from inhalation of mineral dust varies with several factors, but the size, shape, and chemical and mineralogical composition of dust particles, the length of exposure of the subject, and certain lung functions are of notable importance.

Inhaled coarse mineral particles (>10 μm) are commonly lodged in the upper respiratory tract and are rejected by expectoration, but they may constitute a health risk if the mineralogy is toxic, regardless of where the grains lodge in the respiratory system. The respirable fraction (particles <10 μm, the first "PM standard" of the US Environmental Protection Agency) may remain suspended in the atmosphere for some length of time (weeks); the fraction of the dust $\leq$4 μm that penetrates more deeply into the finer lung passages may cause silicosis, asbestosis, and other lung conditions (Fig. 1). Mineral dust finer than 3 μm found in lung tissue from one Chinese postmortem subject made up about 75% by weight of the total dust burden in the lungs (similar grain size to the second "particulate (PM) standard" of <2.5 μm). The denser the ambient dust and the longer the exposure, the higher are the rates of chronic respiratory disease and associated death rates.

Inhalation of the finer ($\leq$4 μm) fractions of mineral dust eventually leads to deposition in the pulmonary alveoli where chronic lung disease is initiated. Some types of inhaled particulates are degraded by macrophages (mononuclear phagocytes in the lung alveoli), but many are highly resistant to this process and persist in the lungs. Some resistant particulates appear to cause no problems, but others stimulate fibroblastic cells (secretionary cells of connective tissue) to deposit collagen, a protein making up the white fibers of skin, cartilage, and all connective tissue. Although the precise nature of the pulmonary response to mineral dust particles is complex, a number of factors are considered to influence potential toxicity. These include the presence of specific minerals within the respirable fraction, the shape of particles (which influences clearance from the lungs), the presence or absence of mineral coatings, and particle surface characteristics including surface area and surface chemistry including the potential to generate free radicals (which can instigate disease by causing damage to lung tissue by abstracting electrons from DNA (11).

The dominant mineral in Eurasian dust is quartz (SiO_2: "free silica"). The measured quartz content in major dust storms is very similar (60.95% in North Africa; 60.26% in China), closely matching the mean value for the Earth's crust (58.98%). Silica is a highly fibrogenic agent in lung tissue, a process that is very different from the granulomatous reaction attributed to many other nondegradable grains.

There is evidence that response varies with the species of silica inhaled. Some forms of biogenic silica (e.g., diatoms and phytolith fragments) with diameters $<$10 μm are common in, for example, Saharan dust, but are generally considered to be benign.

Radiographically visible fibrosis may take years to appear. Radiographic diagnosis of silicosis is made with confidence only after the appearance in a patient's lungs of silicotic nodules 2–5 mm in size. Continued dust exposure leads to an increase in nodular size and number. Eventually, nodules may cover much of the lung, the nodules sometimes coalescing to form conglomerate shadows, a stage often called progressive massive fibrosis (12).

The group of lung diseases known as pneumoconiosis includes silicosis and asbestosis. Silicosis arises from prolonged inhalation of free silica; it is a seriously disabling disease, being progressive and incurable. Silicosis has attracted considerable attention as probably the most widespread of the *occupational* diseases, but nonoccupational silicosis has been relatively little studied even in regions with large populations exposed to massive, ambient dust concentrations. Asbestosis is a degenerative fibrosis of the lung resulting from chronic inhalation of asbestos fibers. Asbestos is a group of fibrous silicate minerals that includes extremely fibrous serpentine (chrysotile) or amphibole minerals (crocidolite, amosite, tremolite, actinolite, and anthophyllite) found in a wide variety of geologic environments. Although not covered by the term "asbestos," the mineral erionite, a fibrous zeolite, is also known to cause asbestosis and related conditions.

The impact of airborne mineral dust may be exacerbated by the presence within fine dust particles of bacteria, fungi, and other microorganisms (13). The global extent of the fine dust transport system has been implicated in intercontinental transport of microorganisms with the potential to damage plants and animals, including human subjects (14–16). Although susceptible to destruction by ultraviolet radiation, a proportion of the included microorganisms may survive in cavities and cracks within suspended dust particles. Deterioration of coral reefs in the Caribbean has been attributed to fungi (*Aspergillus sydowii*) transported by North African dust (17).

Figure 3. Before and during a Mongolian dust pall over Beijing, April 2003. Photograph by the author.

