Wind Erosion and its Control in Western Rajasthan

Priyabrata Santra

Suresh Kumar

P.C. Moharana

P.C. Pande

M.M. Roy

R.K. Bhatt

भाकृअनुप
ICAR

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Director
ICAR-Central Arid Zone Research Institute
Jodhpur – 342 003 (Rajasthan) India
Phone: +91 291 2786584
Fax: +91 291 2788706
E-mail: director.cazri@icar.gov.in
Website: www.cazri.res.in

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Foreword

Arid regions of India covering mostly the western part of Rajasthan and north-eastern part of Gujarat are characterized by harsh climatic conditions involving high temperature and strong wind speeds during summer months. Wind erosion is an active land degradation process in the region causing loss of nutrient rich soil particles from cultivated lands and simultaneously resulting in several environmental problems in the form of dust pollution. About 13.5 per cent geographical area of India is affected by this process out of which 16 million ha (76%) lies in western Rajasthan alone.

Loss of top soil from agricultural lands through wind erosion process has a direct impact on crop productivity. Moreover, deposition of eroded soil at unwanted places like water bodies, residential areas, roads, railway tracks etc causes several ecosystem problems. Minute suspended dust particle in atmosphere also known as dust haze, generated during wind erosion events presents high health hazards to human beings as well as other desert dwellers. During severe dust storms, suspended dust particles reach to upper atmosphere and forms dust aerosol, which causes imbalance in regional climate.

Therefore, it is highly essential to adopt suitable control measures to reduce the soil loss and to avoid negative environmental impacts caused by this severe land degradation process. However, before it, a thorough understanding of the process and field assessment on soil loss from different land use situations of the region is required to adopt specific technology.

A much-needed study on wind erosion processes in the Indian desert has been conducted by a team of scientists at ICAR-Central Arid Zone Research

Institute, Jodhpur and the findings are presented in this publication titled "Soil loss due to wind erosion and its control" for which the authors deserve appreciation. It is hoped that the information contained in this bulletin will be of immense help to planners, agricultural development agencies, professionals, environmentalists and farmers for a better understanding on wind erosion process and thereby help in adopting suitable control measures with an overall aim of developing arid areas of the country.

O.P. Yadav
Director

September, 2016

Preface

Desertification is affecting the livelihoods of millions of people, mainly poor in the dry lands, which occupy nearly 41% of the Earth's land area and are the residence of more than 2 billion people of the world. In India, the western part of Rajasthan is mostly affected by desertification process dominated by wind erosion. Plenty of incident solar energy in the region makes the desert surface very hot especially during summer months. Wind speed also remains very high in the region during summer months. Therefore, the loss of top fertile soils through wind erosion process is very active for most of the time in a year. Eroded dust particles during severe wind erosion events commonly known as dust storms not only make the soils poor but also pose several environmental threats through generating aerosols in atmosphere. For example, average soil loss rate of 17 kg ha^{-1} min^{-1} has been observed during severe dust storm event. Moreover, the content of minute dust particles commonly referred as PM_{10} has also been observed very high.Therefore, soil loss assessment through wind erosion process in western Rajasthan is a key component of land resource management in the region.

In this report, field measurement of soil loss and its control measures have been discussed. Apart from this core content, basic principles of wind erosion and its causative factors have also been discussed. Overall, there are total nine sections in this report. This publication is the outcome of the field experiments on wind erosion conducted under the projects "Study the process of wind erosion and evaluation of wind erosion models in Jaisalmer region of Indian Thar desert (CAZRI/T01/18)", "Rehabilitation of degraded rangelands and stabilization of production in arable land of Thar desert, India (SUMAMAD project phase-II) (CAZRI/T-02/EF/78)" and "Development of dual purpose mechanical barrier to control wind erosion with simultaneous utilization of renewable energy(CAZRI/T-08/EF/88)". Financial supports provided by ICAR-Central Arid Zone Research Institute, Jodhpur, UNESCO-SUMAMAD and Department of Science and Technology, New Delhi under Fast Track Scheme for Young Scientist (SR/FTP/ES-60/2011) to conduct field experiments under above said projects at Jaisalmer, Bhujawar Jodhpur and Khuiyala Jaisalmer, respectively are sincerely acknowledged. The authors are thankful to the publication committee for their critical observations and further improvement of this report. Guidance and supervision of Dr. Pratap Narain, former Director, CAZRI and Dr. R.S. Mertia, former Head, CAZRI RRS Jaisalmer in carrying out field experiments on wind erosion at Jaisalmer are highly acknowledged. The support extended by Drs. Amal Kar, L.N. Harsh, R.K. Goyal, and H.L. Kushwaha in literature review; Drs. Rajendra Prasad, B.K. Kandpal, R.N. Kumawat, N.K. Sinha and H.R. Mahla in field experimentation at Jaisalmer; Drs. N.D. Yadav, J.P. Singh and P. Raja in wind speed data collection are duly acknowledged. Sincere thanks are also due to Sh. C.P. Prajapati and Sh. Nand Kishore for technical assistance in field and to Ms. Preeti Varghese in laboratory and data entry work.

Authors

CONTENTS

INTRODUCTION

Wind erosion is a major land degradation process in the arid and semi-arid regions of the world. It affects about 41% land area in the world (Lal, 1990) and about 13.5% in India (Sehgal and Abrol, 1994; Kar *et al*., 2009). Removal of soil particles by wind is very active in the Indian Thar Desert and poses severe multifaceted problems (Dey, 1957; Kaul *et al.* 1959; Bhimaya *et al.,* 1961; Bhimaya and Choudhury, 1961). Loss of nutrient-rich particles from agricultural fields, suspension of fine particles in air, and deposition of eroded soil particles on railway tracks, roads, and irrigation canals etc. are major wind erosion related problems in the region. During severe dust storm events, the suspended particles may get transported by air over hundreds of kilometers and form a blanket of dust haze over the Indo-Gangetic plains and surrounding area. Prevailing weather and terrain conditions of this desert are also very conducive to wind erosion. Among climatic factors, wind speed plays a vital role and if it exceeds the threshold of 5 m s^{-1} at 0.3 m height from ground surface it initiates wind erosion (Schwab *et al*., 1993). Among terrain properties, soil aggregate distribution, surface roughness, soil moisture and vegetation cover are important factors influencing wind erosion. Indiscriminate grazing in the region also destroys the vegetation and exposes the land surface thus making it more vulnerable to wind erosion. Minute soil particles (<60 µm) blown by wind are one of the major causes of particle air pollution and causes serious health hazard to people and animals dwelling in the desert region, especially to children, sensitive persons and old animals (Santra, 2006). Combating wind erosion in the vast desert requires prioritization of regions according to the severity of problem. In this context the measurement of wind erosion in different land use sites of the desert is essential for the validation of process-based wind erosion model and its application in the mapping of wind erosion prone regions.

PHYSICS OF WIND EROSION PROCESSES

Wind erosion is a set of processes by which soil particles are lifted from land surface, transported to and deposited at another place. The conducive conditions for wind erosion process are i) presence of loose, dry and finely granulated particles on surface, ii) smooth soil surface with negligible amount of vegetation or any other surface cover, and iii) strong and turbulent wind regime. In the Indian Thar Desert, most specifically at western boundary of Rajasthan covering areas of Barmer, Jaisalmer, and Bikaner, all these conducive conditions are prevalent during summer months and thus wind erosion is found as a severe land degradation process in the area. A comprehensive summary on movement of soil particles by wind erosion processes was reported by Bagnold (1943) for desert sands and by Chepil and Woodruff (1963) for agricultural lands. A brief discussion on wind erosion process e.g. the initiation of soil erosion, transport and sorting of eroded particles and abrasion are discussed.

Initiation of soil movement occurs when the wind speed reaches a level that sets the most erodible grains at surface in motion. This wind speed is also known as the threshold wind speed or threshold frictional velocity (u_{*t}). Bagnold (1943) defined threshold friction velocity as $(\tau_0/\rho)^{1/2}$ where τ_0 is the shear stress at the boundary and ρ is the air density and described it to vary as the square root of the product of equivalent diameter of soil particles and density relationship of fluid and grain as follows:

$$u_{*t} = A\sqrt{\frac{(\rho_s - \rho)}{\rho} gd} \tag{1}$$

Where A is experimental coefficient, ρ_s is particle density, ρ is air density, g is gravitational constant and d is particle diameter. Several experiments have reported the value of A ranged from 0.08 to 0.12, which is largely dependent on Reynolds number (R). Frictional velocity is generally dependent on surface conditions and is usually obtained from data on wind velocity-profile as follows:

$$u_* = \frac{\bar{u}_z k}{\ln\left(\frac{z-D}{z_0}\right)} \tag{2}$$

where, $\bar{u}_z$ is the mean wind speed at height z, k is Von Karman's constant (0.4), D is effective roughness height, z_0 is roughness parameter.

