

Desertification and Wind Erosion

Laura J. Brown and W.G. Nickling

Wind Erosion Laboratory, Department of Geography, University of Guelph, Guelph, Ontario, N1G 2W1, Canada

Abstract: Desertification is a complex environmental issue involving many inter-related contributing factors and processes. Wind erosion is an important contributing factor to the desertification process in many dryland environments and can be a major mechanism for soil degradation. Although wind erosion is not limited solely to these environments they are particularly susceptible in that they encompass most of the causative atmospheric and surficial factors responsible for the deflation process. Multiple approaches have been used to assess and monitor the severity and extent of wind erosion including visual indicators, direct measurement, remote sensing and modelling. Of these approaches only modelling allows for prediction and pre-emptive mediation of wind erosion. Ultimately, the occurrence of wind erosion in itself is not indicative of desertification, in that environmental impacts are not solely the result of physical changes but are tied to the adaptive capability of the inhabitants.

Key words: Desertification, dryland systems, wind erosion, wind erosion modeling.

Wind erosion is a serious problem in drylands. It is a major mechanism for the reduction of soil fertility, the subsequent degradation of these systems, and is frequently viewed as synonymous with the desertification process. To address the role that wind erosion plays in desertification an understanding of the concept of desertification is in order. There is a vast quantity of desertification literature with an almost equally large number of definitions as to what it is, its causes and how to mitigate its effects. The term desertification has been used to denote a set of processes as well as to describe an environmental state (Thomas and Middleton, 1994). Questions however, have been asked as to whether it is a naturally occurring phenomenon, is triggered by human mismanagement, or if it is a combination of the two. Despite the lack of consensus as to what desertification

actually is, funding for research is ongoing and conferences continue to address desertification issues. There are many 'players' in the desertification realm including academics, governments, aid agencies, and importantly the United Nations. All of whom have had various levels of involvement in the desertification debate and the implementation of policy and aid over the past several decades. This paper does not have definitive answers to the multitude of questions surrounding the desertification debate. Rather, it presents an overview of the literature on this complex environmental issue. The role that wind erosion plays in desertification will be addressed along with a summary of the interrelated factors that contribute to this process. This brief review will set the stage for an overview of the approaches used to assess and monitor wind erosion in areas undergoing desertification and highlight

recent developments in the study of wind erosion.

Desertification Defined?

The term 'desertification' was coined first by the French scientist Lavauden (1927) to describe the impoverishment of plant cover in the Sahara Desert (Mainguet, 1999; Dregne, 2002) and later by a French forester named Aubreville (1949) working in sub-humid West Africa (Dregne and Tucker, 1988; Mainguet, 1991; Darkoh, 1998; Mainguet and Da Silva, 1998; Dregne, 2002). Aubreville (1949) used this term to describe the process of land degradation initiated by deforestation and resulting in the land being turned into a desert (Dregne, 2002). The United Nations Conference on Desertification (UNCOD) was convened in 1977 in response to the prolonged drought and numerous deaths of people and livestock experienced in the Sahel region of Africa. During this conference it appears that the terms 'desertification' and land degradation became synonymous (Dregne, 2002). The environmental disaster of the Sahelian famine brought media and the public's attention to the plight of Ethiopians and 'desertification' became part of the lexicon. Throughout the 1980s numerous desertification studies were undertaken and consequently various definitions were developed based on the perspective of the researcher and the region being studied. Mainguet (1999) cites more than 130. By the 1990s a critical reassessment of desertification began to surface, questioning the science behind the claims of the extent and severity of the problem and the actual factors contributing to this environmental situation. Thomas and Middleton's (1994) book *Desertification: Exploding the Myth*

represents a comprehensive example of this critical movement.

It can be argued that the reason that there are so many interpretations of the concept of desertification is that it is contextual. Although most desertification definitions include both human and natural factors, researchers tend to emphasize one aspect more than the other. This could be because each researcher brings his own expertise and looks for evidence of desertification based on their sphere of knowledge. It could also be that the differences in the physical, social and cultural attributes of each area studied contribute to a unique set of circumstances. For example, in their review of the Chinese literature on desertification Zha and Gao (1997) state that prior to 1977 the term *tudi shahua* (land sandification) was in common use in China (Dong and Liu, 1993). This term 'refers to the coarsening process of the land surface after fine sandy and nutrient particles are lost due to aeolian erosion' (Zha and Gao, 1997). Just as there have been numerous interpretations as to the definition of desertification in the western literature there has been a similar discrepancy in the Chinese literature. Zha and Gao (1997) state that in China this lack of agreement as to the definition of desertification may in part be due to differing translations. Desertization, translated as *shamohua*, refers to 'desert encroachment in arid and semi-arid areas of non-desert landforms due to improper human activities' (Zha and Gao, 1997), while desertification was translated as *huangmohua* (barrenification). The term *huangmohua* encompasses desert creeping and land degradation due to soil erosion,

waterlogging and soil salinization (Zha and Gao, 1997). Zha and Gao (1997) cite the point made by Zhou and Pu (1996) that the international definition had to be adjusted to better suit the unique circumstances in China. The Chinese definitions place a greater emphasis on loose surficial sand as being an essential component for the initiation of desertification rather than the lack of precipitation implicit in most other definitions. Hence, soil erosion plays an important role in the desertification literature in China. However, it is not only in China where soil erosion is identified as an important factor in desertification. Wickens (1997) incorporates the notion of an inappropriate amount of soil erosion in arid and semi-arid regions resulting in lost fertility, in his definition of desertification in the Sahel.

Despite the many definitions that have been used one of the most commonly cited has been the broad definition offered by the United Nations Convention to Combat Desertification: "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climatic variations and human activities" (UNCED, 1992). Hyper-arid lands are excluded from this definition as it is assumed that they are so dry that the impact of human induced degradation would be negligible and therefore no desertification can take place (Dregne, 2002), underscoring the implication that humans play a role in this phenomenon. Henceforth, references to drylands in this paper will encompass arid, semi-arid and dry sub-humid areas.

