Wind Erosion Process, Factor, Effects on Agricultural Soil and Mitigation Mechanism: A Review

Ewnetu Teshale
Ethiopian Institute of Agricultural Research, Jimma Agricultural Research Center

Abstract
Wind erosion is a significant environmental challenge that has profound effects on soil quality and agricultural productivity. Wind erosion degrades soil quality by removing nutrient-rich topsoil, leading to a decrease in soil fertility. This degradation can significantly impact agricultural productivity, leading to lower crop yields and, consequently, reduced income for farmers. Wind erosion can lead to the loss of organic matter and beneficial microorganisms, further exacerbating soil degradation and productivity loss. Mitigation methods for wind erosion are therefore of paramount importance. These include practices such as cover cropping, windbreaks, and conservation tillage. These methods not only protect the soil but also contribute to sustainable farming
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Introduction

Nowadays one of the major problems on global scale is the rapidly increasing demand to the food. This demand is of course totally parallel to the population growth. Even more land is used for agricultural purposes day by day. Cultivation without using specific control techniques, unplanned land use, such as establishing industrial facilities or constructing summer houses on the agriculture land, uncontrolled urban development and also destroying forests are fundamental factors of soil erosion (Sujay and Topalakatti, 2021).

Soil erosion by wind is a serious problem in many parts of the world. It reduces productivity by removing silts, clays, and nutrients from soil and by damaging young crops. It causes offsite damage with deposition on highways and in waterways, etc. It reduces visibility, causing accidents, and can affect the health of animals, people, and even ecosystems through the transport of contaminants. For example, wind erosion in Africa and the associated dust have been linked to the health of the coral reef and humans in the Caribbean. Wind erosion is a major conservation problem in arid and semiarid regions around the world that support about one-sixth of the world's population. Wind erosion is caused by inadequately protecting soil against wind shear. A lack of vegetative cover to protect the soil surface against wind shear is problematic in arid and semiarid regions because of low precipitation and high evaporation rates. However, soil aggregation, crusting, soil moisture, and humidity also may reduce erosion. Wind erosion occurs across a range of landscapes including playa lakes, cropland, shrub land, forest and desert (Li *et al.,* 218).

Accelerated soil erosion by wind results in both on-site and off-site damage. On-site damage includes the depletion of nutrients, organic matter, and fine particulate matter. In addition, wind erosion causes considerable crop damage, especially to young seedlings, and increased farm maintenance costs. Off-site damage includes adverse health impacts caused by dust storms over vast areas, and harm to transportation, communication and irrigation infrastructure (Sterk, 2003).

Process of wind Erosion

Suspension

Suspension refers to the vertical and (eventual) horizontal transport of very small soil particles that are generally removed from the local source area. They may end up on the neighbor's farm or several states downwind. These particles are the showy part of wind erosion, seen by the observer as dust storms, and collectively have been called black blizzards, bread-basket dust and 'Kansas Grit'. Suspended particles can range in size from about 2 to 100pm, with mass median diameter of about 50 pm in an eroding field. However, in long-distance transport, particles <20 pm in diameter predominate because the larger particles have significant sedimentation velocities. Some suspension-size particles are present in the soil, but most are created by abrasive breakdown during erosion. Because organic matter and some plant nutrients are usually associated with the finer soil fractions, suspension samples are enriched in such constituents compared with the bulk soil source. About 3-38% of the eroding soil could be carried in suspension, depending on soil texture (Van Sebille, 2020).