Transport of soil particles, which are initially dislodged from surface by wind speed, is commonly described by three distinct modes: suspension, saltation, and surface creep. In the suspension mode, aggregates or particles that are removed from local source area are transported to high altitudes and over long distances, depending on their size, shape, and density. Chepil (1945) reported that 3 to 38% of total transport occurred through suspension mode. Size of suspended aggregates/particles ranges from 2 to 100 μm with a mass median diameter of about 50 μm in an actively eroding field. This size range excludes the different size fractions of sand particles and aggregates of corresponding sizes which remain in local area. Suspended particles generated through wind erosion process is generally considered as nutrient rich particles as plant nutrients and organic carbon are mostly associated with finer soil fractions. Nutrient enrichment in eroded soil even increases with the presence of coarse sand content in bulk soil. Consequently, suspension indirectly impacts soil productivity by removing nutrient rich fractions of soil or by leaving behind the less-fertile soil constituents. In the saltation mode, eroded particles are jumped or hopped from one place to another place. Saltating particles leave the surface with wind force but are generally large enough to be suspended and thus returned back to surface. On returning to surface, saltating particles initiate the movement of other particles. Size of saltating particles/aggregates ranges from 100 to 500 μm. The bulk of transport during wind erosion, roughly 50 to 80% occurs through saltation mode. Majority of saltating particles/aggregates rises up to a height of 30 cm and in some cases up to 120 cm. In the surface creep mode, coarse sand sized mineral particles having diameter 500-1000 m are pushed and rolled on soil surface. About 7-25% of total mass transport occurs through surface creep mode (Lyles *et al*., 1985).

Transport of wind eroded particles/aggregates generally sorts the materials present on surface. Finer and lighter particles generally move faster than the coarser and denser ones. Erosive winds separate the soil into several distinct grades as follows (Chepil and Woodruf, 1963): i) residual soil materials representing non-erodible clods and massive rock materials that remain in place, ii) lag sands, lag gravels, and lag soil aggregates constituting semi-erodible grains that have been moved primarily by surface creep, iii) sand and clay dunes in the form of accumulated highly erodible grains that have been moved primarily in saltation, and iv) loess, which are mainly composed of dust lifted off the ground by saltation and carried high in the air and deposited in uniform layers both near and far from dunes. Distinct demarcations of size between various grades of wind-sorted materials do not exist and in most cases the size range of one grade overlaps with other grades. Nonselective removal of surface soil by wind is associated with loess, which was already sorted and deposited from the atmosphere during past. In case of selective removal of materials, winds tend to remove silt and clay particles leaving behind the sands and gravels on surface.

Abrasion by impacts of particles transported along the surface by wind is an important phase of the wind erosion process on all soils (Chepil and Woodruff, 1963). Soils in arid areas usually are covered with a thin crust, which may be depositional crust or biological crust and are somewhat resistant to wind erosion. Abrasion of moving particles by wind disintegrates this thin crust and exposes more highly erodible soil underneath it. Abrasive force of saltating particles also gradually breaks the non-erodible particles. The materials detached from clods and surface crust by abrasion accumulate on the leeward side of fields or, if they are fine, are carried far through the atmosphere.

CAUSATIVE FACTORS OF WIND EROSION

Five major factors were mentioned by Woodruff and Siddoway (1965) to influence wind erosion, based on which wind erosion equation (WEQ) was developed as follows:

$$E = f(I, C, K, L, V) \qquad (3)$$

where, E is the potential annual soil loss (t ha^{-1}), I is soil erodibility factor, C is climatic factor, K is soil surface roughness factor, L is equivalent width of field (the maximum unsheltered distance across the field along the prevailing wind erosion direction), V is equivalent quantity of vegetative factor. In the following sections, wind erosivity or climatic factor, soil erodibility factor and soil roughness factor are discussed in detail.

Wind Erosivity Factor

Erosive energy of moving wind, E (J m^{-2} s^{-1}) is the major force to cause erosion and is directly proportional to the cube of wind speed as follows:

$$E = 0.5 \times \rho_{\text{air}} \times v^3 \qquad (4)$$

where, ρ_{air} is the density of air (1.23 kg m^{-3}) and v is wind speed (m s^{-1}). Strong summer wind blows in the Indian Thar Desert at an average speed of 20-30 km h^{-1} (daily average) resulting into frequent dust storms. Diurnal variation of wind speed for three selected locations at Jaisalmer, Chandan and Bikaner in western Rajasthan is plotted in Fig. 1. In case of Jaisalmer, diurnal variation is plotted at 5 minute interval whereas for Chandan and Bikaner station it was plotted at 30 minutes and 1 h interval, which was actually the measurement interval for each location. Each data point represent the average of (30×3) values corresponding to 30 days for a month in a year for a total of three years. The diurnal plot shows two peaks and two troughs for each location. Two peaks are generally observed during day time roughly between 8:00 am and 4:00 pm and night time roughly between 10:00 pm and 4:00 am. Characteristic troughs with low wind speed are generally observed during morning and evening time of a day. Among the three locations, wind speed is higher at Chandan station than other two stations. Month-wise distribution also showed that wind speed is higher in June month than others.

Monthly average wind speed for three locations in western Rajasthan is given in Table 1. June month has been found more windy than rest months of a year for all three locations. For Jaisalmer and Chandan station, average wind speed during June was >4 m s^{-1}

(~14.4 km h^{-1}), whereas for Bikaner station, it was 1.92 m s^{-1}. Winter months from October to January are calm and the wind speed was <1 m s^{-1} for all three locations.

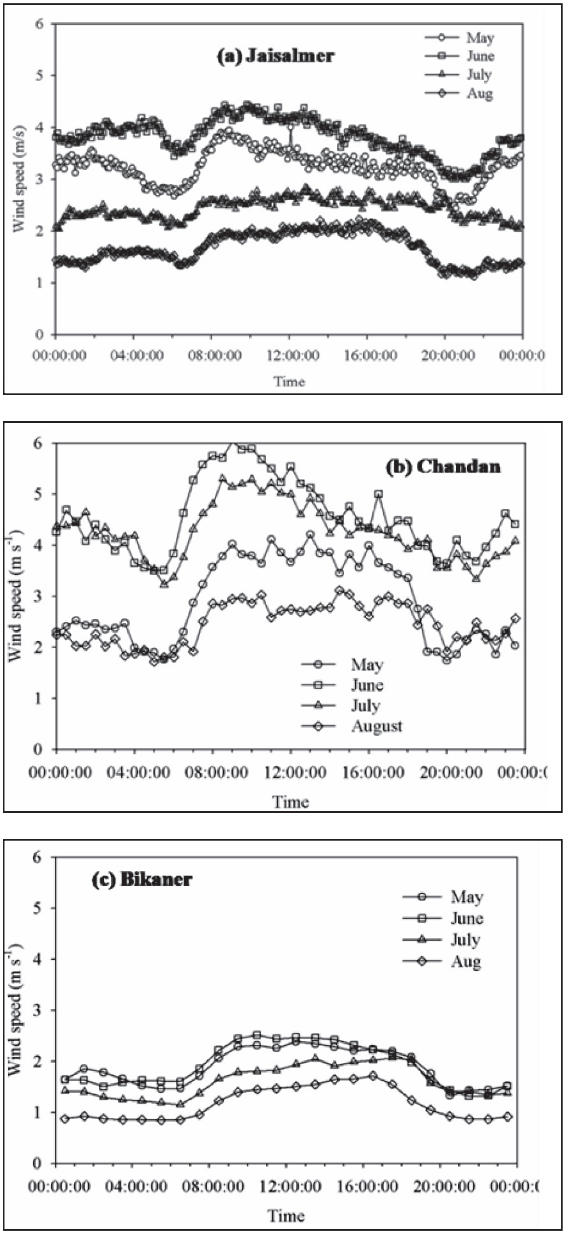

Fig. 1. Average diurnal variation of surface wind speed at three locations in western Rajasthan during 2010-2012.

Table 1. Monthly average surface wind speed at three locations during 2010-2012

Month	Monthly average measured surface wind speed (m s^{-1})		
	Jaisalmer	Chandan	Bikaner
January	0.61	0.83	0.51
February	1.09	1.01	1.08
March	1.19	1.62	0.99
April	1.43	1.88	1.31
May	2.63	2.90	1.89
June	4.03	4.56	1.92
July	3.23	4.27	1.60
August	2.25	2.45	1.16
September	1.38	0.08	0.99
October	0.85	-	0.63
November	0.60	-	0.37
December	0.56	0.83	0.41

Characteristic features of wind regime in western Rajasthan has been analysed through Weibull distribution, which is expressed as:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{k}{c}\right)^{k}\right] \quad (5)$$

where, $f(v)$ is the frequency distribution of wind speed, v; k and c are the Weibull shape parameter and Weibull scale parameter, respectively. Both these parameters characterize the wind resource potential of any region. The shape parameter, k, indicates peak height of the wind distribution. If the wind speeds tend to be very close to a certain value, the distribution will have a high k value and is very peaked. Whereas, the scale parameter, c, indicates how windy is the location and higher is the value more windy is the location or situation. Value of k has been reported to vary from 1.5 to 3.0 for most wind conditions. The Rayleigh distribution is a special case of the Weibull distribution in which the shape parameter, k is 2.0 (Spera, 1995; Persaud *et al.*, 1999).

At first, Weibull parameters (*k* and *c*) were estimated from the measured wind speed data at 2 m height from surface by automatic weather station at sub-hourly interval. Mean wind speed (v_m) and most probable wind speed (v_{mp}) were then calculated using estimated Weibull parameters *k* and *c*. Wind resource characteristics in terms of v_m and v_{mp} for three selected locations in western Rajasthan during summer months are presented in Table 2. Mean wind speed, v_m during June month was observed 4.38 m s^{-1}, 4.96 m s^{-1}, and 2.12 m s^{-1}, respectively for Jaisalmer, Chandan and Bikaner station. Arithmetic average of wind speed following wind speed data as per normal distribution for these three locations during June month (Table 1) showed little lower values than the above mentioned values. It clearly shows that characterizing wind speed data using Weibull distribution is better than assuming it normally fitted and thereby calculating the average wind speed.