Further clarifications of some of the terms in the UNCED (1992) definition are

required to convey its broad nature. For example, land in this context, refers not only to the soil, but extends to include the whole bioproductive system (Darkoh, 1998). Darkoh (1998) describes this system as being comprised of the soil, vegetation, other biota and the ecological and hydrological processes.

The term degradation refers to the reduction or destruction of the whole ecosystem's biological or resource potential by one or more processes acting on the land (Dregne, 2002). These processes include wind erosion and deposition, water erosion, removal or reduction in vegetation cover, and salinization or sodication of the soil. Clearly the above mentioned processes are not limited to drylands however, despite the numerous interpretations of what desertification is, that it is restricted to drylands is not disputed. Similarly, land degradation occurs in all climates and is not found only in arid, semi-arid and sub-humid climates, yet only in the drylands would this degradation be referred to as desertification (Le Houérou, 1996).

For some scientists, true desertification is typified by irreversible land degradation (Dregne, 2002). However, the notion of irreversibility also has various interpretations. For some it refers to the possibility of remediation at the human time scale, which would take place within one to two generations (Okin *et al.*, 2000), for others it is bound by practical economic limitations (Mainguet, 1991) or represents the development of a sterile 'wasteland'. However, according to Dregne (2002) the vast majority of drylands never reach that 'wasteland' end point. Other difficulties associated with the concept of irreversibility

involve the issue of assessment. For example, a decrease in soil fertility may be deemed irreversible in developing countries without the economic resources to add chemical fertilizers to the soil to maintain the growth of crops. Whereas the same level of infertility in another economically rich country could likely be treated with the application of fertilizers and the land would continue to be used for agricultural purposes.

The UNCED (1992) definition of desertification limits its application to degradation of dryland systems. A system is a bounded holistic structure that possesses characteristic properties and consists of interconnected elements (Huggett, 1993). Environmental systems encompass all natural structures within which humans interact (Huggett, 1993). An ecosystem is an example of an environmental system. It is a functional unit that is the result of the interactions between the abiotic, biotic and where applicable, the anthropogenic elements within a defined space.

Dryland ecosystems are found in the arid, semi-arid and subhumid regions that cover nearly a third of the earth's total land surface (Okin *et al.*, 2000). Drylands are characterized by high climatic variability in rainfall and temperature along with higher wind and water erosion potential (Mainguet, 1991). The ecosystems that evolve under the climatic conditions of these regions are adapted to cope with the climatic fluctuations inherent in these environments. Vegetation found in these ecosystems is well adapted to this dry environment; it can withstand high temperatures and is drought resistant (Mainguet, 1991). In a

dryland ecosystem changes are essentially event-triggered. These events may be human, such as increased cattle stocking or managed burning and can be climatically influenced. For example, vegetation dynamics can be linked to fluctuations in rainfall. Systems that have been thought to be severely degraded can exhibit rapid recovery of vegetation cover following a period of sufficient rainfall after years of drought (Dregne and Tucker, 1988).

A crucial element of the ecosystem in relation to desertification is its soils. The soils found in drylands have taken centuries to develop (Mainguet, 1991; Dougill *et al.*, 1999) and if they are degraded sufficiently, the resilience of the whole system may become compromised. Mainguet and Da Silva (1998) state that soil characteristics are the key indicators of the resilience in a dryland ecosystem.

Some research has been done under the assumption that land degradation is caused by human actions alone, entirely disregarding the climatic factors and focusing only on the social, economic and political factors (Agnew, 2002). Although the process may be exacerbated by prolonged drought and desiccation, desertification is the consequence of resource management failure resulting in excessive pressures on resource ecosystems fueled by local and external factors (Kelly and Hulme, 1993). These local forces include, increased population, poverty, land shortages and landlessness, and the external forces are the state of the global economy, the debt burden, brain drain and import barriers in developed countries (Kelly and Hulme, 1993).

Despite the various views of what the underlying causes of desertification are, there seems to be a general consensus that the effects of land degradation are long-term and that it is not simply a consequence of drought alone. The issues regarding the confusion between the effects of drought and those of desertification are discussed below.

Environmental Factors Contributing to Desertification

Many authors have identified drought as a contributing factor to desertification (Charney, 1975). Although there are many context specific definitions of drought, it can generally be defined as deficient rainfall for the needs of vegetation (Mainguet and Da Silva, 1998). Drought is seen as a relatively short-term cyclic phenomenon (Darkoh, 1998; Agnew, 2002) whereas desertification occurs over a longer time scale. According to Mainguet (1991), desertification may be "revealed by drought," but is "caused by human activities". Le Houérou (1996) argues that desertification may result from land abuse alone, without drought. For example, during relatively wet periods grazing and crop areas often expand into marginal areas and when the period of high rainfall ends these areas of low resilience are susceptible to desertification processes. Periods of drought can also result in vegetation dieback, exposing the soil to wind erosion resulting in the removal of soil nutrients and lowering fertility (Okin *et al.*, 2001a).

Other environmental conditions such as topography, soil types and vegetation cover also play a role in the susceptibility of an area to desertification.

Anthropogenic Factors Contributing to Desertification

Some researchers and politicians view desertification as a social problem, where people are the initiators and the subsequent victims. Under this point of view the process maybe exacerbated by prolonged drought and desiccation, but desertification is the consequence of resource management failure resulting in excessive pressures on ecosystem resources. Examples of human-induced factors that exacerbate desertification include: deforestation, water resource diversion, agricultural practices and overgrazing. Deforestation resulting from the collection of fuel wood and plants for medicinal purposes has been identified as a factor contributing to desertification by Zha and Gao (1997).