Figure: 1 Fine soil particles in suspension

Saltation

The characteristics of saltation aggregated particles in wind roughly 50 to 80% of total wind transport is by saltation. During saltation, individual aggregated particles lift off the surface at 50 to 90' angles, rotate at 115 to 1000 r/s,n and follow distinctive trajectories under the influence of air resistance and gravity. Those aggregated particles 100 to 500 pm in diameter (too large to be suspended by the flow) return to the surface at impact an gles of *6* to 14' from the horizontal, either to rebound or to embed themselves, thus influencing the breakdown and movement of other aggregated particles. The size range for saltation excludes the coarse and very coarse sand particles, which remain in the local area. During erosion, saltating aggregates may shift to the suspension mode because of abrasion and may cause other aggregates at the surface to shift modes. Saltation is the major cause of aggregate breakdown during erosion. Its role is to initiate and sustain suspension, drive the creep transport, and influence aggregate-size distribution of the soil surface. Therefore, linkage through those factors must be established to determine the impact of saltation on crop productivity. As with suspension, aggregate-size distribution in the new surface layer may be unchanged when erosion ceases (Cohn *et al.,* 2022).

Fig: 2 Saltation in a cultivated field with 20 km/hr winds ET: LM: SL20: June 2002

Surface Creep

Coarse, sand-sized, mineral-soil A/P's 500 to 1000pm in diameter, too large to leave the surface in ordinary erosive winds, can be set in motion by the impact of saltating aggregated particles. Reportedly, surface creep constitutes 7 to 25% of total transport. In high winds, the entire surface appears to be creeping slowly forward at speeds much less than 2.5 cm/s pushed and rolled (driven) by the saltation flow. Surface creep normally excludes very coarse sand particles and gravels greater than 2000 pm in diameter which, if contained in the bulk soil, must remain near their current location during wind erosion. Creep appears nearly passive in the erosion process, but creep-sized aggregates may abrade into the size ranges of saltation and suspension and thus shift modes of transport. The impact of surface creep on productivity appears to be linked primarily to aggregate-size distribution effects (Chen *et al*., 2022).

Abrasion

The percentage of erodible soil in the surface layer is highly correlated with the mass of soil removable from that surface in wind-tunnel tests. On long fields, the amount of soil that passes from a control volume on the soil surface increases nearly linearly with field length. Such a result implies abrasive breakdown of both erodible and non-erodible aggregates. Indeed, on long, erosion susceptible fields, the total amount of soil that can be lost is usually several times the amount of erodible material initially present at the surface. Thus, resistance to abrasive breakdown of surface aggregates is important in wind erosion. However, until recently the effects of abrasion in the erosion process have been neglected and the physics of soil aggregate abrasions was largely unknown. An abrasion susceptibility term *(w)* can be defined as the mass of material abraded from target aggregates per unit mass of impacting abrader. To determine how various factors effect *w,* large soil aggregates (50-100 mm in diameter) have been abraded with sand particles and soil aggregates using a calibrated nozzle (Cohn *et al.,* 2022)..