Table 2. Mean wind speed (v_m) and most probable wind speed (v_{mp}) during summer months

Month	Jaisalmer			Chandan			Bikaner		
	v_m (m s^{-1})	v_{mp} (m s^{-1})	Average speed (m s^{-1})	v_m (m s^{-1})	v_{mp} (m s^{-1})	Average speed (m s^{-1})	v_m (m s^{-1})	v_{mp} (m s^{-1})	Average speed (m s^{-1})
May	3.00	1.33	2.63	3.26	1.45	2.90	2.01	1.45	1.89
June	4.38	3.27	4.03	4.96	4.86	4.56	2.12	1.59	1.92
July	3.33	2.81	3.23	4.69	4.55	4.27	1.62	1.24	1.60
August	2.40	1.52	2.25	-	-	2.45	1.24	0.73	1.16

Wind velocity profile is logarithmically related with height (z) through the following equation:

$$U = \sqrt{\left(\frac{\tau}{\rho}\right)} . \left(\frac{1}{k}\right) . \ln\left(\frac{z + z_0}{z_0}\right) \quad (6)$$

where, U = wind speed at a particular height z, τ = shearing stress, ρ = density of air, *k* = van karman constant (0.4), z_0 = aerodynamic roughness length. Wind velocity at three heights above surface (1 m, 2 m and 2.5 m) was recorded at a rangeland site in Chandan during three windy situations, calm, moderate and high wind regimes. Mean wind velocity data for three different heights were fitted in Eq (6) and plotted in Fig. 2. It has been observed from Fig. 2 that with increase in height from surface wind speed increased rapidly up to 0.5 m and then increased gradually. In case of low wind regimes (bottom and middle line), wind speed near ground surface was almost nil. In case wind speed at 1 m height exceeds about 2.5 m s^{-1}, then only near surface wind speed will be greater than zero. It actually indicates the threshold wind speed at 3 m height, commonly measured at meteorological observatory to initiate the wind erosion process.

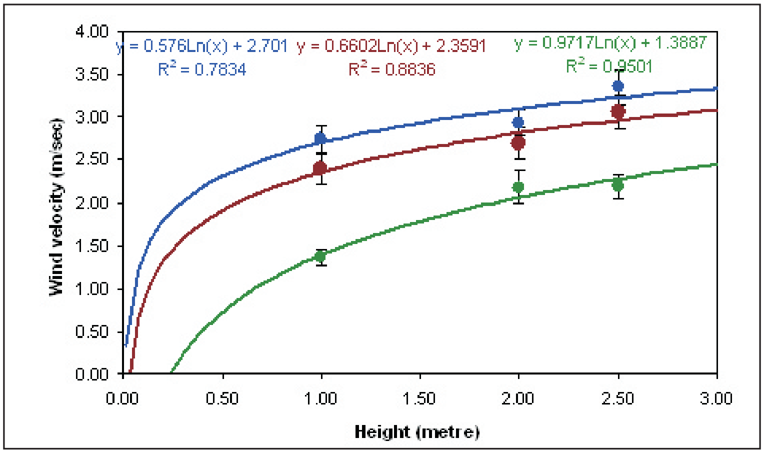

Fig. 2. Wind velocity profile measured at Jaisalmer during three different windy periods.

Spatial pattern of erosive winds in the Indian Thar Desert was quantified by Kar (1993) by quantifying wind erosion index for different meteorological stations of the desert for the period of March to July. For calculating the wind erosion index the formula developed by Chepil *et al*. (1962) at Garden City, Kansas, USA was used, which was later on modified by Yallon and Garner (1966) as follows:

$$C = 100\, v^3 / 2.9 * (PE)^2 \qquad (7)$$

where, C is climatic wind erosion index, v is mean wind speed at 10 m height, PE is Thornthwaite's measure of precipitation effectiveness and 2.9 is annual average climatic index for Garden City, Kansas. However, above formula is not suitable to study short term temporal variation of wind erosivity because in the above equation [Eq(7)] monthly PE index was used. Wind erosivity map of Western Rajasthan based on wind erosion index C showed that the south-western part of Jaisalmer district was under extremely high wind erosion potential, while the area roughly between Barmer, Shergarh, Phalodi and Jaisalmer qualified as the area with very high erosion potential. Spatial gradient in the strength of summer wind decreased from west to east in western Rajasthan (Narain *et al.*, 2000). This decrease is not only from west to east but also towards North and South from the high wind belt of Jaisalmer and Phalodi (Krishnan, 1977).

Short term temporal variation of wind erosivity may be quantified through wind factor W_f as per revised version of WEQ (RWEQ) (Fryrear *et al.*, 2000). It is hereby noted that the basic empirical model WEQ for soil loss estimation as mentioned in Eq (3) was later on revised by incorporating few process based inputs to improve the accuracy of estimation. In RWEQ, the basic driving force is wind, which is calculated as follows:

$$W_f = \sum_{i=1}^{N} \rho \frac{(U_i - U_t)^2 U_i}{gN} \tag{8}$$

where, W_f is the wind factor (kg m^{-1} s^{-1}), U_i is the wind speed at 2 m height (m s^{-1}), U_t is the threshold wind speed, N is the number of wind speed observations in a time period, ρ is the air density (1.293 kg m^{-3}), g is the acceleration due to gravity (9.8 m s^{-2}).

Wind erosivity for above four stations has been assessed through calculating wind factor (W_f) of revised wind erosion equation (RWEQ) as per Eq (8). Threshold wind speed at 2 m height has been found in literature as 5 m s^{-1} (Fryrear *et al.*, 1998), which depends on soil surface characteristics. In India, reports by Gupta *et al.* (1981) and Ramakrishna *et al.* (1990) revealed the threshold daily average wind speed for Chandan, Bikaner and Shergarh (Jodhpur) as 2.78, 1.39 and 1.11 m s^{-1}, respectively at 3 m height. Averaging and conversion of these reported threshold values from 3 m height resulted in to the threshold value at 2 m height as 1.66 m s^{-1}, which has been used as the threshold wind speed throughout the study. Jaisalmer and Chandan site have been found more erosive than other sites (Fig. 3). Highest wind erosivity has been observed during second fortnight of July at Chandan (2.81 kg m^{-1} s^{-1}).

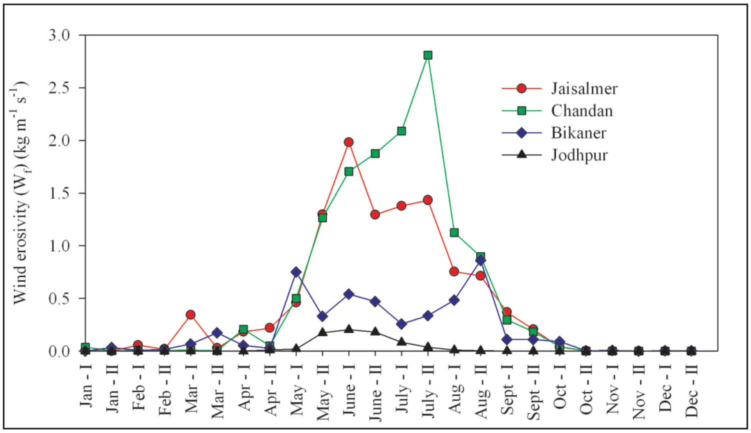

Fig. 3. Wind erosivity (W_f) for four selected locations in western Rajasthan (Data used: Daily wind speed data during 2000-2010)

Weather Factor

Weather factor (*WF*) was calculated with an aim to estimate soil loss through RWEQ approach. Wind factor (*Wf*) and soil wetness (*SW*) may be calculated separately to obtain *WF* as follows:

$$WF = W_f \times SW \times SD$$

Snow depth (*SD*) factor may be considered negligible for hot arid situation. Soil moisture content is an important control factor for wind erosion, so description of soil moisture status is necessary for prediction of wind erosion events for either a small region or for a large scale. For prediction of wind erosion events at a small scale, frequent observations on soil moisture condition is sufficient but for a large scale it is necessary to model the soil moisture change. So an attempt had been made to quantify surface as well as subsurface moisture condition at wind erosion experimental site of Jaisalmer, Rajasthan. For this study a time period of two weeks from 29th April to 10th May, 2005 was chosen when three rainfall events of 2 mm, 25 mm and 7 mm occurred respectively on 29th April, 1st May and 3rd May. Soil moisture of 0-10 cm, 10-20 cm and 20-30 cm soil surfaces were quantified gravimetrically for four locations of the experimental site on 1st, 2nd, 4th, 8th and 12th day. Before rainfall events, soil moisture for surface (0-10 cm) was observed as low as 0.40% (w/w), which was improved to 3.96% (w/w) after three rainfall events of 34 mm (Fig. 4). Significant amount of soil moisture was observed for 10-20 cm soil (2.87%, w/w) although soil surface has dried to 1.88% (w/w) after 7 days from last rainfall events of 7 mm on 3rd May.

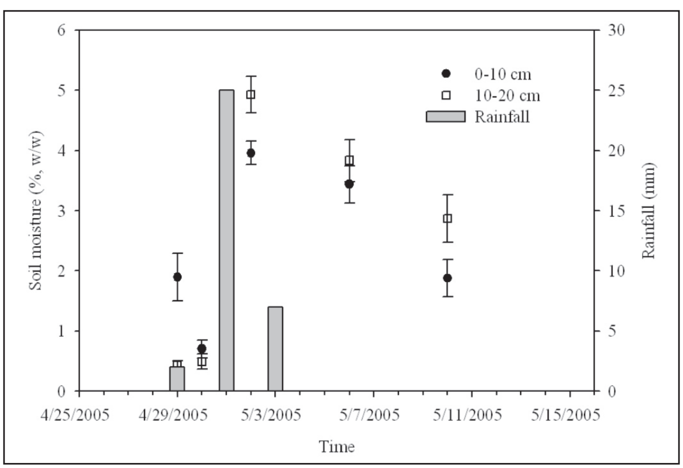

Fig. 4. Soil moisture regime as affected by rainfall events at Jaisalmer.