Water resource diversion can result in what Le Houérou (1996) called 'technogenic desertification'. For example, the diversion of water from the Aral Sea to irrigate land for cotton production has had severe environmental ramifications in the wake of the receding shoreline and salinization of the irrigated soils (Griffin *et al.*, 2001). Aeolian activity has also increased in the region due to the exposure of the sea bed giving rise to sand and salt storms (Tatyana and Zonn, 2000)

Agricultural practices can exacerbate desertification. Some examples of these types of practises are, not leaving the land fallow long enough to recover from cropping (Sterk, 2003), the expansion of cultivation into marginal lands during wet years and tillage practises that leave the soil bare and prone to wind or water erosion.

Many authors have cited overgrazing as an important contributing factor in rangeland degradation (Dregne, 1983; Mainguet, 1991; Darkoh, 1998; Fredrickson *et al.*, 1998; McClure, 1998; Puigdefabregas, 1998; Dougill *et al.*, 1999; Okin *et al.*, 2000; Dregne, 2002). Grazing animals not only remove vegetation, but their hooves break soil crusts removing another form of protective soil cover. Research on grazing patterns has shown that animals tend to graze selectively on the more nutrient rich or palatable plants (Li *et al.*, 2000; Teague and Dowhower, 2003), and have a preference to return to these previously grazed patches repeatedly instead of grazing uniformly throughout the area (Teague and Dowhower, 2003). This 'patch selective grazing' results in patches of rangeland being more heavily grazed than others. As a result selected areas are more highly stressed than that intended by the stocking rates for the area as a whole (Teague and Dowhower, 2003). These grazing patterns, coupled with heterogeneity of the spatial distribution and species composition of vegetation cover in rangelands, means that stocking rates based on per unit area estimations will likely be over-optimistic.

Overgrazing results in the replacement of tall perennial grasses with shorter perennials, which in turn are replaced by annual grasses and eventually, bare ground (Li *et al.*, 2000; Teague and Dowhower, 2003). Overgrazing affects wind erosion by decreasing the roughness of the surface through the reduction of vegetation canopy height and ultimately vegetation cover (Li *et al.*, 2000). Charney (1975) proposed that overgrazing in the Sahel initiated a feedback mechanism that would result in the

expansion of deserts through albedo enhancement. His biophysical feedback theory is based on the premise that the bare ground uncovered after the removal of vegetation would enhance surface albedo, thereby reducing the absorption of solar radiation, which could induce a sinking motion in the troposphere, leading to drier conditions in the Sahel (Charney, 1975). Drier conditions would result in less plant growth and less vegetation cover would in turn result in further enhancement of the albedo, perpetuating the cycle. Hence a positive feedback mechanism is established culminating in desertification.

Most of the above factors involve a substantial reduction or the removal of perennial vegetation, laying the soil bare, and leaving it susceptible to water and wind erosion.

Factors that Influence the Wind Erosion Process

Much of our understanding of wind erosion has not been directly tied to desertification and stems from a wide range of disciplines including, agriculture, soil science, meteorology, climatology and earth surface sciences. To understand the role that wind erosion plays in desertification an understanding of the wind erosion process is practical. The physical processes involved in wind erosion and dust emission have been investigated through empirical evidence gathered in wind tunnel experiments or from direct field measurements. Whether or not wind erosion occurs is determined by the interrelationship of numerous factors outlined in Table 1 and described below. In general wind

Table 1. Factors influencing wind erosion

Atmospheric factors		Surface characteristics		
Climate	Weather	Soil attributes	Surficial features	Land-use
• Aridity	• Lack of rainfall	• Organic matter	• Vegetation cover	• Cultivation
• High evaporation	• Humidity	• Particle size	• Lag pavement	• Grazing
• Circulation cells	• Wind speed and variability	• Mineral content	• Rocks	
		• Moisture content	• Surface crusts	

provides the energy input to entrain and transport the particles but the soil's erodibility is dependent on the characteristics of the surface and soil composition.

Atmospheric factors

Le Houérou (1996) has identified wind erosion as one of the overriding factors of desertification in regions characterized by strong and persistent winds throughout an annual dry season. Dryland regions are characterised by their climatic conditions of low rainfall, high potential evapotranspiration rates and periodic droughts. Ultimately these environmental conditions have some bearing on indigenous vegetation type and soil development (Okin *et al.*, 2001a). The wind erosion process is driven by winds produced either at a regional scale by global atmospheric circulation patterns or at a local scale by weather systems. Goudie and Middleton (2001) provide a comprehensive list of Saharan dust-bearing winds along with their associated meteorological conditions. Two types of wind associated with wind erosion in Africa illustrate the regional and local scale wind phenomena. On the regional scale, the Harmattan winds develop due to the continental effect on the global

circulating trade winds and originate over the Sahara desert and coincide with the annual dry season in the Sahel (Le Houérou, 1996). A shift in the Intertropical Convergence Zone northward results in unstable moist air spawning localized convection thunderstorms. These storms are preceded by relatively short-lived strong downdrafts called haboobs.

High velocity winds reaching the surface result in strong forces (turbulent shear stress) being exerted on the soil (Li *et al.*, 2003). The threshold shear or friction velocity (u_{*t}) is a function of the wind velocity and represents the force at the surface required to overcome the resistance of the surface particles to movement. It is an important parameter in wind erosion research as it is not only a function of wind speed but incorporates all factors affecting soil erodibility (Lopéz, 1998), such as particle size and mass and the presence of nonerodible elements (pebbles, rocks and vegetation) at the surface (Alfaro and Gomes, 2001).

