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TOPICAL REVIEW

Impacts of sand and dust storms on food production

Nick Middleton

St Anne's College, University of Oxford, Oxford OX2 6HS, United Kingdom

E-mail: nicholas.middleton@st-annes.ox.ac.uk

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Abstract

Sand and dust storms (SDS) are common in the world's drylands, regions that are also critically important for global food production. Agriculture is the most prevalent land use resulting in anthropogenic SDS sources, resulting in impacts on cropland and rangeland, but food production is also affected by impacts from natural SDS sources. This review assesses our knowledge of SDS impacts on all the major types of food production in terrestrial and oceanic environments, impacts that occur in all three phases of the wind erosion system: during particle entrainment, during transport, and on deposition. These effects are short term and long term, direct and indirect. Wind erosion is a major cause of land degradation and there is good evidence to indicate that the deleterious effects of SDS can reduce food production via substantially diminished yields of crops, pastures and livestock. However, it is also clear that soil dust plays an important role in major biogeochemical cycles—especially phosphorus, nitrogen and iron—with implications for the valuable environmental services provided by numerous ecosystems, both terrestrial and marine. Ultimately, these nutrients have particular significance for soil formation, ecosystem productivity and food webs on land and at sea, and hence the provision of food for human societies. Efforts to mitigate the negative impacts of SDS on the sustainability of agriculture should be balanced with an appreciation of the significance of soil dust to the Earth system.

1. Introduction

Large amounts of soil are eroded by wind in numerous regions to create sand and dust storms (SDS). Such events are particularly characteristic of the world's drylands—deserts and semi-deserts—because soils in these areas are typically dry and unconsolidated, with little or no protection by vegetation: conditions favorable to the operation of wind erosion processes. The world's drylands are also important for food production. Approximately 40% of global cropland is located in drylands (Prăvălie *et al* 2021) and some 78% of rangelands (grasslands, shrublands and savannas typically used for livestock production) are classified as drylands (ILRI, IUCN, FAO, WWF, UNEP and ILC 2021). The global prominence of drylands as SDS sources and as critically important regions for food production creates impacts that are mutually significant. Dryland farmers and herders are affected by wind-eroded particles from natural SDS sources in deserts, and disturbances caused by the use of land for food production in drylands can easily create new anthropogenic SDS sources.

Much of the interest in SDS and food production stems from the interactions with agriculture and the impacts of SDS have long been recognized (FAO 2023). SDS is a form of accelerated soil erosion, which is widely considered to be one of the most serious threats facing world food security (Pimentel and Burgess 2013, Quinton and Fiener 2024). The impacts occur in several ways, including the loss of soil particles, nutrients, seeds, fertilizers, and associated damage to plant tissue. Hence, SDS is seen as a major cause of land degradation.

The distinction between SDS source areas that naturally emit sand and dust, and locations where human mismanagement renders soil surfaces susceptible to wind erosion is commonly made in global assessments of SDS activity, and agriculture is widely considered to be the most prevalent form of land use resulting in mismanagement and the occurrence of SDS (Ginoux *et al* 2012). Agricultural practices disturb soils and/or change the vegetation cover that otherwise protects soils, by ploughing up grassland for cultivation, for example (Viglizzo and Frank 2006). Farming operations on cropland that can enhance wind erosion include activities associated with land preparation, cultivation and harvest (Nordstrom and Hotta 2004). Abandoned fields are also frequently recognized as SDS sources (Moridnejad *et al* 2015), and the excessive use of water for irrigated agriculture can create new SDS hotspots on the desiccated lakebeds of shrunken water bodies (Zucca *et al* 2021). On rangeland, wind erosion can occur in areas where excessive grazing has depleted vegetation cover and trampling by livestock has destroyed soil crusts (Eldridge and Leys 2003). All these practices are prevalent in drylands, but they can also leave land susceptible to SDS in almost any climate zone and the erosion of soil by wind thus occurs in agricultural regions outside dryland environments when conditions are right (Bartkowski *et al* 2023), often in combination with adverse climatic conditions such as drought.