Soil Erodibility Factor

Aggregate size distributions (ASD) and dry soil aggregate stability are primary factors of surface conditions affecting the surface erodibility. The size distributions are generally determined through rotary dry sieve (Chepil, 1962). Skidmore (1988) had suggested only one parameter of aggregate size distribution i.e. percent of aggregates > 0.84 mm in diameter to describe soil erodibility. Aggregate stability can be calculated through measurement of either crushing energy/ surface area (J m^{-2}) or crushing energy (J kg^{-1}) or rupture stress (kPa) or initial break force (N) (Skidmore and Layton, 1992). Among these parameters, initial break force is easiest to measure but requires the highest number of measurements (Tatarko, 2001).

Kar and Joshi (1995) identified five soil erodibility classes in Western Rajasthan based on percentage of aggregates >0.84 mm in diameter as proposed by Skidmore (1988). Much of this desert region comes under severe and very severe categories of wind erodibility irrespective of whether the areas have similar wind erosivity or not (Narain *et al.,* 2000). It has been observed that particles in the range of 0.1 to 0.25 mm are more in eroded soil than field soil, thereby higher susceptibility of this fraction to erosion (Gupta, 1993). Sometimes soil crust may also form over soil surface after rainfall, which prevents soil particles to erode by wind. Average silt content of this crust is comparatively higher (8-10%) than that of soil layers below the crust (3-4%) (Gupta, 1976).

Besides presence of higher per cent of erodible fraction, dry soil moisture regime at soil surface further aggravates its susceptibility. Soil moisture content at field capacity is very low (3.5-6%) whereas infiltration rate is very high (10-60 cm hr^{-1}) and thus surface soil remains dry for most of the time (Dhir, 1985). Presence of moisture generally creates fragile soil aggregates through cohesive forces and thus makes temporary non erodible clods in the fields. Therefore, the threshold friction velocity (u_{*t}) required to initiate wind erosion process increases. The intensity, amount and distribution of rainfall events are so scarce in the Indian Thar Desert, the effect of rainfall on formation of non-erodible clods was found for a very short period.

The erodibility factor is comprehensively calculated in RWEQ as the erodible fraction (EF) and soil crust factor (SCF) using data on sand, silt, clay, organic matter and $CaCO_3$ content as follows:

$$EF = \frac{29.09 + 0.31Sa + 0.17Si + 0.33Sa/Cl - 2.59OM - 0.95CaCO_3}{100} \quad (9)$$

$$SCF = \frac{1}{1 + 0.0066(Cl)^2 + 0.021(OM)^2} \tag{10}$$

where, *Sa* is sand content (%), *Si* is silt content (%), *Cl* is clay content (%), *OM* is organic matter (%), $CaCO_3$ is Calcium carbonate content (%). Thematic maps on both these factors were prepared in GIS environment considering their spatial variation within Rajasthan and presented in Fig. 5. Area covering Jaisalmer, Bikaner, and Churu, Jhunjunu, Sikar, Jodhpur and Nagaur district of western Rajasthan lies under high EF factor (0.57-0.60). Jaisalmer, Bikaner and western most part of Jodhpur lies under high SCF factor (0.69-0.84).

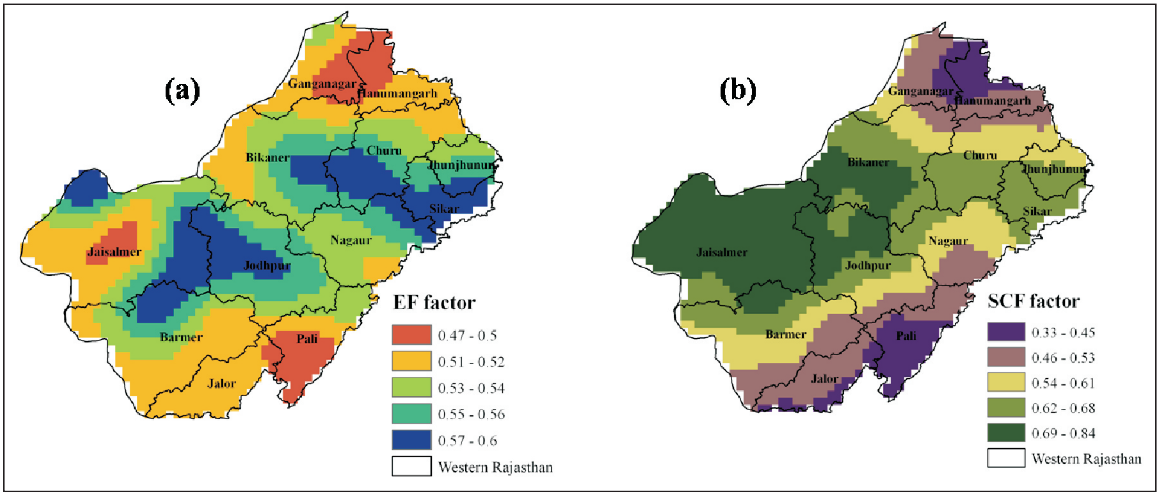

Fig. 5. RWEQ factors in western Rajasthan; (a) Soil erodible fraction (EF) factor and (b) soil crust factor (SCF).

Soil Roughness

Presence of non-erodible clods over undulating soil surface of the desert provides roughness and increases threshold friction velocity. Such type of roughness can broadly be classified into two main categories-random roughness and ridge roughness. Measurement of random roughness in field was difficult and cumbersome and can be done either using a pin meter (Wagner and Yu, 1991; Skidmore *et al*., 1994) or through chain method (Saleh, 1993, 1997). However, with the application of laser technology, it is now east to quantify soil roughness. Ridge roughness is generally computed from ridge height and ridge spacing and their alignment with wind direction (Fryrear *et al*., 2001). Vegetation covers either in the form of flat residue or standing biomass are other important roughness elements, present over desert area. Flat residue lying over ground surface can be quantified through collecting and air-drying residue content (g m^{-2}). Protruding roughness provided by tussocks of *Lasiurus sindicus,* a dominat grass species of the desert, can be computed through measurement of tussock diameter, tussock height and tiller count for each tussocks in a selected framed area and the average distance between them. All the above parameters describing surface condition should be measured at regular interval or at the time of possible significant changes.

Soil Properties Affecting Erodibility

Soil properties that are affecting erodibility may be classified into four major groups of soil properties: i) stability of soil against erosion as influenced by cohesive and adhesive forces of water and raindrops, ii) state of soil structure such as size, shape and density of erodible and non erodible soil fractions, iii) stability of soil structure against breakdown by mechanical agents such as tillage, abrasion from windblown materials, and direct force of winds, iv) stability of soil structure against breakdown by natural causes such as wetting and drying. Most of these primary properties are affecting the erodibility directly and are influenced by basic soil factors such as soil texture, water stable structure, organic matter content etc.

Clay particle (<0.002 mm) rather than silt or clay plays a predominant role influencing erodibility by wind. Nevertheless, silt content tends to decrease whereas sand content tends to increase the erodibility. In general, higher the proportion of silt (0.002-0.05 mm) in soil, higher is the percentage of non-erodible clods and the lower the soil erodibility. On the other hand, higher the proportion of fine sand (0.05-0.5 mm) lower the percentage of non-erodible fraction and higher the erodibility. Sand grains have little or no cohesive property and hence are easily carried by wind except for coarse sand (0.5-1 mm). Silt and clay particles due to their cohesive property form nonerodible clods after wetting and drying. However, relative effectiveness of silt and clay as binding agent depends on the relative proportion of each other.

Soil structure that influences erodibility is the proportion of water stables particles as conventionally determined by sieving of soil in water. In field soil, some of the water stable particles are primary particles of sand, silt or clay and some are water-stable aggregates, which are generally called as primary aggregates. These primary particles or aggregates grouped together into secondary aggregates or clods, however some primary particles or aggregates exist individually. Water stable particles of both coarse (>0.84 mm) and fine

(<0.02 mm) fractions increases the cloddiness and decreases the erodibility. However, whole size distribution of water stable particles in soil depicts the better picture of erodibility rather than considering the water stable aggregates below or above of a certain size.

Addition of organic matter in soil decreases the soil erodibility during the initial stage may be up to 2 years but increases the erodibility thereafter. At the initial stage, when organic matter is decomposed by microorganisms, several binding or cementing agents were formed, which may be grouped into three groups: i) lyophilic and lyophobic colloids consisting of decomposition products of plant residues, ii) the microorganisms themselves and their secretory products such as mucus, slime or gum, iii) polysaccharides synthesized by some microorganisms (Chepil and Woodruff, 1963). The aggregation of particles into non-erodible clods at the initial stage is temporary upto the decomposition stage. After decomposition process ceases, gradually the initial cementing materials lose their sticky property or are replaced by secondary materials. These secondary products of organic matter decomposition form a friable mellow soil, which is very erodible by wind. Therefore, incorporating the vegetative matter into the soil is not as important as leaving it on the surface, where it decomposes less rapidly and therefore continues to replenish the cementing products for much longer period. It has been reported that the benefits obtained from the primary products of decomposition by decreasing soil erodibility are small as compared to the detrimental effect from the secondary products of decomposition called as humus. However, high humus content in soil must be maintained, because the beneficial effect of humus in augmenting soil fertility far exceeds the detrimental effects.