Surficial characteristics

Soil attributes: The attributes of the soil and characteristics of the surface influence whether sediment is available for wind erosion to occur. Loose sediment at the

surface is highly susceptible to wind erosion but particles that are sheltered from the wind's force or bound to one another are better able to resist wind erosion. Soil attributes such as organic content and mineral composition, and moisture content all contribute to the soil's ability to resist wind erosion. For example, soluble salts (Nickling, 1978; Nickling and Ecclestone, 1981; Nickling, 1984), silts and clays (Chepil and Woodruff, 1963) and plant litter (Chepil, 1951) all contribute to the soils ability to form aggregate clods or develop surface crusts that resist wind erosion.

Soil moisture content is another important parameter of a soil as it controls the threshold shear velocity. Wind tunnel research has shown that soil moisture increases the threshold shear velocity (McKenna-Neuman and Nickling, 1989; Chen *et al.*, 1996; Fecan *et al.*, 1999). Fecan *et al.* (1999) have developed parameterization coefficients to describe threshold wind speed based on soil moisture and clay content for several soil types (typical of semi arid locations), based on the work of McKenna-Neuman and Nickling (1989). Soil moisture is unlike the other soil attributes that remain relatively stable in that it can be depleted rapidly by dry winds reducing the soil's ability to resist erosion during a wind erosion event.

Surficial features: Surface protection provided by armouring (gravel lag development), vegetation cover, and surface crust cover also contribute to the system's ability to resist wind erosion by increasing the surface roughness and reducing the force of the wind at the soil's surface. In areas where soil erosion has already been active,

the surface may be protected from further removal of particles by the development of a deflation lag surface. As a result of wind and water erosion episodes, fine and sand sized particles are removed, leaving behind the larger sediments, and eventually the soil surface is composed of pebbles, gravels, stones and rocks. These non-erodible roughness elements absorb some of the wind's momentum, which reduces the wind's erosive capability on the intervening surfaces (Minvielle *et al.*, 2003).

Vegetation also absorbs momentum from the wind and further protects the soil surface from wind erosion by covering a proportion of it (Wolfe and Nickling, 1993; Vigiak *et al.*, 2003). Its role in the wind erosion process is not only one of protection but it also traps sediment in transport, inducing deposition. Vegetation cover has long been recognized as a means of reducing wind erosion and cover crops, post-harvest residues, wind strips and windbreaks of trees and shrubs have been employed to protect agricultural soils (Wolfe and Nickling, 1993; Grant and Nickling, 1998; Vigiak *et al.*, 2003).

Outside of the agricultural context, however, vegetation cover in drylands is typically sparse. A body of aeolian research has focused on developing a method to partition the total shear stress of the wind between that absorbed by vegetation and that which reaches the intervening surface (Marshall, 1971; Wooding *et al.*, 1973; Gillette and Stockton, 1989; Musick and Gillette, 1990; Stockton and Gillette, 1990; Raupach, 1992; Raupach *et al.*, 1993; Marticorena and Bergametti, 1995; Wolfe and Nickling, 1996; Wyatt and Nickling,

1997; Gillies *et al.*, 2000; Crawley and Nickling, 2003; Minvielle *et al.*, 2003). The shear stress reaching the intervening surface has the potential to initiate or perpetuate wind erosion. Predominately, two approaches are used to estimate the shear stress reaching the surface. One originated in agricultural and forestry literature and utilizes the aerodynamic roughness length (z_0) (Marticorena and Bergametti, 1995). The other was developed more recently and utilizes the drag coefficient of the roughness elements (Raupach, 1992; Raupach *et al.*, 1993). While most numerical models assume that vegetation is evenly distributed, Okin and Gillette (2001) observed elongated areas of bare soil aligned with the prevailing winds that they called 'streets'. They propose that these unprotected streets may emit more dust than if vegetation was more evenly distributed. An alternative approach to deriving the surface shear stress within a canopy from wind velocity measurements is to directly measure it using an instrument that measures near-surface vertical pressure gradients. Crawley and Nickling (2003) in the wind tunnel and Wyatt and Nickling (1997) in the field have used Irwin sensors (Irwin, 1980) to measure shear stress on the intervening surface between roughness elements.

Although the intervening surface between vegetation and other nonerodible roughness elements is subject to the erosive force of the wind, surface crusts commonly provide protection. Many researchers have studied the effect of surface crusts on reducing wind erosion (Williams *et al.*, 1995; Cahill *et al.*, 1996; Belnap and Gillette, 1997; Marticorena *et al.*, 1997; Belnap and

Gillette, 1998; Rice *et al.*, 1999; Wolfe and Helm, 1999; Gillette and Chen, 2001; Gillette *et al.*, 2001; Houser and Nickling, 2001; Li *et al.*, 2002; Eldridge and Leys, 2003; Rajot *et al.*, 2003). Intact surface crusts protect the surface from wind erosion and can be composed primarily of minerals and salts or biotic material (Belnap, 2001 for a brief review). Physical crusts are formed by either compaction of moist soil, or raindrop impact. Raindrop impact on soil aggregates can dislodge small particles that are washed into pore spaces between larger particles, effectively sealing the soil surface. Chemical crusts often form on top of physical crusts as pooled water evaporates leaving behind salts, lime and silica (Gillette *et al.*, 1980; Gillette *et al.*, 1982; Belnap, 2001). Crust damage increases the erodibility of the soil (Gillette *et al.*, 1980; Gillette *et al.*, 1982). However, despite their protective role in wind erosion physical crusts, composed of minerals or salts, can have a detrimental influence on vegetation as they inhibit infiltration and increase surface runoff, hinder root penetration and reduce the likelihood of germination and seedling establishment. Hence the presence of physical or chemical crusts is often interpreted as an indicator of desertification.