The effects of SDS are also felt in other sectors, including health, electricity generation and the transport industry (Middleton 2017). During major SDS events these impacts occur over large areas and in multiple countries (Middleton *et al* 2021), often at great distances from source areas and outside the drylands (Liu *et al* 2006, Conceicao *et al* 2018). The hazardous nature of SDS means they are likely to impede the achievement of several Sustainable Development Goals (SDGs). This often transboundary threat has brought SDS to the attention of the United Nations General Assembly, which in 2023 proclaimed 12 July as the International Day of Combating SDS, to be observed annually. The following year, the United Nations Decade on Combating Sand and Dust Storms was declared for 2025 to 2034. These decisions followed General Assembly resolutions on the issue adopted every year beginning in 2015. The threat to the SDGs is especially marked in drylands because of the prevalence of SDS in these regions but also because many drylands are characterized by high levels of poverty among subsistence and small-scale food producers (Lucatello and Huber-Sannwald 2020).

However, while SDS are certainly hazardous to human societies, some authors have advocated a more balanced approach to the issue, highlighting the benefits of soil erosion by wind as part of a natural system (Poortinga *et al* 2011). The occurrence of SDS plays numerous roles in the Earth system, affecting the atmosphere, biosphere, lithosphere, hydrosphere, and cryosphere (Ridgwell 2002, Goudie and Middleton 2006). This review is written in the spirit of a more holistic approach. It evaluates the impacts of SDS, both negative and positive, on the production of food from terrestrial (predominantly cropland and rangeland) and oceanic (capture fisheries and mariculture) ecosystems. Within these sections, the article is divided according to the three phases of the wind erosion system: initial particle entrainment in SDS source areas, transport, and deposition, although SDS impacts on marine food production occur only in the deposition phase. The emphasis on land is on drylands for reasons stated above but, to reiterate, SDS impacts on land-based food production can occur in most climate zones when conditions for wind erosion are appropriate or due to the deposition of wind-blown material transported from dryland sources.

2. SDS impacts on land-based food production

2.1. Soil erosion by wind

The erosion of topsoil by wind from a field or an area of rangeland has a variety of impacts, on-site and off-site (table 1). Damage by a high-velocity wind itself can have major impacts on crops as plants re-orientate themselves, reconfigure canopies, or shed leaves and branches in order to reduce the drag. In a particularly strong wind, plants can be shaken until roots or stems fail (Gardiner *et al* 2016). Soil particles mobilized by wind move in three distinct modes: surface creep, saltation, and suspension. The largest particles (roughly 0.5 mm to 2 mm in diameter) move by surface creep, effectively rolling across the soil surface. Smaller, typically sand-sized, particles (roughly 0.05 mm to 0.5 mm in diameter) move by bouncing or saltating up to 1 or 2 m above the surface. The finest particles (less than 0.05 mm diameter) become suspended in the air high above the surface and can be transported in the wind away from their source areas. Particles moving by surface creep and saltation can damage plants by abrading plant tissue, a process known as sandblasting that is detailed in section 2.2. Effects associated with particles in the suspension phase are covered in section 2.3, and effects associated with deposited particles are covered in section 2.4.

2.2. Impacts in SDS source areas associated with particle movement

The physical effects caused by sandblasting are dependent on several factors, including the wind speed, duration of exposure, and nature of the abrasive material (particle size, shape and density), but young plants at early stages of growth are particularly susceptible (Skidmore 1966, Armbrust 1984). Leaves are more sensitive to sandblasting damage than stems. Leaf damage or loss results in reduced photosynthetic activity and therefore less energy (sugars) for plant growth, reproduction and the development of grain, fiber or fruit. The net result is usually lower yields (Stefanski and Sivakumar 2009).

Table 1. Some of the implications of sand and dust storms occurring on cropland and rangeland (after Riksen and De Graaff 2001).

Location	Physical effects
On-site	
Crops/pasture	Wind damage Sandblasting damage to plant tissue Burial of crops/pasture Seeds removed Roots exposed Infection of crops by pathogens
Soil	Fine soil particles and organic material removed, degrading soil structure Nutrients removed Fertilizers and pesticides removed Soil depth reduced
Equipment	Sandblasting damage to farm machinery Postponement of operations
Off-site	
Adjacent	Sedimentation at field borders, in drainage ditches, irrigation channels, reservoirs and on roads Dust in farm machinery
At distance	Infection of crops and livestock by pathogens

Evidence from laboratory wind tunnel studies on rangeland grasses in North America indicates that blowing sand kills seedlings or retards their growth by rupturing plant cells, drying out the exposed tissue and exposing damaged seedlings to diseases and insects (Fryrear *et al* 1973). However, with increasing age, young grass plants become more tolerant to wind and sand damage, their tissure becoming hardier with age. Sandblasting can also damage farm machinery and infrastructure. Scouring by wind may expose plant roots (‘pedestaling’), which may in turn result in plant mortality. This scouring process can also undermine fence posts.