Surface Cover Factor

Surface roughness provided by protruding vegetative surface in rangelands of the Indian Thar Desert changes the wind velocity profile and increases the threshold wind velocity to cause erosion. In the semi-arid zone of the Indian Thar Desert, the rangelands occupy 15-20% lands whereas it is around 45% in arid region (Mertia, 1992). In extreme arid tracts of the Indian Thar Desert, grazing lands even occupy 85-90% of the total area. The growth of vegetation in the rangelands of the Indian desert starts with the onset of monsoon in the end of June or beginning of July, each year. The top growth is attained in September or October and then it declines upon maturity as most of ephemerals have very short life cycles. The above ground production in the semi-arid regions in Jodhpur (350 mm yr^{1}) has been estimated at 1.2-2 t ha^{-1} yr^{-1} whereas in the driest region, Jaisalmer (180 mm yr^{-1}) the dry herbage yield of 2-2.5 t ha^{1} has been recorded (Mertia, 1992).

Surface cover provided by dry grass tussocks of *Lasiurus sindicus* (sewan) in an experimental site at Chandan was measured during summer season of 2004 using quadrat technique. Number of grass tussocks per unit area along with height and diameter of the tussocks were measured to calculate soil loss ratio factor as follows:

$$SLRs = e^{-0.0344(SA^{0.6413})} \quad (11)$$

where, SLR_s = soil loss ratio for standing plant silhouette, SA = silhouette area computed by multiplying the number of standing tussocks per m^2 area times average diameter (cm) times tussock height (cm). Number of dry tussocks of sewan grass, which act as a silhouette was found 0.4 per m^2. Average diameter and height of sewan tussock was 30 and 43 cm, respectively. Accordingly, SLRs was calculated as 0.15. However, after rainfall events, dry tussocks immediately sprout and green foliage growth started.

WIND EROSION AND DESERTIFICATION IN WESTERN RAJASTHAN

The hot arid regions in Rajasthan constitutes 62% of country's total hot arid area and is mainly confined to western part of the state distributed over 21 Mha area covering 12 desert districts e.g. Jaisalmer, Barmer, Bikaner, Jodhpur, Ganganagar, Hanumnagarh, Churu, Jhunjhunun, Sikar, Nagaur, Pali and 3 tehsils of Sirohi districts. As per aridity index this region is classified as arid and semi-arid regions. Wind erosion is considered as the dominant form of desertification process in this region. Geomorphological assessment and related studies indicated that about 80% of landforms are of aeolian origin. A recent mapping by CAZRI also indicates more than 48% area is still covered under sand dunes of various morphology and dimensions. Landforms and their manifestations present first hand understanding of desertification and few such manifestations are depicted in Fig. 6.

Earlier desertification mapping by CAZRI in 1990's (updated and published in 2005) using coarse resolution satellite images of Landsat and with limited field data indicated about 19.15 Mha area (~92% total mapped area, 20.77 Mha of western Rajasthan) was degraded by various process of desertification. In this mapping, two stages were followed: (a) mapping of dominant land uses and (b) identification of dominant and associative processes. This follows severity recognition from the field and visual interpretation of remote sensing data products. Overall, this depicts desertification as a result of combined processes. For example, wind erosion and vegetal degradation, water erosion and salinity etc. The data statistics indicated 77.71% area affected by wind erosion/deposition. Severity-wise, 32.6% area is categorised under slight, 37.08% under moderate, 21.21% under severe and 0.93% area under very severe.

A recent assessment under National Level Desertification Mapping in which SAC (ISRO) and CAZRI and other institutes were involved (SAC-2007) indicates about 83.85% area of western Rajasthan is degraded by various process of desertification out of total mapped 210399 km^2 area. Wind erosion accounted for ~75% area of which severe types occurred in ~16% area.

However, there is a spatial variability in terms of their severity categories. The availability of canal water irrigation and management measures/technology like sand dune stabilization, checking of sand movement through wind breaks and shelter belt plantation and other strategies like soil and water conservation, management of rangelands, permanent pastures and arable lands. However, with the advent of availability of very high resolution

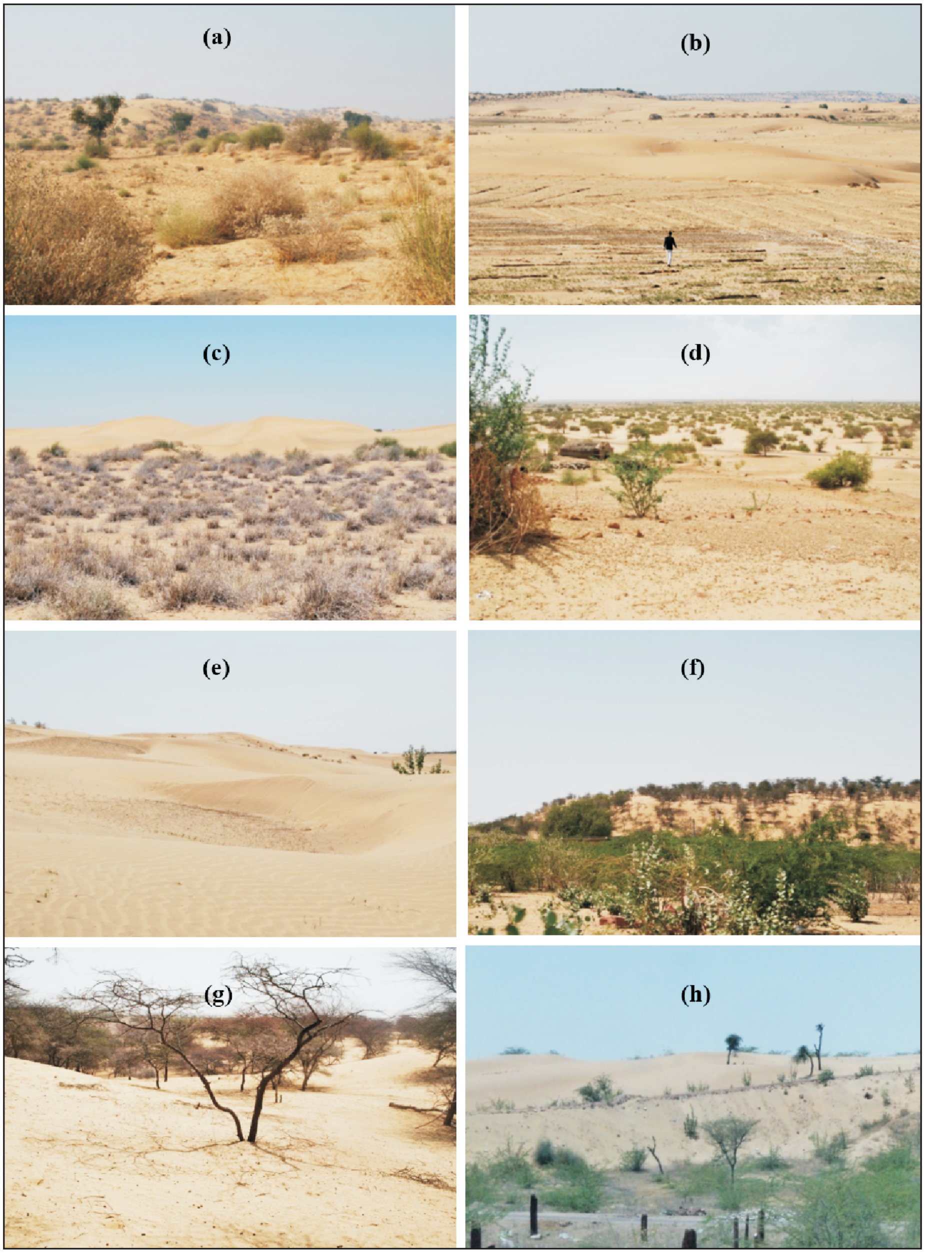

Fig. 6. Surface manifestations of wind erosion/deposition; (a) Stable parabolic dunes at Bikaner representing slight to moderate wind erosion activity; (b) Barchan dunes at Bikaner representing severe wind erosion activity; (c) Severe wind erosion activity at Jaisalmer; (d) Sand encroachment in oran; (e) Severe wind erosion on barren dunes at Barmer; (f) Slight wind erosion on vegetated dunes; (g) Sand dunes under stabilization through tree plantation at Jodhpur; (h) Moderate wind erosion activity at Balesar.

images through aerial, optical and microwave remote sensing, these field manifestations are now mapped and assessed more accurately for better understanding of their origin, distribution and trends. The satellite images, used for this purpose were Indian Remote Sensing satellite images during 2010-2012 and past Landsat data.

Decadal Changes in Wind Erosion

Jaislamer District located in the westernmost frontier of the state, experiences the highest wind speeds. The district receives an annual normal rainfall of 200 mm or less over much of its area. Peak wind speeds are observed in June which records a mean monthly wind speed of 27.2 kmph. Sand dunes cover 56.79% area of the district of which majority is longitudinal dune types in 21.29% area. Assessment of desertification status carried out during 1977 and also in 2010 using satellite images indicated that wind erosion/deposition as the dominant land degradation process in Jaisalmer.

Barmer District is another westernmost district of Rajasthan, experiencing severe wind erosion problems. About 55.82% area in Barmer district is under sand dunes of different types and out of them, parabolic dunes are dominant. Sand sheet is another major landform occurring in 34.77% area. About 24% area is affected due to wind erosion of moderate to severe categories while 22% area are slightly affected.