Biological crusts (also referred to as cryptogamic, cytobiotic, microbiotic or microphytic crusts) result from an intimate association between soil particles and cyanobacteria, algae, microfungi, lichens and bryophytes that live within the top few millimetres of the soil (Belnap *et al.*, 2001a). These living crusts increase soil fertility by fixing carbon and nitrogen and by trapping negatively charged fine clay particles that bind positively charged

macronutrients (Belnap *et al.*, 2001b). Damage to these biological crusts not only increases the erodibility of the soil (Belnap and Gillette, 1997; Marticorena *et al.*, 1997; Belnap and Gillette, 1998) but also results in a reduction of the soil's fertility and thereby contributing to desertification (Belnap and Gillette, 1998). Damage to these crusts can be caused by abrasion of sand-sized particles during a wind erosion event or by land use practises. Wind tunnel testing has provided some insight as to the stability of biological crusts to grain impact or abrasion during a wind erosion event (McKenna-Neuman *et al.*, 1996; McKenna-Neuman and Maxwell, 1999; 2002). These studies have shown that filaments in microphytic crusts can be broken by low magnitude grain impact (McKenna-Neuman and Maxwell, 2002), analogous to metal fatigue, and that a temporal aspect is important in the deterioration of these crusts.

Land use: Land use practises that increase the erodibility of the soil are those that decrease the protection offered by soil and surface features. For example, tillage of the soil breaks down soil aggregates and crusts leaving the soil more vulnerable to erosive winds. Grazing animals not only remove the protective cover of vegetation but their hooves also damage soil crusts.

Although wind erosion is not limited solely to dryland environments they are particularly susceptible to wind erosion as they encompass all of the atmospheric and surficial factors contributing to the wind erosion process (Sterk, 2003 for an comprehensive review of wind erosion in the Sahelian environment).

Wind Erosion's Role in Desertification

Wind erosion is principle mechanism of land degradation in dryland environments. Soil is created over a long period of time, through biological, chemical and physical processes that break down bedrock. In dryland environments physical processes are dominant, therefore, the development of soils takes a longer time than the development of soils in humid climates. Many soils in drylands have been inherited from humid phases preceding the current dry climates (Mainguet, 1999). Hence, soil lost due to erosion in these regions will not be replaced within a human time scale.

Nutrients and fine grains are found in the upper few centimetres of thin soils, and wind erosion removes the dust-sized particles and plant litter. This results in a reduction of soil fertility, infiltration capacity, soil moisture retention and the ability of the soil to form aggregates (Mainguet, 1999). A decrease in these components lessens the soil's ability to support plant life and lessens the particle cohesion of the soil, which in turn leaves, the soil susceptible to further wind erosion (Mainguet, 1999).

The movement of sand-sized particles as part of the wind erosion process also has consequences. For example, sand movement can damage plants during an erosion event. This damage can consist of lacerations in the epidermis of a plant's leaves, which lead to higher evaporation and results in the leaves drying out more quickly as well as scarred fruits, flattened crops, and the burial of plants by sand (Mainguet, 1999). Okin *et al.* (2001a)

identified plant damage and land degradation not only on abandoned agricultural areas in California's Manix Basin, but on the adjacent land as well. Removal of natural vegetation and tillage had left the fields susceptible to wind erosion and made them sources of material for sediment transport. Downwind of the cultivated fields they found that vegetation had been buried or sand blasted, resulting in leaf stripping and damage to the cambium, effecting the plant's ability to use water (Okin *et al.*, 2001a). This damage killed the shrubs, reducing vegetation cover, increasing the potential for surface runoff and wind erosion, and reducing latent heat flux, leading to higher surface temperatures. Okin *et al.* (2001a) concluded that a feedback mechanism might be attained where these factors will continue to reduce vegetation cover in previously undisturbed areas (Fig. 1).

With the soil's ability to support vegetation severely compromised, the re-establishment of vegetation is unlikely

as Okin *et al.* (2001a) found in agricultural fields that had been abandoned for several decades. These fields did not support any native vegetation and did not resemble the surrounding undisturbed ecosystem (Okin *et al.*, 2001a).

Assessing and Monitoring Wind Erosion

Assessing and monitoring wind erosion serves to quantify the spatial extent and evaluate the changes in the erosion rates or the factors influencing wind erosion through time. To gain a better understanding of wind erosion processes and test the theoretical relationships field and laboratory wind tunnel experiments have been carried out. These experiments are replicable and allow researches to study the various aspects of wind erosion under controlled conditions.

Laboratory wind tunnels have been used to study saltation (Bagnold, 1941; Rice *et al.*, 1999), sandblasting (Alfaro *et al.*, 1997; 1998; Alfaro and Gomes, 2001), shear stress

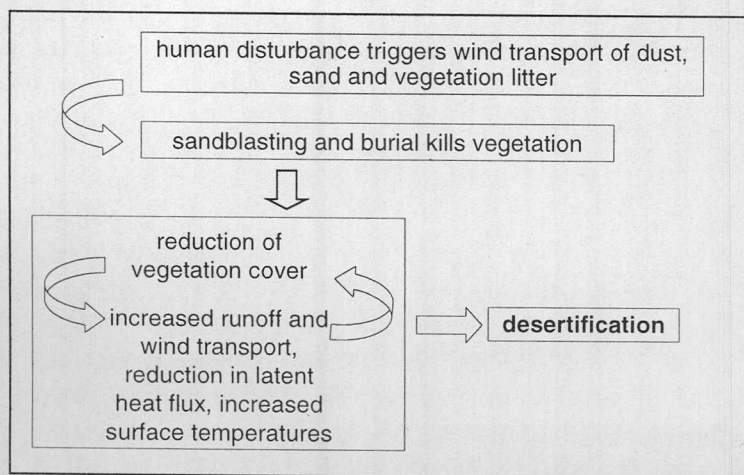


Fig. 1. Impact of abandoned fields on adjacent lands (after Okin 2001a).

partitioning (Crawley and Nickling, 2003), and the effects of wind erosion controlling factors such as vegetation (Leys, 1991; Dong *et al.*, 2001), and soil moisture (McKenna-Neuman and Nickling, 1989; Chen *et al.*, 1996).