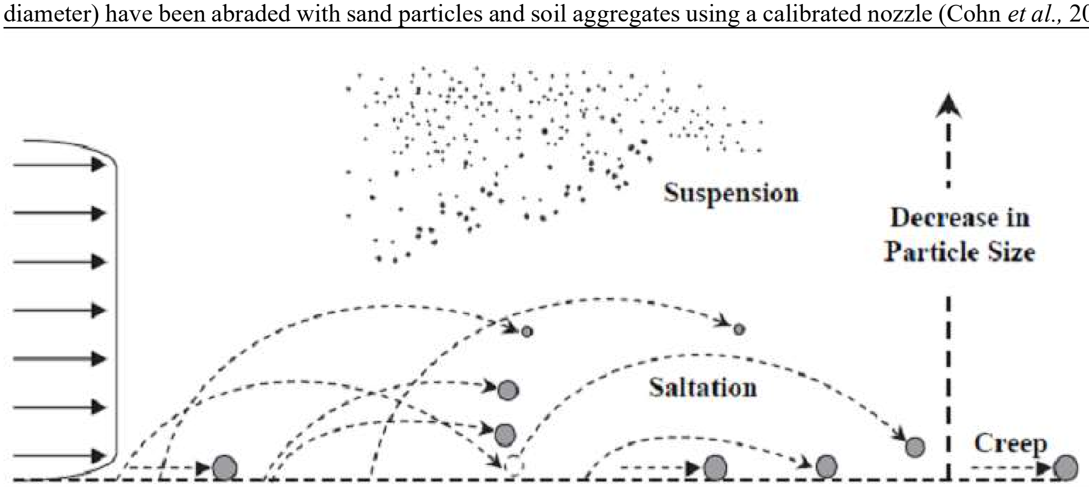

Fig 3: Modes of soil particle transport during wind erosion

Factors influence wind Erosion

Climate

All factors relating to climate play vital roles in wind erosion. Meteorological observations indicate that dust emission can be suppressed by rainfall. It is also observed that wind speed and duration directly influence wind erosion. Although soil moisture may be a highly variable parameter, spatio-temporally due to the heterogeneous nature of soil properties, evapotranspiration, land cover, topography and precipitation but it can also influence wind erosion. Low levels of soil moisture during droughts or at the surface of excessively drained soils may release particles to wind erosion Freeze drying in the surface is produced by this effect during winter months (Zhao *et al.,* 2021).

Landform

It was shown by wind tunnel simulation there are two effects of slope on wind erosion. Firstly, the wind velocity increases with slope along the up-slope direction of a landform and strengthens the wind erosion on the slope, and secondly, the threshold velocity of grain increases with slope and weakens the wind erosion. However, in the usual circumstances with slope less than 25°, wind erosion increases generally with slope along the up-slope direction of a landform (Xiao *et al.,* 2021).

Surface roughness

Surface roughness is an important physical parameter related to land surface erosion. It means a height where the average wind speed decreases to zero. For a fixed location, the surface roughness is often considered a constant if the surface properties had not changed. Its value varied depending on the terrain undulation, vegetation coverage and other factors. To some extent, the increase of surface roughness could control soil wind erosion, suppress blowing sand and improve ecological environment. Thus, the surface roughness is one of the important factors for accessing soil wind erosion potential (Zhao *et al.,* 2021).

Types of surface soil

Soil erosion is related to the regional geological environment and is affected by the soil texture. Soils with various textures have different water contents, water retention, gummy cohesion and plastic pressure of soil particles. Accordingly, under the same wind speed, the degrees of soil erosion are different for different soils. Based on the soil classification of the U.S. Department of Agriculture, sandy clay, loam and clay are categorized according to the percentages of sand, silt and clay in the soil. Without considering other factors, loam soil is more easily eroded by wind than clay soil, while sandy clay soil is most easily eroded. The plasticity of various soils horizontal component of the plastic pressure (Ps) of the sandy clay soil usually was 20, while the Ps of loam was only 0.5 and that of clay was 350. Ps is a physical parameter which represents the soil erodibility and is determined by the soil density. Soils with textures such as sandy clay and loam have a small Ps and big erodibility. Compact soil has a relatively larger Ps and smaller erodibility (Wu *et al.,* 2022).

Vegetative Cover

Extensive erosion by wind results when there is lack of permanent vegetation cover in certain locations. While bare soil that is loose and dry, is the most vulnerable to wind erosion, crops residue may provide enough resistance. Also, in severe cases even crops that yield a lot of residue may not shield the soil. The most effective vegetative cover in terms of soil protection should include a combination of living windbreaks networked adequately with crop selection, good tillage and residue management. Vegetation seasonality as also has a tremendous influence on wind erosion (Wang *et al.,* 2020).