Bikaner district is a unique case of an aeolian terrain where 77.11% landforms are sand dunes of various types. Most of them are parabolic (16.28%), followed by transverse types (19.58%). The extent of area affected by this process has reduced from 92% in 1992 to 84.21% in 2005-06 due to irrigation impact through IGNP canals. Area under severely affected by wind erosion and deposition process has reduced by about 9%.

Jodhpur District, in comparison to districts described above is comparatively less affected by wind erosion process. Geomorphologically, 23.12% area of Jodhpur is under sand dunes. In the eastern part of the district, the area between Bilara and Jodhpur is covered by alluvium deposited due to fluvial action of Luni river system. Parabolic dunes cover the maximum area (19.57%) followed by longitudinal types (1.14%). As per recent data (IRS-L3, 2010), about 45% area is affected by slight wind erosion activities in the form of sand sheet. Such surface manifestations are result of wide spread levelling of sand dunes with the advent of tube well irrigation. The dominant wind prone areas of Jodhpur are located in Dechu, Balesar and Setrawa with 30-40 m high parabolic and linear sand dunes.

WIND EROSION SAMPLING DEVICES

Aeolian sediment load to atmosphere generated during wind erosion events is generally quantified through different type of sampling devices viz sampler, traps, catchers and collectors. Among wind erosion samplers, more popular ones is the Big Spring Number Eight (BSNE) sampler (Fryrear, 1986) and Modified Wilson and Cook (MWAC) sampler (Wilson and Cook, 1980). Besides these, several indigenous samplers like suspended sediment trap (SUSTRA), Pollate Catcher (PULCA), Saltiphone and Cox sand catcher are available at different arid regions of the world (Goosen and Offer, 2000). In the Indian Thar Desert, dust catcher in the design of Bagnold sampler has been used for collecting the eroded soil mass from wind erosion events.

Dust Catcher

Dust catcher contains several samplers at different heights, which are attached to an iron pole. The individual samplers are funnel shaped with its open top having a diameter of 0.35 m. A metal strip of 0.089 m in height is attached at the top brim of the funnel with an opening area of 0.035 m^2 at one side. A collector is attached at the bottom of the funnel (Fig. 7). Earlier reports by Singh *et al*. (1992) suggested that dust storms mostly arrived over the Indian Thar Desert from South to South Westerly direction (SSW). The meteorological records on wind direction during the last 30 years also showed that SSW was the prevalent wind direction in the Indian Thar Desert during April-September. Hence, the opening of these samplers is fixed towards SSW. A similar type of sampler was previously used in the Indian Thar Desert by Mann (1985).

However, the dust catcher has few drawbacks. Firstly, the dust catcher is fixed type and do not rotate along with the wind direction. Secondly, it is more suitable for collecting suspension flow. Thirdly, top of the sampler being open both suspended soil particles and eroded soil particles generated due to wind erosion events are deposited in the collector. Keeping in view the constraints of dust catcher and the need to specifically record the eroded soil particles a new wind erosion sampler was developed at Central Arid Zone Research Institute, Jodhpur (Santra *et al*., 2010).

Wind Erosion Sampler

Wind erosion sampler has been designed in such a way so that it can collect eroded particles from any direction (Fig. 8). For this purpose a vane has been attached to its back. The orifice of the sampler is 5 cm in height and 2 cm wide. The sampler has the ability to adjust its orifice towards the wind direction, which is also a feature of the BSNE sampler and many other samplers outside India.

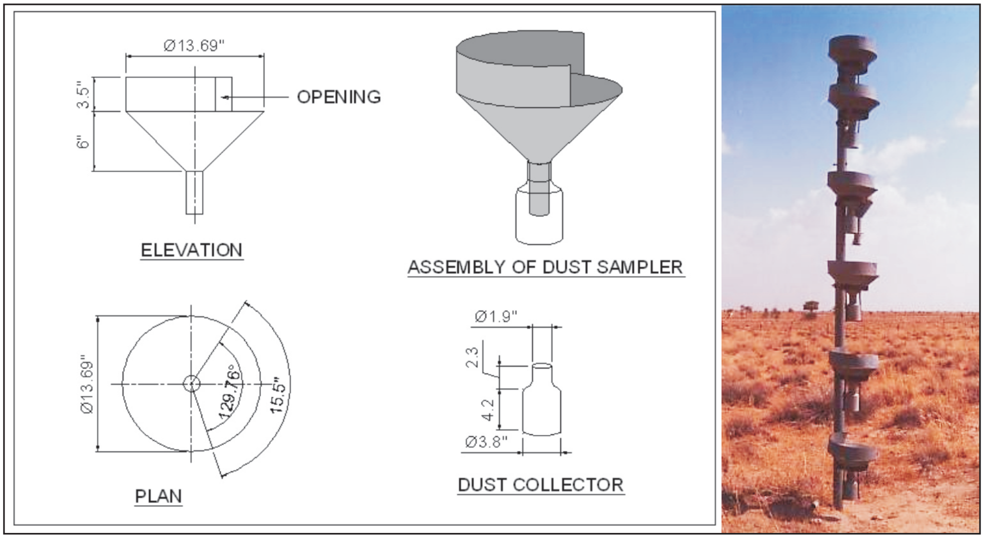

Fig. 7. Dust catcher for collecting wind eroded soil particles; (a) design of the catcher, (b) dust catcher installed in field at Jaisalmer.

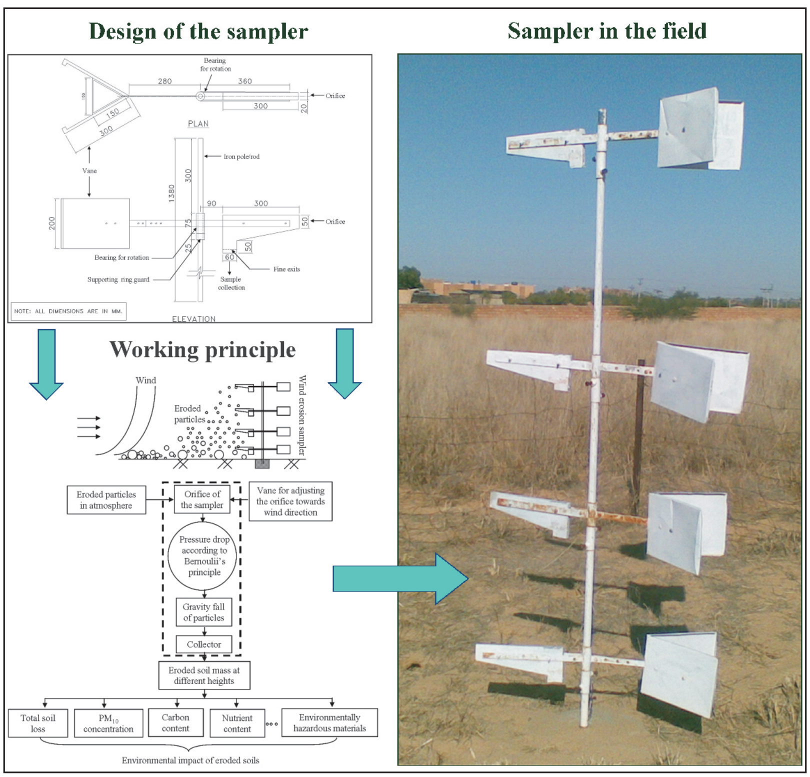

Fig. 8. Design and working principle of the new wind erosion sampler.

Other characteristic features of the new erosion sampler are listed below:

i) The top of the sampler is closed and therefore prevents the deposition of fine suspended particles during calm atmospheric condition after a wind erosion event.

ii) There is no requirement of rain hood for the newly designed sampler and is able to collect eroded soil particles during dust storm events associated with rainfall.

iii) It is very cheap to fabricate and needs a maximum of Rs 8000/- to construct a single assembly with five samplers.

iv) The vertical gap of the sampler from centre of the orifice to the bottom most part of the vane is 10 cm and therefore it is able to collect eroded soil particles starting from 10 cm height from surface to any desired height.

v) It is more suitable to study the wind erosion in the form of suspension flow and some portion of saltation flow but not for surface creep.

FIELD MEASUREMENT OF SOIL LOSS DUE TO WIND EROSION

Extent of soil loss through wind erosion in western Rajasthan has been studied by several research workers (Gupta and Aggarwal, 1978; Gupta *et al*., 1981; Mann, 1985; Gupta, 1993; Dhir and Venkateswarlu, 1996; Soni *et al*., 2013). Using erosion pins, Gupta and Aggarwal (1978) measured the soil loss and found that within a period of 75 days from April to June, 9 cm of top soil may be removed from bare sandy plains of desert, which may be as high as 37 cm from bare sand dunes. Gupta *et al*. (1981) reported a soil loss of 31.2-61.5 kg m^{-2} during April-June. Dust blowing in the zone of three meters above the soil surface in different parts of the desert was measured by Mann (1985) using fixed dust catcher and revealed that on a stormy day soil loss varied from 50 kg ha^{-1} to 420 kg ha^{-1} and sometimes reached up to 511 kg ha^{-1} for extreme part of the desert. Using similar type of dust catcher, Mertia *et al*. (2010) reported soil loss of 827 kg ha^{-1} at the overgrazed site at Jaisalmer and 240 kg ha^{-1} at the controlled grazing site at Chandan during summer (May-July) of 2004 (Mertia *et al*., 2010). At Bikaner site, soil loss was computed through erosion pins as described in Soni *et al*. (2013) and annual soil loss rate has been observed as 50 t ha^{-1} yr^{-1}. Soil loss in the rangelands of the Indian Thar Desert had been measured previously by dust catcher, whereas in the present section whereas in the present section soil loss measured by wind erosion sampler is presented.