At the landscape scale, the reduced growth and enhanced mortality of plants that can result from saltating soil particle impacts (abrasion of plant tissue, leaf stripping, pedestaling and burial) could have indirect repercussions for ecosystem structure. Research in the Chihuahuan Desert indicates that the combined effects of these processes could be partly responsible for initiating a rapid change in vegetation community from grassland to shrubland (Okin *et al* 2006). Woody plant encroachment into grasslands frequently reduces forage production, reducing the land’s utility for grazing livestock.

The longer-term impacts of SDS are also discernible in source areas due to a net loss of soil as opposed to its local redistribution. This is because the finest soil particles are carried in suspension, sometimes over considerable distances (figure 1). The preferential loss of these silt and clay sized particles is detrimental to soil structure (Chepil and Woodruff 1963), resulting in a lower moisture storage capacity, declining organic matter content and reduced fertility. Significant change in soil texture driven by wind erosion could happen within a few years (Li *et al* 2009). Loss of nutrients is reflected in the fact that windblown sediment is characteristically more fertile than the surface material of the parent soil (Leys and McTainsh 1994, Larney *et al* 1998). Dust blown from agricultural soils is also highly enriched with soil organic carbon (Chappell *et al* 2013). In addition, an erosive wind carries away seeds, fertilizers and beneficial microorganisms (Acosta-Martinez *et al* 2015). In extreme cases, or where a soil is thin, the loss of soil can significantly reduce soil depth, with adverse effects on plant development because root space is minimized. The overall effect of topsoil being lost due to wind erosion is frequently a measurable drop in field crop yields and decline of pasture quality in rangelands (Larney *et al* 1998). Soil lost to wind erosion is cumulative, but it can occur rapidly. A study of one poorly managed fallow period in the semi-arid Canadian prairies found that the topsoil lost in a single year would require 17 years to replace at the fastest reported rate of soil development (Larney *et al* 1995).

Figure 1. Plumes of soil particles blown from cropland in Baja California, Mexico. (NASA Earth Observatory).

2.3. Impacts associated with dust in the atmosphere

Soil particles carried in suspension represent a hazard to livestock, which can be lost when visibility is reduced in clouds of dust or, in extreme circumstances, perish due to suffocation and/or burial. The severe SDS in Mongolia in March 2021 killed more than 35 000 livestock—most of them sheep and goats—in one of the hardest-hit districts of Dundgobi province. Wind chill in the sub-zero temperatures added to the stress, and some animals froze to death (Enkh-Amgalan 2023). Strong winds associated with storms can damage livestock shelters and unsheltered animals become stressed, resulting in reduced productivity and growth.

Dust in the atmosphere presents a range of hazards to honeybees. Monitoring of a domesticated honeybee colony in China demonstrated that the poor air quality during a dust event could potentially be a major constraint for bee foraging and ultimately their contribution to pollination (Cho *et al* 2021). The duration of foraging trips increased during an Asian dust event and for some time afterwards, a finding attributed to the high levels of atmospheric particulate matter altering the degree of polarization of sunlight, which is used by honeybees for navigation during foraging trips. This reduction in foraging performance may help to explain a number of other SDS impacts on honeybees documented by Maleki *et al* (2017) in Iran. The effects include a reduction in pollen and nectar, and a decline in the quality and quantity of honey production.

Dust in suspension in the atmosphere could suppress rainfall because of effects on cloud microphysics and radiative transfer (Yu *et al* 2015). This process, if it occurs over large areas, has been suggested to act as a positive feedback mechanism that may prolong drought conditions, with consequent repercussions for agricultural production. A reduction in vegetation cover due to drought-induced plant mortality in marginal drylands can result in enhanced dust emissions. Great volumes of atmospheric dust can, in turn, intensify or prolong the drought by suppressing precipitation, further reducing vegetation cover (figure 2). This effect could act in tandem with another drought-induced dryland feedback loop whereby an increased ground surface albedo caused by the loss of vegetation results in a net loss of incoming radiation and an increase in radiative cooling. The outcome is subsiding air, greater atmospheric stability and a reduced probability of rainfall. A combination of these two feedbacks, which may be related to human-induced desertification as well as drought, are likely to have suppressed precipitation and amplified the 1930s Dust Bowl drought in the US Great Plains, with devastating effect on agricultural production (Cook *et al* 2009). Similar impacts have been implicated during the prolonged drought in Sahelian Africa during the late 1970s and early 1980s (Hui *et al* 2008).