Soil erodibility

Soil erodibility was originally thought to remain essentially constant for a given soil. But with the research processing in great depth, more and more researchers have discovered that soil erodibility is a relative concept, it is strongly affected by spatially variable, temporally dynamic soil properties, and human activities. Soil has different erodibilities under various forms and intensities of erosive force, so the condition of erosive force should be considered for selecting the index of soil erodibility. It is obvious that erodibility of different types of soil is impossible to be compared because this type of index fails to directly reflect the influence of soil properties. Properties that determine erodibility, such as soil aggregation and shear strength, are strongly affected by climatic factors such as rainfall distribution and frost action, and show systematic seasonal variations. They can also change significantly over much shorter time scales with subtle variations in soil water conditions, organic composition, microbiological activity, age-hardening and the structural effect of applied stresses. The sensitivity of soil erodibility to drying appears to be determined by the tendency of soil to form aggregates. Soil erodibility is also closely connected with human activities. It can vary with the change of agricultural activities, land-use transformations and the expansion of wildfires (Zhao *et al.,* 2021).

Wind erosivity

Wind force is the principle factor that affects wind erosivity. Wind tunnel tests and field measurements showed that, the rate of soil movement is proportional to the cube of wind velocity. The threshold velocity, which initiates the wind velocity, was found to be lowest than (8-9) miles per hour at 6 inches above the ground) for particles of diameter ranging from 0.1 to 0.15mm. The nature of atmospheric flow and ground surface roughness also govern wind velocity. It is generally accepted that wind erosion occurs when three conditions are occurring the wind is strong enough, the soil surface is susceptible enough, and there is no surface protection from crops, residues or snow cover. Under these conditions, the magnitude of an erosive event is governed by the eroding capacity of the wind and the inherent potential of the land to be eroded (Wu *et al.,* 2022).

Table 1: Global extent of human–induced soil degradation (Lal, 2001)

World Regions	Total Land Area (10 ha)	Human induced soil degradation (10 ha)	Soil erosion (10 ha)	
			Water	Wind
Africa	2966	494	227	186
Asia	**4256**	**748**	**441**	**222**
South America	1768	243	123	42
Central America	306	63	46	5
North America	1885	95	60	35
Europe	950	219	114	42
Oceania	882	103	83	16
World Total	**13013**	**1965**	**1094**	**548**

Effects of wind soil erosion on agricultural soil

Top soil loss

The loss of topsoil through wind erosion is a significant concern in agriculture and has detrimental effects on soil health and crop production. Topsoil, also known as the A-horizon, is the uppermost layer of soil that is rich in organic matter, nutrients, and microorganisms. It plays a crucial role in supporting plant growth and providing essential resources for crops. Wind erosion occurs when strong winds blow across bare or poorly vegetated soil surfaces, causing the detachment and transport of soil particles. As these particles are lifted and carried by the wind, they can be deposited elsewhere or lost from the system entirely. This process leads to the loss of topsoil, which has several negative consequences for crop production. One of the primary impacts of topsoil loss is the depletion of essential nutrients. Topsoil is rich in organic matter, which serves as a source of nutrients for plants. When topsoil is eroded, the nutrient content is diminished, resulting in nutrient deficiencies in the remaining soil. This can lead to stunted growth, reduced crop yields, and poor overall plant health (Wu *et al.,* 2022).

Seedling damage

Seedling damage caused by wind erosion can have detrimental effects on crop establishment and overall plant health. When strong winds blow across bare or poorly protected soil surfaces, they can dislodge and transport soil particles, which can physically harm emerging seedlings. One of the primary effects of seedling damage is poor establishment. Wind-blown soil particles can directly impact emerging seedlings, causing physical injury to their delicate stems, leaves, and roots. This can result in reduced germination rates, uneven emergence, and patchy crop stands. Seedlings that are damaged or uprooted by wind erosion may struggle to recover, leading to gaps in the crop canopy and decreased overall plant density. In addition to physical injury, seedling damage can also disrupt the root development of young plants. Wind-blown soil particles can dislodge or expose the delicate root systems, leading to root desiccation, nutrient deficiencies, and reduced water uptake. This can impair the ability of seedlings to establish a strong root system, limiting their access to essential resources for growth and development (Wang *et al.,* 2020).