Procedure of Soil Loss Computation

The wind erosion sampler is installed at the site by fixing four samplers on an iron pole at 0.25, 0.75, 1.25, and 2.00 m height from surface. Polythene bags were attached at the bottom of each sampler (see Fig. 8). The collected eroded masses were recorded after each dust storm event as well as periodically. During the periods with rainfall events, collected aeolian soil samples in rain water were decanted and air dried along with the residual soil left on filter paper used. For each sampler opening and observation, the collected aeolian sediments were converted to mass flux ($M\,L^{-2}\,T^{-1}$). Fitting of the mass-flux values obtained in different mass-height profile curves lead to the selection of power decay model as the best model for the Indian Thar Desert (Mertia *et al*., 2010):

$$q(z) = a z^{b} \qquad (12)$$

where, q is the mass flux ($M\,L^{-2}\,T^{-1}$) of aeolian sediments at height z (L) from surface; 'a' and 'b' are empirical constant of the equation. Total aeolian mass transport rate ($M\,L^{-1}\,T^{-1}$) was computed through integration of Eq (12) with lower limit of $z = 0.25$ m to upper limit of $z = 2$

m. Total aeolian mass transport rate ($M\,L^{-1}\,T^{-1}$) was defined by several researchers as the total mass of aeolian sediments carried over by wind per unit distance across the wind direction per unit time at a downward position of the field. However, to calculate the approximate estimate of total soil loss lower and upper limit of z was taken as 0.01 m and 2 m, respectively. The calculated mass transport rate was converted to soil loss (kg ha^{-1}) by dividing the aeolian mass transport rate with the distance (L) of non-eroding boundaries from the sampling point and multiplying with the duration of wind erosion event (T). The conversion of aeolian mass transport rate to soil loss depends on the windward distance up to the clear non-eroding boundaries. In case of absence of clear non-eroding boundaries, presence of rocky outcrops or sparsely distributed few tree barriers is approximated as semi-eroding boundary at a windward distance.

Field Observations at Jaisalmer

The new wind erosion sampler was used to collect eroded aeolian masses during several dust storm events and wind erosion events at Jaisalmer farm of CAZRI during 2009 and 2010 (Fig. 9).

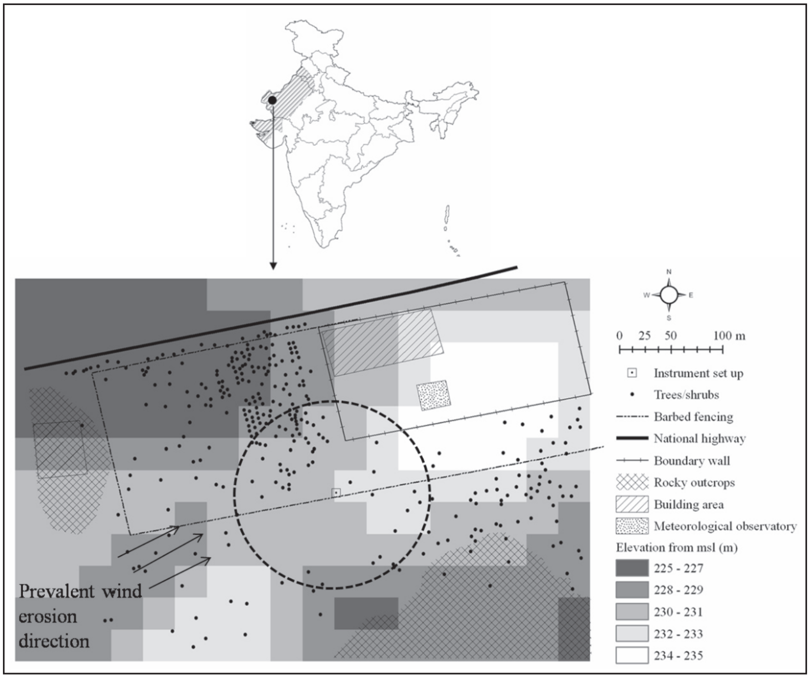

Fig. 9. Wind erosion experimental site at Regional Research Station, Central Arid Zone Research Institute, Jaisalmer.

Fitting parameters of power decay mass-height profile of collected aeolian masses at different heights during severe dust storm events as well as during periodical observations are given in Table 3. The R^2 values from Table 3 indicated that data on eroded mass at different heights were well fitted in power decay mass-height profile, which was also reported earlier as the best fit for Indian Thar Desert condition. It was also observed that eroded mass data from severe dust storm events were fitted better than those collected during mild dust storm events.

Parameter 'a' of the power decay mass-height profile indicates the aeolian mass flux, q at a height of 1 m from surface. Therefore, parameter 'a' indirectly indicates the comparative severity among several dust storm events. Parameter 'b' indicates how aeolian mass flux changes with height from surface. More is the magnitude of 'b', steeper will be the mass-height profile curve, and more difference will be in q between near-surface and 2 m height from surface. Thus, the parameter 'b' indirectly indicates the contribution of suspension (occurs above 30 cm from surface) and saltation process (occurs within 30 cm layer from surface) in the eroded mass for a wind erosion event. Both these parameters are expected to vary according to variation of weather parameters and land surface characteristics, which are temporally highly variable and therefore parameter 'a' and 'b' are expected to vary within a season. Moreover, if the measurements are done over a similar land surface, then these parameters will indicate the effect of weather parameters. Significant variation in weather parameters was observed during June-September of 2009 and thus both the parameters 'a' and 'b' varied across different observation periods. Land surface characteristic was mainly controlled by presence of sewan grass and associated hummocks at the experimental site. Due to lack of sufficient rainfall in the year 2009, growth of this grass species was limited and therefore variation of surface characteristics among the observation periods was less. Soil moisture is another land surface characteristic, which varied across the observation periods and thus contributed to the variation of parameters 'a' and 'b'.

From Table 3, it is found that parameter 'a' was highest for the dust storm on 15-06-2009 and may be considered as most severe dust storm. The same dust storm event was earlier guessed as most severe dust storm of the year 2009 from visual observations in the field and was reported in several local news coverages.

The mass-height profile curves during dust storm events and periodical observations of wind erosion are presented in Fig. 10. These figures characteristically show how aeolian mass flux reduced with height above the surface. Characteristically it was also observed that variation of observed mass flux at lower most sampling height (0.25 m) was more than those observed for higher sampling heights. On an average, mass flux at 1 m height, as indicated by parameter 'a', was 46.351 g m^{-2} min^{-1} during dust storm events whereas it was 40.947 g m^{-2} day^{-1} during periodical observations on wind erosion from June to September, 2009. Magnitude of parameter 'b' was comparatively higher during periodical observations on wind erosion than during dust storm events. This indirectly indicated that eroded mass fluxes were more differentiated with height during periodical observations on wind erosion than during dust storm events.

Table 3. Fitting parameters of power decay mass-height profile of wind eroded mass flux and the associated soil loss at Jaisalmer region of Indian Thar Desert during 2009-10

Name of the observations	Wind erosion events (dd/mm/yy)	§Parameter 'a'	Parameter 'b'	Fitting R^2
Dust storm events (DSE)				
DSE-1	15/06/09	89.933	-1.095	0.99
DSE-2	17/06/09	94.303	-0.788	0.93
DSE-3	24/06/09	8.606	-1.111	0.85
DSE-4	09/07/09	26.730	-1.683	0.99
DSE-5	14/07/09	8.224	-0.773	0.91
Periodical observation on wind erosion (POWE)				
POWE-1	25/06/09-02/07/09	27.586	-0.321	0.55
POWE-2	15/07/09-30/07/09	61.510	-1.801	0.94
POWE-3	31/07/09-18/08/09	61.510	-1.892	0.99
POWE-4	19/08/09-03/09/09	26.691	-0.464	0.59
POWE-5	04/09/09-23/09/09	12.108	-1.334	0.98
POWE-6	17/04/10-05/05/10	125.629	-0.396	0.69
POWE-7	06/05/10-10/06/10	265.336	-0.559	0.89

§Parameter 'a' of power decay model indicates aeolian mass flux at 1 m height from surface. Here, unit of 'a' refers to g m^{-2} min^{-1} for dust storm events and to g m^{-2} day^{-1} for periodic observations of wind erosion events.

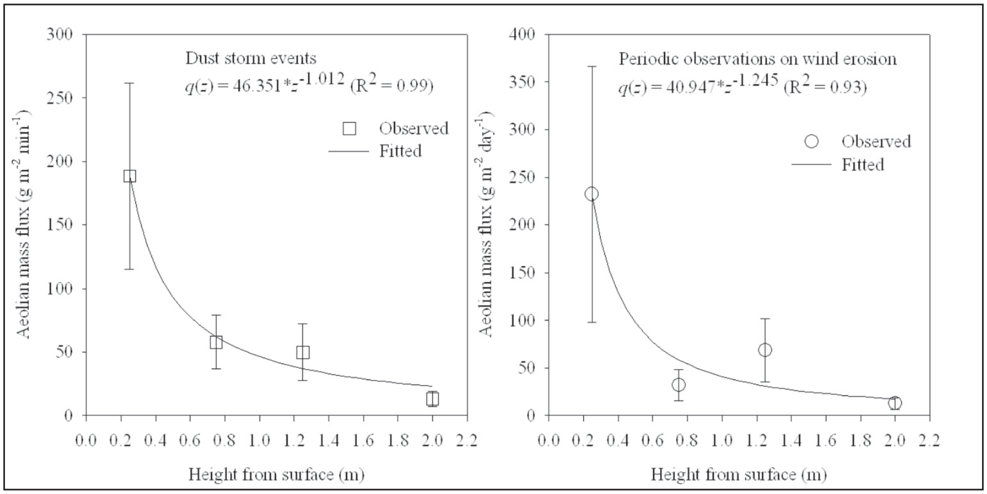

Fig. 10. Mass-height profile of wind eroded aeolian masses of (a) dust storm events and (b) periodical observations on wind erosion events in the Indian Thar Desert at Jaisalmer during June to September, 2009.