The geophysical impacts on food production associated with SDS are augmented by a series of health hazards that may be particularly acute for people working in agriculture, who are not uncommonly exposed to atmospheric particulate matter in dryland regions. Health effects stem from the chemical, physical and biological properties of dust and can be conveniently categorized into short-term and long-term impacts.

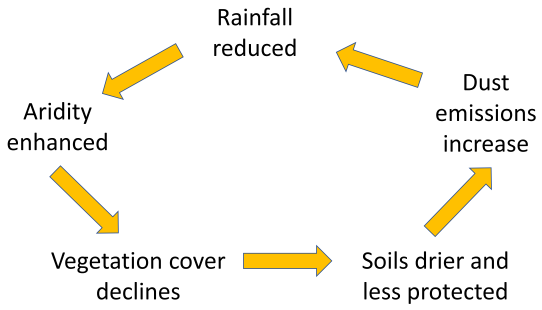

Figure 2. Positive feedback effect of drought and atmospheric dust.

Atmospheric dust has been associated with conjunctivitis and dermatological disorders and inhalation is thought to be a significant risk factor for cardiovascular and respiratory health in particular (Tobias *et al* 2019). Reports of respiratory difficulties among farm workers date back to the early eighteenth century (Darke *et al* 1976) and agricultural dusts include a wide variety of organic material, not all of which originates in the soil (Donham 1986). Nevertheless, certain human ailments can be linked to soil constituents. Examples include silicosis (also known as desert lung syndrome), a lung disease caused by the inhalation of silica, which is primarily composed of quartz dust, one of the most common components of SDS. Other health conditions that can plausibly be linked to inorganic components of soil dust in dryland farming areas include chronic bronchitis, interstitial fibrosis, and chronic obstructive pulmonary disease (Schenker 2000). Some of the microorganisms found in soil—which include protozoa, fungi, bacteria and viruses—are also pathogenic for humans. Several soil-borne diseases are capable of transmission to the air (e.g. aspergillosis, coccidioidomycosis, Q fever, sporotrichosis, tularemia) and could therefore be transported in wind erosion events (Nieder *et al* 2018).

2.4. Impacts associated with sand and dust deposition on land

Soil particles eroded from one place may affect vegetation directly following deposition on plants or indirectly by changing soil composition and chemistry. Larger soil particles moving by surface creep and saltation do not typically travel far and most are deposited within the same field or on fields nearby. On occasion, this material can bury a growing crop, particularly if in its early stages of development. In Sahelian Africa, where pearl millet is traditionally planted in small depressions, the depressions fill with sediment during SDS. Young plants then suffer from the weight of the sediment, reduced daylight and hence lower photosynthesis, as well as higher daytime soil temperatures. The result can be reduced growth and development and lower production. In extreme cases, the crops may be totally destroyed, compelling farmers to resow their fields (Michels *et al* 1993).

Such harmful sedimentation can also occur in rangeland, contaminating or burying pasture. A study conducted among pastoralists in southwestern Iran found that herders considered the greatest impact of dust to be on the palatability of forage: livestock avoided grazing the dusty plants (Zeidali *et al* 2015). Sediment deposited by wind may also contribute to low plant density over the longer term if the seed stock becomes deeply buried (Hiernaux *et al* 2009).

Large amounts of dust deposited on the leaves of crops may clog leaf stomata, adversely affecting their functions, including transpiration, respiration, and consequently photosynthesis. Finer dust particles (<2.5 μm in diameter) may act as a desiccant on leaf surfaces, so reducing the drought tolerance of plants (Burkhardt 2010). Deposits of dust can also exacerbate a range of stress factors such as pest infestation, pathogens and drought, and allow phytotoxic heavy metals or gaseous pollutants to enter exposed tissues (Farmer 1993, Soheili *et al* 2023). In a review of the evidence, Lewis *et al* (2017) concluded that dust deposition may also significantly reduce the successful reproduction of plants, directly by physically preventing pollination, or indirectly by reducing resources allocated to reproduction through altered physiological processes.