Notwithstanding increased awareness and understanding of the main pathways and pathological impact of naturally occurring dusts, including a number of case studies such as those illustrated in the following section, information on the disease burden arising from exposure to naturally occurring dusts in different populations around the world remains sparse. Specifically, the strength of the relation between known high frequency atmospheric dust concentrations and the type and frequency of community illness requires critical assessment, especially in a number of perceived high risk environments. Current trends in climate change and aridification make this a matter of some urgency, especially in the drylands along the margins of the middle latitude desert zone that extends across the Old World from West Africa to the Yellow Sea.

SELECTED CASE STUDIES

Nonindustrial Silicosis

Nonindustrial silicosis has long been recognized in northeast Africa and the Middle East, where it is referred to as "desert lung syndrome," the earliest know cases being found in some ancient Egyptian mummified bodies (18). Nonindustrial deposition of silica in human lung tissue was first reported in living populations in a study of three inhabitants of the Sahara Desert more than half a century ago (19). Typical autopsy results showed a high content of fine ($<$3 μm) silica dust.

A radiographic study of 54 Bedouin people in the Negev Desert strongly suggested that the incidence of fibrosis is age related, with progression more notable in women (13 out of 22) than in men (only 4 out of 32), perhaps related to greater exposure in and around the family tents (20). Other findings from different parts of North Africa include radiological evidence of multiple micronodules in reticular disposition scattered throughout the lungs, and considered to be consistent with silicosis (21).

More recently, the human health impact of Saharan dust storms (local Spanish: *calimas*) has been recognized in the Canary Islands (Las Canarias), where the respirable dust percentage is high, some 35%–40% by volume being finer than 10 μm and about 20% finer than 5 μm. This is known to give rise to cases of breathing disorders, including asthma, in autumn but especially in the late winter to early summer season. Dust samples taken regularly during *calimas* at several sites on the island of Gran Canaria, including a summit site (1930 m) include measurable contents of several elements implicated in lung disease. Silicon is dominant in all cases [quartz $>$ 60%: (22), Gelado et al., unpublished].

Research studies undertaken in Ladakh are of particular interest (23–25).This is a region without any mines or industries, but one in which dust storms are frequent. Mineral dust found on the upper surfaces of wooden roof beams of Ladakhi houses is all finer than 15 μm, more than 25% by weight being finer than 1 μm; the silica content is $>$60%. Study of necropsy lung tissue samples from villagers revealed heavy dust deposition with abundant hard, 1–3 mm diameter nodules and a lymph node largely replaced by hyaline collagenous nodules, a classic feature of silicosis. More than 20% of the mineral dust extracted from the lung tissue consisted of quartz; bulk chemical analyses yielded 54% elemental silica and 19.2% aluminium. In the study by Norboo and others (24), radiographic evidence was derived from an equal number of men and women between the ages of 50 and 62 years in two villages at different altitudes (3200 and 3500 m above sea level). These data revealed important differences evidently arising from the higher dust concentrations found in the lower of the two villages. Several cases of progressive massive fibrosis were found in the lower village, with none in the upper village, suggesting that silicosis may cause appreciable morbidity at lower altitudes in this environment.

The large population subjected to frequent dust storms in north China probably includes substantial numbers of people with nonoccupational silicosis, although the number of available published studies is sparse.

One published study in China (26) involved a group of 395 people (294 men and 101 women) in two communes in the middle of the Hexi Corridor, Gansu Province. Lying between the stony desert (Mongolian: *gobi*) of Inner Mongolia to the north and the 700 km long Qilian Mountains and Tibetan Plateau to the south, the Hexi Corridor is subject to dense, and often violent dust storms driven by strong westerly winds associated with the Siberian high pressure cell, especially between spring and early summer. Measured dust concentrations reached 42 mg/m^3 at outdoor sites, rising to 200 mg/m^3 indoors, with a free silica content of 61%. A 7% incidence of pneumoconiosis was found in the tested population, but no significant difference in incidence was found between the sexes, despite the much higher dust concentrations found inside domestic dwellings. A clear increase in incidence with age was found, however, with pneumoconiosis occurring in more than 40% of subjects over 40 years of age. An extension of radiographic studies to domestic animals showed that even the lungs of camels are affected by silicosis in this region. The situation in the Hexi Corridor is complicated by the presence of industries associated with some of the main cities and towns, adding fly ash and potentially toxic elements, including Cu, V, Pb, Zn, and As to the dust burden (27).

Silicosis: Link to Tuberculosis

Silicosis has some deleterious effects upon the immune system. Some rheumatic diseases, as well as chronic kidney diseases, also show higher than average incidence in individuals exposed to silica, and such increased susceptibility of subjects to several mycobacterial diseases is, to some extent, due to impaired function of macrophages in silicotic lungs.