Field wind tunnels are portable and study aspects of the wind erosion process as well but on natural soil surfaces. Aspects such as threshold shear velocity (Marticorena *et al.*, 1997), dust emission (Nickling and Gillies, 1989), aerodynamic roughness length (Xian *et al.*, 2002), and soil crusts (Belnap and Gillette, 1998; Houser and Nickling, 2001; Eldridge and Leys, 2003) are studied in the field setting under controlled winds.

The results of these wind tunnel studies have provided a much better understanding of wind erosion and have been used to develop empirical relationships. However, equations that describe the processes observed in the simplified, controlled environment of the wind tunnel may not adequately describe the processes in complex, spatially and temporally heterogeneous natural environments. Okin (2001) points out that our mathematical understanding of the dynamics of wind relationships with the surface are derived from wind tunnel studies that oversimplify wind, soil, and vegetation conditions. Wind erosion in the natural environment is strongly variable in space and intermittent in time (Lopéz, 1998; Shao, 2000). Field wind tunnels can quantify wind erosion in a natural setting, however, for monitoring purposes too many sites would have to be sampled to capture the inherent heterogeneity of the study site. Similarly,

the short-term studies done with a wind tunnel cannot capture the temporal variability inherent in the wind erosion process (Lopéz, 1998). Hence, to assess the full extent of wind erosion in the natural environment other methods must also be used.

The approaches used to study wind erosion in the field are the same whether they are used in desertification studies or in another context. These approaches include: indirect evidence such as blowouts and the presences of nabhka or coppice dunes (Nickling and Wolf, 1994), direct measurement, remote sensing and modeling. Direct measurement involves using data collection instrumentation in the field or collecting soil samples. The field instrumentation consists of sediment traps for particles moving in saltation or creep (Goossens *et al.* (2000) for an extensive list) and dust samplers or fallout traps (Nickling *et al.*, 1999; Stout, 2001; Chung *et al.*, 2003) for particles moving in suspension. Wind speed and direction are often recorded as well to correlate with the soil flux data using anemometers mounted with dust samplers on towers (Gillette, 1977; Nickling and Gillies, 1993; Nickling *et al.*, 1999). Recently, differential pressure port instrumentation has been used to directly measure the shear stress acting on the surface (Wyatt and Nickling, 1997). However, direct measurement still suffers from a limited spatial scale and temporal scale. The use of satellite imagery has been used to identify the source (Gillette, 1999) and extent of dust storms. This measurement technology covers a large spatial scale but the satellite's orbit limits the temporal scale. An alternative method that does not suffer

from the same spatial and temporal limitations of the previous approaches is wind erosion modeling.

Indirect evidence of wind erosion

Erosional and depositional features such as bare soil depressions, blowouts around root structures and the presence of dunes have been used as rapid appraisal indicators of desertification and wind erosion. In particular the development of nabhka dunes (also known as nebhka or coppice dunes) has been used to infer a decline in soil fertility. These dunes develop when sediment-laden wind encounters shrubs and particles are trapped and deposited. This can result in dune growth and if the sediment is nutrient-rich plant growth increases. As larger plants trap more sediment, further dune growth occurs. Deflation of the interdune surface through both wind and water erosion further depletes these areas of nutrient-rich topsoil and organic matter reducing the likelihood of the establishment of vegetation in these areas. Areas beneath the shrubs become 'islands of fertility' (Schlesinger *et al.*, 1990; Wezel *et al.*, 2000). Dougill and Thomas (2002) question whether the presence of these dunes should be used as indicators of desertification or simply evidence of localized wind erosion in the form of saltation and creep. They maintain that the higher nutrient content of dunes is likely indicative of nutrient cycling within the dune itself instead of being deposited by wind blown sediments (Dougill and Thomas, 2002). Therefore, according to Dougill and Thomas (2002), nutrient-enriched nabhka dunes could occur without the depletion of the surrounding soil.

Direct measurement

Although few long-term wind erosion studies have been carried out to assess wind erosion in the field, at least one long term investigation has been undertaken at the Jornada Experimental Range, New Mexico due to the concern over the documented encroachment of mesquite into grasslands. Desertification in North America primarily is the replacement of grasslands or shrublands capable of supporting livestock with shrublands unable to support livestock (Jackson *et al.*, 2003). In Jornada, metal stakes were set in locations of differing mesquite and grass vegetation coverage in the 1930s (Gibbens *et al.*, 1983). At the point where the surrounding soil met the stake an etch mark was made. At one location the fluctuation in soil depth measured at the etched stakes was measured at three different time periods between 1935 and 1980. Gibbens *et al.* (1983) report that the period between 1935 and 1950 had a net loss of 2.9 cm; between 1950 and 1955 another net loss of 2.7 cm, which coincided with the a severe drought and vegetation dieback that likely accounted for the soil loss being almost equal to that of the prior 15 years; and from 1955 to 1980 there was a net gain of soil higher in the former grassland (3.4 cm) than that of the perennial dune area (1.4 cm). A long-term study of this type is rare; more frequently shorter-term studies are made.

A recent study in China by Li *et al.* (2003) was undertaken to quantify the sand transport rates found in grasslands with differing levels of 'desertification severity' over two wind erosion events. They found that there was a linear relationship between

the level of desertification and sand transport rates for both events (Li *et al.*, 2003). Mean wind speed was highest for the category with the least vegetation cover and declined progressively as the level of desertification increased. The friction velocity and surface roughness length were lowest for the least amount of vegetation cover and increased along the desertification gradient (Li *et al.*, 2003). These results are consistent with the observations made through wind tunnel testing and other field studies, which find that vegetation protects the surface from erosion by increasing surface roughness and absorbing some of the winds momentum, reducing the shear stress exerted on the soil. Although vegetation cover had the most influence on sand transport rates soil surface hardness (or crusting) also affected the transport rate but soil moisture and the height of the plants did not (Li *et al.*, 2003). The later two results are surprising and contradict conventional wisdom as to the effect of soil moisture on wind erosion and the dimension of plant structure and its role in wind erosion.