Our knowledge of many of these impacts is derived from studies of non-soil dust (mainly limestone dust from cement plants and quarries, and road dust) and their effects on all types of vegetation. However, the harmful effects of high soil dust deposition rates on yields of wheat (*Triticum aestivum* L.) and cowpea (*Vigna unguiculata* L.) have been demonstrated in field experiments conducted in Iran (Hatami *et al* 2017, 2018), and similar findings reported for grape (*Vitis vinifera*) yields by Behrouzi *et al* (2019) and date palms (*Phoenix dactylifera* L.) by Torahi *et al* (2021). Dust may also reduce the efficacy of herbicides used on cropland. Experimental dust dosing on seedlings of wild barley (*Hordeum spontaneum*) and field mustard

Table 2. Some examples of microorganisms found in dust samples and related animal diseases (after Gonzalez-Martin *et al* 2014).

Origin of dust	Dust sampled	Pathogens isolated	Related disease
Sahara Desert	Bamako, Mali (Kellogg *et al* 2004)	*Aspergillus versicolor*	Aspergillosis (e.g. ruminants, bees, poultry)
		Staphylococcus gallinarum	Bumblefoot disease in poultry
	Northern Caribbean (Griffin *et al* 2003)	*Microsporium* spp.	Dermatophytoses (e.g. cattle, horses)
		Bipolaris spp.	Mycotic granuloma in cattle
Australian deserts	Canberra and Melbourne, Australia (Lim *et al* 2011)	*Bacillus spp.* *Pseudomonas spp.*	Mastitis, anthrax in mammals Skin and mucosal infections (e.g. sheep), bacterial canker in cereal
Gobi Desert	Seosan, South Korea (Yeo and Kim 2002)	*Fusarium* spp.	Keratomycosis (e.g. horses), toxicity in animals
		Aspergillus spp.	Aspergillosis (e.g. ruminants, bees, poultry)

(*Sinapis arvensis*) resulted in the performance of certain commonly-used herbicides decreasing significantly on both species (Asadi-Sabzi *et al* 2020).

Soils contain substantial numbers of microorganisms that can be lifted into the atmosphere during SDS. Many of these microbes, which are highly stress-resistant, can be transported over considerable distances in a viable state (Maki *et al* 2019), potentially changing the make-up of soil microbial communities in deposition areas and/or introducing pathogenic microorganisms to crops and livestock. Reviewing the impact of SDS derived microbiota on agriculture, Behzad *et al* (2018) pointed out that most studies on the aerial dispersal of plant pathogens (phytopathogens) have focused primarily on fungi. Several global outbreaks of plant diseases have been linked to the intercontinental dispersion of fungal spores that have affected plantations of coffee, banana, potato, sugarcane, tobacco and wheat. Samples of dust transported from Asian and African drylands have yielded several species of fungi known to cause common plant diseases, including leaf spot, stem rust, black mold, scab and root rot. While evidence of direct links between the long-range atmospheric transport of bacteria and the spread of plant infectious diseases has not been found, many putative bacterial plant pathogens have been detected in regional and intercontinental dust samples. In the case of viruses, which usually require vectors for the transmission of infection, our knowledge of the potential for long-range aerial transport of plant pathogenic viruses and disease transmission is poor. Overall, Behzad *et al* (2018) highlighted the fact that since modern crops lack genetic diversity and are susceptible to similar sets of pathogens, aerial dispersion of plant pathogens and invasive microorganisms by SDS could have major implications for agricultural productivity. In the case of livestock, Gonzalez-Martin *et al* (2014) highlight a number of animal diseases that are likely to have been dispersed by atmospheric transport, often in SDS, some between continents. Some examples of microorganisms found in dust samples from various deserts and related animal diseases are shown in table 2.