Soil structural degradation

Soil structure degradation caused by wind erosion is a serious concern that can have detrimental effects on soil health and agricultural productivity. When strong winds blow across bare or poorly protected soil surfaces, they can dislodge and transport soil particles, leading to the breakdown of soil aggregates and the degradation of soil structure. In this discussion, we will explore the impacts of soil structure degradation caused by wind erosion. One of the primary effects of soil structure degradation is increased soil compaction. As wind-blown soil particles are removed from the surface, the remaining soil becomes more compacted, reducing pore space and limiting the movement of air, water, and nutrients within the soil profile. This compaction can lead to poor root penetration, restricted water infiltration, and decreased nutrient availability for plants. As a result, crop growth and productivity can be significantly compromised. Another consequence of soil structure degradation is the loss of soil organic matter. Soil aggregates play a crucial role in protecting organic matter from decomposition and promoting its accumulation in the soil. When soil structure is degraded by wind erosion, the stability of organic matter is compromised, leading to its accelerated breakdown and loss. This results in a decline in soil fertility, reduced nutrient cycling, and decreased microbial activity, all of which are essential for healthy plant growth (Wu *et al.,* 2022).

Nutrient depletion

Nutrient depletion caused by wind erosion is a critical issue that can have severe consequences for soil fertility and crop productivity. When strong winds blow across bare or poorly protected soil surfaces, they can dislodge and transport soil particles, including those rich in essential nutrients. As a result, the loss of these nutrient-rich particles can lead to nutrient depletion in the remaining soil. In this discussion, we will explore the impacts of nutrient depletion caused by wind erosion. One of the primary effects of nutrient depletion is the reduction in essential macronutrients and micronutrients available for plant uptake. Nutrients such as nitrogen (N), phosphorus (P), potassium (K), and various micronutrients are crucial for plant growth, development, and overall productivity. When these nutrients are lost through wind erosion, the remaining soil may become deficient in these essential elements, leading to nutrient imbalances and deficiencies in crops (Yan *et al.,* 2018).

Mitigation mechanisms of wind erosion

Many conservation practices can be implemented to control wind erosion. Conservation practices are designed to either reduce the wind force at the soil surface - or - create a soil surface more resistant to wind forces. Some practices also trap saltating particles to reduce the abrasion of soil surfaces downwind.

Strip Cropping

Cross wind strip cropping is the practice of growing crops in strips, arranged perpendicular to the prevailing wind erosion direction. Strips susceptible to wind erosion should alternate with strips having a cover resistant to wind erosion. This practice reduces the downwind avalanche effect by limiting the distance particles can travel before being trapped. As prevailing wind direction deviates from the perpendicular, correspondingly narrower strips are required. When designing strip cropping systems, soil aggregation, machinery size, and exposure to knolls, residue management, and the presence of windbreaks must all be considered. In addition, the prevailing wind erosion direction is important. On extremely erodible soils where very narrow strips are required, consideration should be given to permanent vegetation such as grass or grass- legume mixtures or even barriers between strips. . Although each method to control wind erosion has merit and application, establishing and maintaining vegetative cover, when feasible, remains the best defense against wind erosion (Böhm, *et al.,* 2014)

Crop Residues

A conservation practice that preserves crop residue or keeps growing vegetation in the field is the most practical way to reduce wind erosion potential. Plants and crop residues protect soil particles on the surface by absorbing a portion of the direct force of the wind, trapping moving soil particles, and enhancing soil particle cohesion. Crop rows perpendicular to the prevailing winds will control wind erosion more effectively than rows parallel with the wind. Also, standing residues are more than twice as effective as flattened residues. Other conservation practices such as windbreaks, grass barriers, strip cropping, or clod-producing tillage should be considered to supplement vegetative cover (Tatarko *et al.,* 2019).