Impairment of the immune system may give rise to a reduction in the ability of macrophages to inhibit growth of tubercle bacilli. Nontuberculosis mycobacterial infections (involving intercellular bacterial parasites) may occur, but long, continued exposure to silica has been linked to increased rates of infection with pulmonary tuberculosis, a notable public health problem in many developing countries. The causal relation between silicosis and tuberculosis has been demonstrated in occupational health studies in which South African gold miners with silicotic lungs were shown to be more susceptible to tuberculosis.

Tuberculosis seems an unlikely disease to be found in drylands, because sunlight and aridity are antipathetic to the development of tubercle bacilli, and droplet transmission of pulmonary tuberculosis is favored by *lack* of sunlight, higher humidity, and overcrowding. However, data from the Thar Desert in northwest India show a prevalence of tuberculosis in the desert areas of Rajasthan that is some 25% higher than in the nondesert parts. Radiographic evidence of nonoccupational silicosis in desert people thus offers some support for the view that silicosis may be an important factor in the higher prevalence of tuberculosis in some deserts (28).

Nonindustrial Asbestosis

Natural release of asbestiform minerals from the host rock occurs by the processes of weathering and erosion, the fibers frequently becoming concentrated by overland flow of surface water such as sheetwash and rilling. In seasonally dry climates, concentrations of fibers dry out and so become susceptible to deflation.

The health effects of asbestos inhalation include asbestosis, mesothelioma (a cancerous tumor of the lung lining or pleural cavity), and lung cancer. Some asbestos fibers penetrate body tissue and remain in the lungs, lung lining, and abdominal cavity. Radiographically visible fibrosis may take as much as 15–20 years to appear following initial exposure.

Interstitial lung disease is best documented in the scientific literature on occupational situations, but cases of nonoccupational asbestosis have been reported in several countries in Europe and around the Mediterranean, including Czechoslovakia, Austria, Bulgaria, Greece, and Turkey.

In central Turkey, inhalation of agricultural soils rich in tremolite (a common fibrous amphibole) and erionite is responsible for an endemic malignant pleural mesothelioma. Incidence of this disease is specific to certain villages surrounded by soils containing one or both of these minerals (29).

In northern Corsica, incidence of pleural plaques (a fibrous thickening of the lining of the lung cavity walls), associated with mesothelioma, has been found in residents with no history of occupational contact with asbestos. A clear regional contrast exists between northeast and northwest regions (separated by a mountain range exceeding 2300 m in altitude). Of more than 1700 subjects examined by radiograph, 3.7% of those born in northeast Corsica (with rocks rich in serpentine, asbestos, and chrysotile) were found to have bilateral pleural plaques, compared with only 1.2% of those born in the northwest. Residents born close to asbestos outcrops showed an excess of subjects with bilateral plaques (94.6%), compared with only 5.4% of subjects born in unexposed villages (30). The evidence of high levels of chrysotile fibers in the atmosphere of the northeastern region points to a direct link between disease incidence and inhalation.

CONCLUSIONS

i) The geologic and meteorological study of dust sources, sinks, transport, and geochemistry is an essential foundation for improved understanding of the extent and magnitude of the potential impacts of natural minerogenic aerosols on human health.

ii) The pathological effects of prolonged exposure to natural mineral dust have been recognized in a general way since ancient times, but the number of modern studies of pneumoconiosis outside occupation-specific contexts remains small.

iii) The specific health effects of direct inhalation of high concentrations of fine minerogenic dusts, generated by natural deflation from loose, poorly bound soil surfaces, including those exposed by accelerated erosion of weak geologic formations such as loess, thus remain rather poorly known and relatively little researched.

iv) The magnitude of the world's population affected by inhalation of fine mineral aerosols can only be estimated at present. It is likely to number millions of people in the middle latitude desert zone especially across Eurasia between the eastern Mediterranean and the Yellow Sea.

v) Way of life is an important factor in any assessment of the health impact of respirable mineral dust because it directly affects dust generation, resuspension, and inhalation in many of the world's drylands.

vi) Systematic, transdisciplinary research programs designed to quantify the respiratory health status of people in the same environments, but with contrasting dust exposure potential, and taking full account of other risk factors, including those of anthropogenic origin (occupational conditions, cigarette smoking, life-style, etc.), will be needed to complement any environmental monitoring. Much more detailed characterization of the properties of natural ambient dusts will also be needed to underpin such programs.

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