The nature of effects due to inputs of mineral dust depends on the characteristics of the windblow particles, including pH, trace metal content, nutrient content, surfactant properties, and salinity (Grantz *et al* 2003). The impacts may be detrimental, as in the case of dust blown from some desiccated lakebeds in drylands. This material is often rich in salts, which can be toxic to plants and soils if concentrations are high. In northwestern China, the shrinkage of Lake Ebinur—caused by increased water consumption for agricultural, domestic and industrial use—has resulted in a desiccated lakebed larger than 500 km^2 that has become a source of highly saline dust. Aeolian inputs from this lakebed are the prime reason for soils downwind becoming increasingly saline (Abuduwaili *et al* 2008), adversely affecting oasis economies on the northern slopes of the Tian Shan mountains (Ge *et al* 2016). Similar effects have been reported on a larger scale from the desiccated lakebed of the Aral Sea, now known as the Aralkum Desert, in Central Asia (Issanova *et al* 2023).

In addition to the impacts on crops, livestock and soils outlined above, deposition from SDS may result in other indirect detrimental effects on food production. Dust deposits degrade the radiative properties of greenhouses, so reducing the amount of solar radiation transmitted through the covering—typically glass or polymers such as polyethylene film—with detrimental consequences for crops growing within (El-Shobokshy and Hussein 1993). Small sand and dust particles can easily become lodged in farm machinery, with subsequent repair and maintenance costs. Deposition of wind-driven sediment along field margins can cause damage or temporary malfunction of infrastructure. Examples include drainage ditches

Table 3. Saharan dust contributions to soils in Africa, Europe, the Caribbean and the Middle East.

Soil location	References	Soil location	References
Africa		**Europe**	
Northern Ghana	Tiessen *et al* (1991)	Mallorca, Spain	Muhs *et al* 2010)
South-western Niger	Drees *et al* (1993)	Crete, Greece	Nihlen *et al* (1995)
Northern Nigeria	McTainsh 1984	Croatia	Durn (2003)
Southern Nigeria	Vine (1987)	Sardinia, Italy	Genova *et al* (2001)
South-western Cameroon	Dia *et al* (2006)	Southern Italy	Vingiani *et al* (2018)
Canary Islands	Menéndez *et al* (2007)	South-eastern Bulgaria	Jordanova *et al* (2013)
North-eastern Libya	Shaltami *et al* (2018)	Southern Germany	Küfmann (2008)
South-western Morocco	Khiri *et al* (2004)	Southern Portugal	Herrmann *et al* (1996)
Caribbean		**Middle East**	
Barbados	Muhs *et al* (2007)	Taurus mountains, Turkey	Atalay (1997)
Florida Keys and islands	Muhs *et al* (2007)	South Levant, Israel	Sandler *et al* (2023)
Bahamas	Muhs *et al* (2007)	Jordan	Lucke *et al* (2014)
Puerto Rico	McClintock *et al* (2015)		
Jamaica	Muhs and Budahn (2009)		
Panama	Diaz *et al* (2016)		
Southern Mexico	Cabadas *et al* (2010)		

and irrigation canals becoming filled with soil and transport routes covered in sand. Water quality may also be adversely affected by storm deposits. The resulting disruption to the availability of goods and services increases the costs of agricultural production.

Another important indirect effect on agricultural food production occurs via dust deposition on mountain snow-cover. Most dust is a darker colour than snow so that its deposition decreases albedo, triggering earlier and faster snowmelt which alters the availability of meltwater (Painter *et al* 2007), a substantial contributor to irrigation water supply in many dryland agricultural regions. The outcome can potentially be a lower total water supply and less late-season water in areas where seasonal water scarcity occurs (Field *et al* 2010).

In contrast to these negative impacts associated with deposition on land used to produce food, a number of positive effects can also be noted. Dust deposited on the leaves of certain crops may provide nutrients by direct foliar uptake. Gross *et al* (2021) demonstrated experimentally that chickpea (*Cicer arietinum*) and wheat (*Triticum aestivum* cv Gedara) plants can acquire phosphorus directly from desert dust via the leaf surface. These crops originated in dust-rich desert ecosystems, leading the authors to conclude that they have adopted specialized strategies to utilize phosphorus delivered to their leaves with desert dust particles.