Permanent Vegetation

Permanent vegetation is a highly effective method for controlling wind erosion and maintaining soil stability. It involves establishing and maintaining a cover of perennial plants, such as grasses, shrubs, or trees, to protect the soil from the erosive forces of wind. In this discussion, we will explore the concept of permanent vegetation as a wind control method and its numerous benefits. One of the key advantages of permanent vegetation is its ability to provide a physical barrier against wind erosion. The dense network of roots and above-ground vegetation acts as a protective layer, reducing the impact of wind on the soil surface. This barrier helps to prevent soil particles from being detached and transported, thereby minimizing erosion. Permanent vegetation also plays a crucial role in maintaining soil structure and stability. The extensive root systems of perennial plants bind the soil particles together, creating a strong and stable soil matrix. This helps to prevent soil compaction and crusting, which can further reduce the risk of wind erosion (Böhm, *et al.,* 2014)

Minimum Tillage

Minimum tillage is an effective method for controlling wind erosion and promoting sustainable agricultural practices. It involves reducing the intensity and frequency of soil disturbance during planting and cultivation, thereby minimizing the risk of soil erosion caused by wind. In this discussion, we will explore the concept of minimum tillage as a wind control method and its benefits. Minimum tillage, also known as reduced tillage or conservation tillage, aims to disturb the soil as little as possible while still achieving effective crop establishment. Unlike conventional tillage, which involves intensive plowing and soil inversion, minimum tillage practices focus on maintaining soil structure and reducing soil erosion. One of the key advantages of minimum tillage is its ability to preserve soil structure and stability. By minimizing soil disturbance, minimum tillage helps to maintain the integrity of soil aggregates, which are essential for preventing soil erosion. The presence of intact soil aggregates improves water infiltration, reduces surface runoff, and enhances the soil's ability to retain moisture. Tillage disturbs the natural soil structure and breaks down soil aggregates. Since small soil particles are least resistant to wind erosion it follows that tillage must be avoided or kept to a minimum. In particular, rotary tiller used at high speed can pulverize the soil making it susceptible to wind erosion. Frequent disking and any other operation that leaves the soil finely granulated at high risk times is an invitation to wind erosion and must be avoided (Pi and Sharratt, 2017)

Contour farming

Contour farming involves shaping the land to follow the natural contour lines of the slope. This is achieved by creating ridges and furrows that run parallel to the contour lines. The ridges act as barriers, slowing down the flow of water and preventing it from gaining enough velocity to erode the soil. By reducing the speed of water runoff, contour farming minimizes the risk of wind erosion. One of the key advantages of contour farming is its ability to manage water runoff effectively. The furrows between the ridges collect and channel the water, allowing it to infiltrate into the soil rather than causing erosion. This helps to retain moisture in the soil, which is crucial for plant growth and reduces the need for additional irrigation. By conserving water and preventing excessive runoff, contour farming contributes to sustainable water management practices (Sharma, 2017)

Recommendation

Wind erosion refers to the detachment, transport and deposition of loose sediment material together with organic matter and winds happen to be very effective when vegetation is sparse. The effects of wind erosion include fertility depletion in agricultural fields; leading to a reduction in crop harvest and desertification in the long run. Wind erosion rate and magnitude are controlled by a number of factors which include the erodibility of the soil, climate, soil surface roughness, and vegetation cover. Land degradation due to wind erosion is a serious threat to the quality of the soil, land and water resources upon which man depends for sustenance generally describes wind erosion as the detachment and transportation of the soil from land surface by wind particles are transported may deposited at some distance downwind because of the abrupt change ability of wind. Wind erosion is one of most serious environmental problems in the arid, semiarid and dry sub-humid areas around the world. Accelerated soil erosion by wind results in both on-site and off-site damage. Generally Understanding the mechanisms and magnitude of wind erosion is vital to manage and develop erosion control practices. Mitigating wind erosion requires a multi-faceted approach that combines vegetation cover, windbreaks, conservation tillage, soil stabilization techniques, education, and research. The importance of wind erosion mitigation and promoting these strategies, can contribute to a healthier environment, sustainable agriculture, and the preservation of our precious soil resources.

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