Bielders *et al.* (2002), working in the Sahel, used sand traps to measure wind erosion in traditionally cultivated fields and adjacent fallow bush land. They found that the wind erosion from the cultivated fields resulted in short distance saltation and creep transport to the fallow land (Bielders *et al.*, 2002) although the loss of finer sediment was not accounted for in this study.

Rajot *et al.* (2003) carried out a field study in Niger as to whether surface crusting of the sandy soils protects them from wind erosion. They used sediment traps, and a saltiphone (an acoustic saltation sensor

that records the number of saltating particles that strike a microphone membrane over a given time period) to measure horizontal flux and found that the crusting of these sandy soils did not protect them from wind erosion (Rajot *et al.*, 2003).

Direct measurement through sediment traps or dust samplers rarely produces data that can capture the spatial variability of erosion within a study site. For example, if a sediment trap or a dust sampler is placed near an area of low erodibility then measured amounts of eroded particles will be low and not necessarily representative of the area of study in general. As an alternative several authors have used an indirect measurement approach by using the occurrence of Caesium-137 (^{137}Cs) found within a soil profile to estimate fluctuations in soil depth. ^{137}Cs is a by-product of nuclear reactions and large quantities of it were released and circulated throughout the atmosphere during the nuclear testing of the 1960s (Warren *et al.*, 2003). This isotope was deposited by rainfall on soil surfaces throughout the world and was absorbed by clays, hence by comparing the amount present in a soil profile with that of an undisturbed reference sample results in a measure of soil loss or gain over a 30 to 40 year period (Warren *et al.*, 2003). The Fandou Beri area of Niger had been labeled a 'global hot spot' for soil erosion, however using this technique Chappell *et al.* (1998) found that soil erosion rates in Fandou Beri exceeded the previous estimates by approximately four times. However, the ^{137}Cs technique does not separate wind and water erosion and in the Sahel these two processes can be quite closely related. Sterk (2003)

describes how the shift in the Intertropical Convergence Zone northward results in unstable moist air and convection thunderstorms. Strong downdrafts traveling ahead of these thunderstorms, called haboobs, cause relatively short-lived dust storms, i.e., followed by heavy rains, wind erosion followed closely by water erosion (Sterk, 2003). Measurements with traps and samplers will generally isolate wind erosion from water erosion, however, in their field study on the effect of surface crusts on wind erosion Rajot *et al.* (2003) did not use the sediment collected immediately after a heavy rainfall as they felt that rain splash would result in sediment entering the trap.

Remote sensing

Goudie and Middleton (1992) argue that "dust storms have often been regarded as one of the most important manifestations of desertification" (p. 197). Major dust emission source areas can be identified through observations at the surface, the use of mineral tracers and remote sensing (Goudie and Middleton, 2001). Several studies have used remotely sensed data to identify dust emission sites. Total Ozone Mapping Spectrometer (TOMS) data and its associated Aerosol Index (AI) has been used to identify major source areas for desert dust emissions (Goudie and Middleton, 2001). AI data provide the intensity of dust content, and not a measure of total dust flux. The Infrared Difference Dust Index (IDDI) indicates a presence of dust by the decrease of outgoing thermal infrared radiation (Brooks and Legrand, 2000).

Satellite imagery, as previously mentioned, has been used in desertification

research to study changes in vegetation cover, but can also be used to provide land cover attributes and parameters for wind erosion models (Callot *et al.*, 2000). Chomette *et al.* (1999) proposed that threshold wind speed data could be estimated by coupling reanalyses of 10 m wind speed with satellite imagery. Recently work has been done to develop techniques for extracting soil moisture data from satellite data. Advances in passive microwave remote sensing have made it possible to estimate soil moisture up to a few centimetres in depth over large areas (Walker *et al.*, 2003). Although much of this work is being done primarily for hydrologic models, this data source may prove to be of some use in wind erosion models. Work is also being done to improve the interpretation of remotely sensed data for the retrieval of vegetation type and cover and soil type data in drylands where vegetation cover is sparse (Okin *et al.*, 2001b).

Modelling

Soil erosion in the field is difficult to measure particularly at broad spatial and temporal scales. As a result, several investigators have used models with varying levels of sophistication to estimate soil loss and dust emissions in arid and semi-arid environments. Wind erosion models have been used to assess the extent and severity of desertification (Dregne, 1983). These models represent the application of our knowledge of the wind erosion process gained through theoretical study, wind tunnel investigation, and field research. Some models focus on a specific sub-process of wind erosion such as sandblasting (Alfaro *et al.*, 1997; 1998). Others use a more

comprehensive approach by combining these sub-processes into one model. Alfaro and Gomes (2001) combined a saltation model and sandblasting model. They tested and validated both model components with data obtained from semi-arid agricultural fields in Spain and Niger in field experiments (Gomes *et al.*, 2003).

Other models incorporate many sub-processes into one model. For example, the most widely used model has been developed in the United States to estimate annual soil erosion from agricultural lands, the Wind Erosion Equation (WEQ) (Woodruff and Siddoway, 1965). This is an empirical model that combines soil type, vegetation, surface roughness, climate and field length data. However, as Haggett and Chorley (1967) identified, all models are in constant need of improvement as new information appears and concepts develop. Fryrear *et al.* (1999) state in their overview of the development of the WEQ that modifications were suggested almost immediately after its publication. Eventually a need to incorporate land management factors such as planting date, tillage method and amount of plant surface residue prompted the development of the Revised Wind Erosion Equation (RWEQ) (Fryrear *et al.*, 2000). The RWEQ is a combined empirical and process-based model. Fryrear *et al.* (1999) state the major difference between the two models is that WEQ focuses on the erodibility of the soil while RWEQ focuses on the erosivity of the wind. However, the empirical aspects of these models compromise their transferability beyond the agricultural soils they were designed for. Another more process based model developed to replace WEQ for

agricultural soil erosion is the Wind Erosion Prediction System (WEPS) (Hagen, 1991). This model includes submodels for hydrology, management practices, soils, crops, decomposition of vegetation, and a weather generator (Hagen, 1991). All of these models are designed to compute soil erosion for areas the size of agricultural fields with relatively homogenous attributes, such as uniform vegetation spacing and height. However, wind erosion also affects rangelands characterized by varied topography, vegetation cover and density of that cover.