The loss of topsoil from a field or pasture negatively affects soil productivity on the land it was removed from, as outlined in section 2.2, but can of course benefit areas where the soil is deposited. Indeed, a village-scale study in Burkina Faso demonstrated that most sediment blown from farmers' fields was redistributed within the same area: although significant soil and nutrient losses were measured from bare fields this local dust was deposited on neighbouring fields with vegetation cover (Visser and Sterk 2007). The farmers participating in this study also appreciated the deposition of Harmattan desert dust from distant natural sources for its nutrient input to their fields. Over the long term, inputs of airborne dust have a variety of effects on soil development and on soils after they have been formed. Simonson (1995) noted that dust dominates processes of genesis in a few soils, but affects soil horizon differentiation in many more, and can contribute nutrient elements that are important for plant growth. Dust transported from the Sahara Desert, the world's largest, predominantly natural source of SDS, has provided such inputs to soils in numerous parts of the world (table 3). Windblown material from other major deserts has also contributed to soils in important agricultural areas downwind, such as dust from the Thar Desert to the Central Punjab in India (Sidhu *et al* 1976), from the deserts of northern China and Mongolia to the Loess Plateau of China (Sun *et al* 2008), and from the Strzelecki Desert in Australia to the plains of northern New South Wales (Cattle *et al* 2002). Desert dust inputs have also been discovered to make significant contributions to the nutrient budgets of the fynbos ecosystems of South Africa (Soderberg and Compton 2007) and the humid tropical forest ecosystems of west Africa (Stoorvogel *et al* 1997) and the Amazon Basin (Swap *et al* 1992), sources of many food products for local communities. Similar findings have been reported for freshwater ecosystems, including the Okavango Delta in Botswana (Humphries *et al* 2020) and alpine lakes in the southwestern USA (Ballantyne *et al* 2011).

2.5. SDS and land degradation

Land degradation (known as desertification in drylands) has been related to SDS in numerous parts of the world (Xu 2006, Mendez and Buschiazzo 2010, Holmes *et al* 2012, Indoitu *et al* 2015, Houyou *et al* 2016, Duniway *et al* 2019) and in several ways. Land affected by degradation often becomes more susceptible to SDS. Where SDS occur on productive agricultural land, the result is frequently reduced soil productivity and ultimately less food production (see section 2.2). Land degradation may also occur when material deposited in an SDS results in negative impacts as outlined in section 2.4. Direct connections can be discerned between SDS and the three interactive indicators used to monitor land degradation neutrality (LDN), the voluntary target designed to halt and reverse land degradation under the United Nations 2030 Agenda for Sustainable Development (specifically target 15.3 of SDG 15, which calls for action to combat desertification, and halt and reverse land degradation). These three LDN indicators or metrics—land cover change, land productivity, soil organic carbon—are in turn directly connected to food production and the sustainable management of agricultural resources. The risk of SDS occurring is increased in areas where vegetative land cover is reduced; SDS events themselves almost invariably result in a decline in productivity in the source area; and wind erosion rapidly depletes soil organic carbon stocks. These links also create positive feedbacks: SDS causing land degradation which, in turn, results in further SDS; land degradation causing SDS which, in turn, result in further land degradation. Efforts to promote LDN, reduce wind erosion and manage soil organic carbon have also been promoted as actions for climate change adaptation (Evans *et al* 2022).

3. SDS impacts on marine food production

3.1. Sand and dust deposition on the oceans

The total amount of windblown sediment injected into the global atmosphere each year is estimated to be between 1 billion and 3 billion tonnes (Zender *et al* 2004) of which some half a billion tonnes are deposited over the oceans (Jickells *et al* 2005). This airborne material provides an important flow of nutrients (particularly phosphorus and nitrogen) and trace metals (particularly iron) to the world's oceans (UNEP 2020). These elements affect the composition and growth of phytoplankton, which are responsible for the great majority of new organic material production in marine waters which forms the basis of oceanic food webs (Mahowald *et al* 2018). There is little research that makes the connection between desert dust and higher trophic levels in marine environments. An exception is the study by Rodríguez *et al* (2023) who present evidence on capture fisheries in their study of Atlantic skipjack-tuna (*Katsuwonus pelamis*). The main fishing area for this important commercial tuna species is located off the coast of northwestern Africa in waters affected by significant Saharan dust deposition, and the seasonal migration of the skipjack-tuna tracks the seasonal shift of Saharan dust deposits in this part of the North Atlantic. The seasonal supply of iron carried in desert dust from northwestern China to Sanggou Bay, one of the most important centers of aquaculture in China, has also been noted (Zhu *et al* 2017). Atmospheric deposition is the largest external source of iron in Sanggou Bay, where primary production fuelled by iron and other nutrients supports the cultivation of kelp, scallops and oysters.

Nutrients carried with desert dust to ocean waters can sometimes enhance the growth of algal blooms. These algal blooms represent an important food source for marine life, although some blooms can be harmful to marine wildlife and human health (Griffin and Kellogg 2004). A number of links have also been established between desert dust deposition and coral reefs, ecosystems that provide the daily food requirements for many human coastal communities. The supply of essential bioelements in aerial dust deposition has been shown to enhance chlorophyll concentration and photosynthesis in Red Sea corals (Blanckaert *et al* 2022), and dust particles are directly incorporated into some coral skeletons during growth (Mukhopadhyay and Kreycik 2008).

On the negative side, however, a connection has been made between Saharan dust and coral reef decline in the Caribbean Sea (Shinn *et al* 2000). One of the most extensive diseases affecting Caribbean reefs is Aspergillus, also known as sea fan disease because it primarily affects sea fans. Its causative agent, the fungus *Aspergillus sydowii*, is common in soils and has been found in Saharan dust samples as well as diseased sea fan corals in the region (Garrison *et al* 2003). The link is supported by Hunter and Cervone (2017) who showed that African dust storms contribute to an increased prevalence of coral disease in the Caribbean, and that the correlation between them is influenced by other climate parameters, including sea surface temperature in particular. The possible dangers to marine biota associated with pathogens present in desert dust are not well known. In an early review, Griffin and Kellogg (2004) highlighted the potential link between a disease outbreak in Caribbean sea urchins (*Meoma ventricosa*) and bacteria isolated from Saharan dust events sampled in the Virgin Islands in the Caribbean. Research into these desert-derived bioaerosols remains at a relatively early stage.

4. Conclusions

The studies reviewed in this paper show the many ways in which SDS can affect food production, both on land and at sea. These effects are short term and long term, direct and indirect. Although not all of these impacts have been well quantified, and some can be positive for farmers and herders, there is good evidence to indicate that they can substantially reduce the yields of crops, pastures and livestock. These impacts are especially prevalent in the world's drylands, which are particularly important for global terrestrial food production, although some of the impacts can also be felt beyond the drylands because soil dust is frequently carried great distances in high-level winds and because SDS occur in more humid environments under the right conditions.

The negative impacts of SDS undermine the sustainability of agriculture, reducing its capacity to meet the food needs of present and future generations. For this reason, many successful wind erosion control practices have been developed for commercial and subsistence farming and herding (Middleton and Kang 2017), although the persistence of the SDS problem on agricultural land—the most common type of anthropogenic SDS source—indicates that the implementation of these techniques is by no means always successful. It is important, therefore, to continue efforts to reduce wind erosion on land used for food production (Quinton and Fiener 2024), efforts which have received a boost in recent years due to acknowledgement of SDS impacts on the SDGs in general and SDG 15 in particular.

However, our perception of the threats to food production associated with SDS should be balanced with an appreciation of the significance of soil dust to the Earth system. It is clear that dust plays an important part in several major biogeochemical cycles. The deposition of dust contributes to soils in many parts of the world, and SDS endows terrestrial and marine ecosystems with key nutrients that enhance their productivity, with implications for the valuable environmental services these ecosystems provide. Of course, the production of food, both on land and at sea, is a key component of these environmental services.

It is not known where the balance lies between these positive impacts of SDS, largely associated with the deposition phase, and the negative effects, mainly associated with the entrainment and transport phases. Future research efforts that will help to identify the relative importance of these influences should focus on microbiological research and planetary dust movement and the impacts of dust-borne protozoa, fungi, bacteria and viruses on human, plant, animal and ecosystem health. Research that examines connections between desert dust and marine environments, particularly at higher trophic levels, is also needed, as is a deeper understanding of how dust is involved in biogeochemical cycles in both marine and terrestrial environments. At a more direct and specific level, important topics related to food production include the provision of nutrients in dust to crops by direct foliar uptake, and SDS impacts on honeybees and other pollinators. The outputs of these research initiatives will inform strategies designed to mitigate the negative impacts of SDS on the sustainability of food production, balanced appropriately with an appreciation of the significance of soil dust to the Earth system.

Data availability statement

No new data were created or analysed in this study.

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ORCID iD

Nick Middleton https://orcid.org/0000-0001-5873-1453

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