A physically-based wind erosion model has been recently developed by Marticorena and Bergametti (1995) and Marticorena *et al.* (1997) to estimate dust emission and improve treatment of this process in Global Circulation Model (GCM) simulation. Their soil-derived dust emission model is based on the erodibility of the soil and the roughness of the surface (Marticorena and Bergametti, 1995). Ten metre wind fields derived from the European Centre for Medium Range Weather Forecasts supply wind data input for this model. This model has been applied by Callot *et al.* (2000) to compute dust emission for the Sahara Desert. Their results for both frequency and relative intensity of emissions were in good agreement with Satellite data. Another physically-based model has been developed by Shao and Leslie (1997), Lu and Shao (1999) and Lu and Shao (2001), called the Integrated Wind Erosion Modelling System (IWEMS). The IWEMS model integrates an atmospheric model with a wind erosion model, a land-surface scheme and a GIS database. This comprehensive model not only predicts atmospheric but

models the changing soil moisture conditions (Lu and Shao, 2001). IWEMS has been used to estimate and predict dust-storm events for all of Australia, encompassing regions of multiple land use and topographic features (Lu and Shao, 2001). Recently another dust entrainment and deposition model (DEAD) has been developed to model dust from a local to global scale (Zender *et al.*, 2003).

Advancements in technology have paved the way for these comprehensive models capable of computing wind erosion for large spatial scales. Perhaps the advancement of greatest importance is that of the increase in computing power. This has reduced the calculation limitations previously imposed on numerical modelling (Haff, 1996). The advancements in remote sensing have allowed for surficial features to be estimated over large spatial scale and in remote regions. Other advancements in GIS have allowed for the development of spatial databases documenting surface features and their attributes for large areas.

However, the development of these large-scale wind erosion models is still relatively new and there are several issues that need to be addressed. Much of the literature on issues of scale in modeling can be found in the hydrologic modeling literature. For example, there is no universal theoretical framework for transferring the small scale physics derived in the lab to the scale required for modelling large areas (Beven, 1989; Jensen and Mantoglou, 1992). Even if small scale modelling is quite successful in the lab, the effect on the large scale simulation of small errors multiplied many times and distributed over the modelled area are unknown (Seyfried

and Wilcox 1995). The scaling up of non-additive properties of input parameters is a problem, as the scales of model elements (metres to kilometres) are typically orders of magnitude larger than those elements measured in the field (millimetres to centimetres) (Oreskes *et al.*, 1994). Seyfried and Wilcox (1995) note that small-scale parameters useful for modelling in the lab may lose their physical significance at larger scales. The larger the spatial scale and the longer the time period of interest the more likely it is that more than one important process will be active (Haff, 1996). Haff (1989) suggests that 'emergent' rules different from those derived from the small-scale physics of the laboratory may control larger systems.

Ongoing research is needed to address these scaling issues and verify the quantitative output of these models. Just as Gomes *et al.* (2003) used field-collected data to test their model continual work is being done to test the components of these more comprehensive models and their final output. Direct measurements of horizontal and vertical transport using instrumentation such as samplers mounted vertically and spatially on a site offer a method of verification. However, the stationary placement of these devices means that the instruments may over-sample or under-sample depending on local conditions where they sit and whether the dust plume passed these sensors.

Another method is to use satellite imagery to confirm that dust emission occurred where it was computed to occur. For example, the TOMS carried on the Earth Probe Satellite can detect UV-absorbing aerosols and determine the

Aerosol Index. Lu and Shao (2001) and Callot *et al.* (2000) used satellite imagery to confirm their predictions of dust emission areas.

Despite the challenges posed by these large-scale models, they can be used to identify potential erosion areas and predict the resultant wind erosion expected due to land use and climatic changes. The future of wind erosion research includes continued work on wind erosion modeling and the coupling of remote sensing and GIS technology in these models.

Summary

Wind erosion is an important sub-process of desertification that can result in decreased soil fertility or the total removal of the organic and nutrient-rich layer of soils in dryland regions. Due to the multiple approaches and instrumentation used to quantify wind erosion and dust emission, comparison of results between studies is difficult (Sterk, 2003). The presence of erosional or depositional features, direct measurement and remote sensing all assess wind erosion as or after it has happened. Wind erosion modelling is the only proactive method of prediction and offers the option of pre-emptive mediation over large spatial areas. Unlike the early empirical models, such as the WEQ, process-based wind erosion models are relative newcomers. As such there is an opportunity for much more work to be done to improve and develop this modelling approach and extend the estimation of wind erosion beyond that of the agricultural fields.

However the occurrence of wind erosion in itself does not signify desertification.

In their study of wind erosion and its impact on the farmers in Niger, Warren *et al.* (2003) concluded that although soil erosion rates were greater than previously predicted, the soil was deep and it would take a long time for it to be worn away to a critical level. It should be noted that environmental impacts are not the sole result of physical changes, but are tied to the ability of a society or culture to adapt to those changes (Agnew and Warren, 1996). Desertification represents an interface of a human and an environmental system; as such future desertification studies should encompass both social scientists and physical scientists to provide a holistic approach to assess this phenomena.

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