The most severe dust storm of the year 2009 was observed on 15th June, which was one of the most severe dust storms over last two decades. Wind speed during this dust storm event was 50-55 km h^{-1} and it started at 4:00 pm and lasted for around half an hour. The second most severe dust storm events of the year 2009 occurred on 17th June, just two days after the first severe dust storm of the year. The severity of the second dust storm event in terms of the soil loss was comparatively less because of the previous day rainfall event (15.2 mm), which resulted in formation of fragile soil aggregates on the desert surface and prevented the erosion of loose sands. Besides these, three more dust storm events on 24th June, 9th July, and 14th July were recorded and corresponding aeolian masses were collected. During 2010, occurrence of wind erosion event was comparatively less because of good monsoon rainfall during mid June and onwards. Two periodical wind erosion events and one dust storm event was recorded during April-June. It was characteristically observed that most of these dust storm events were of short duration (15-30 min) and occurred mostly during the evening time of the day. Another characteristic feature of these dust storm events was that most of them were associated with drizzling at their dissipating stage. Significant amount of eroded masses were also collected periodically during June-September of 2009, which mostly occurred due to sudden occurrence of gusty wind and associated erosion over small scale. All these periodic observations were also recorded and presented in Table 4 with their duration.

Table 4. Wind erosion/dust storm events recorded during 2009 and 2010 at Jaisalmer and the approximate soil loss during each event

Name of the observations	Time of occurrence	Duration	§Soil loss in suspension mode (kg ha^{-1})	§Total soil loss (kg ha^{-1})
Dust storm events (DSE)				
DSE-1	June 15, 2009	30 min	389	1166
DSE-2	June 17, 2009	20 min	246	466
DSE-3	June 24, 2009	15 min	19	58
DSE-4	July 09, 2009	25 min	128	1485
DSE-5	July 14, 2009	15 min	16	30
DSE-6	June 5, 2010	20 min	503	870
Periodical observations on wind erosion (POWE)				
POWE-1	June 25-July 2, 2009	7 days	23	30
POWE-2	July 15-July 30, 2009	16 days	203	3244
POWE-3	July 31-Aug 18, 2009	19 days	255	5287
POWE-4	Aug 19-Sept 3, 2009	15 days	49	68
POWE-5	Sept 4-Sept 23, 2009	20 days	39	188
POWE-6	April 17-May 5, 2010	18 days	273	366
POWE-7	May 6-June 4, 2010	29 days	953	1434

§Soil loss in suspension mode was computed within 0.25 to 2 m height, whereas total soil loss was calculated from very near to soil surface (0.01 m) up to 2 m height

Computed soil loss in suspension mode during dust storm events revealed a maximum soil loss of 389 kg ha^{-1} during dust storm event on 15-06-2009, which was of only 30 minutes in duration. However, extrapolation of power decay model downward up to 0.01 m height from surface resulted in total soil loss of 1166 kg ha^{-1} during the same dust storm event. On an average, soil loss rate during dust storm events of the year 2009 was found as 17 kg ha^{-1} min^{-1}. Periodical observations on eroded soil mass revealed an average soil loss rate of 25 kg ha^{-1} day^{-1}. Cumulative soil loss in suspension mode during middle of June to end of September of 2009 was 1.36 t ha^{-1} whereas total soil loss was 12.02 t ha^{-1}. Total amount of soil loss from mid of April to 1st week of June during 2010 was 2.7 t ha^{-1}.

Field Observations at Bhujawar, Jodhpur

Wind eroded mass flux at two land use situations of Bhujawar village at Jodhpur was determined: a) Fallow land (FL) and b) cultivated land (CL) (Fig. 11). Fallow land was kept fallow for last three years and ground surface was mainly covered with grasses e.g. *Crotolaria burhia*, *Eleusine compressa* and 'lump'. Cultivated land was mainly used for rainfed cultivation of pearl millet, sesamum and moong. Soil erodibility factor as per revised wind erosion equation (RWEQ) was found 0.61 in FL and 0.59 in CL. Surface cover factor as per RWEQ was found 0.014 in FL and almost 1 in CL, which indicated that grass cover significantly protected the surface soil from erosion. Wind eroded mass flux at 0.25 m height from surface in CL was observed as 0.14 kg m^{-2} day^{-1} during May-June, 2012. Computed annual soil loss from the observed mass flux data was approximated as 1.3 t ha^{-1} yr^{-1}.

Fig. 11. Wind erosion experimental sites at Bhujawar village of Jodhpur district; a) Fallow land (FL) and b) cultivated land (CL).

Field Observations at Khuiyala, Jaisalmer

Soil loss from a denuded sand dune site at Khuiyala village located on the western boundary of Jaisalmer district was quantified using wind erosion samplers during 2013-14. For this, four freely rotating wind erosion samplers on a single iron pole at 0.25, 0.75, 1.25, and 2.00 m height from surface were installed at the centre of a circular field with radius of around 100-150 m and having non-eroding boundaries at the periphery (Fig. 12). Mass-flux ($M L^{-2} T^{-1}$) data of collected eroded soil in samplers at different heights were fitted in power decay mass-height profile [Eq (12)].

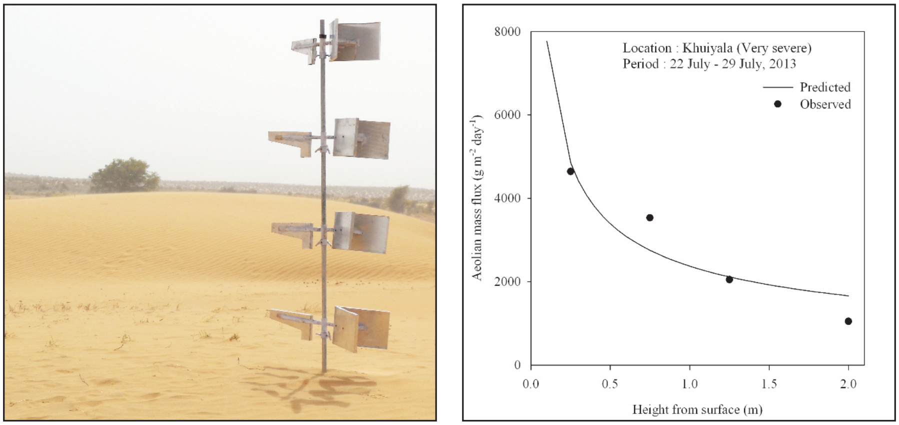

Fig. 12. Measurement of wind eroded soil loss in field (a) installed wind erosion sampler in field (b) mass-height profile of eroded mass flux.

Total aeolian mass transport rate (M L^{-1} T^{-1}) up to a standard height of 2 m, which is generally defined as the total mass of aeolian sediments carried over by wind per unit distance across the wind direction per unit time at a downward position of the field, was found as high as 7 kg m^{-1} day^{-1} (Fig. 13). Characteristically, wind erosion was most severe during July-August (Julian day 180-240).

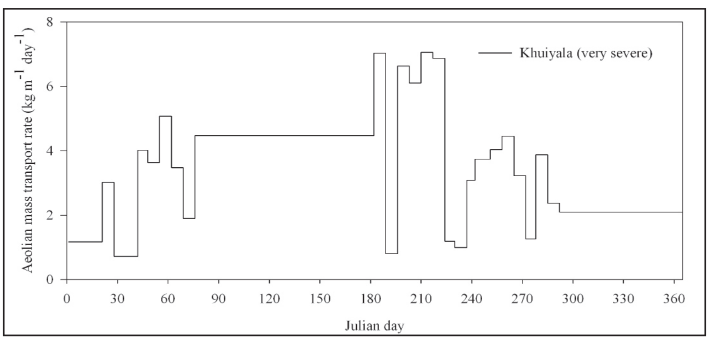

Fig. 13. Aeolian mass transport rate at Khuiyala and Jaisalmer, western Rajasthan.

The calculated mass transport rate was converted to soil loss (kg ha^{-1}) and annual soil loss rate was observed as 83.3 t ha^{-1} yr^{-1} (Table 5). It was also noted here that wind erosion and deposition processes occurred simultaneously in the field and in this study deposition process was not quantified. Generally, fine dust particles carried over by suspension mode are completely lost from that particular field and deposited elsewhere whether coarse eroded soil particles are deposited in nearby areas within the field through surface creep and saltation process. As per previous research reports, 3-38% of total eroded soil occurred through suspension mode and considering this fact, soil loss from open sand dunes from western Rajasthan may be approximated as 32 t ha^{-1} yr^{-1}.

Table 5. Wind erosion events recorded during 2013-14 at Khuiyala, Jaisalmer and the approximate soil loss during each event

Name of the observations	Time of occurrence	Duration	§Soil loss in suspension mode (kg ha^{-1})	§Total soil loss (kg ha^{-1})
Periodical observations on wind erosion (POWE)				
POWE-1	01-Jul-13 to 08-Jul-13	7 days	2398	3297
POWE-2	08-Jul-13 to 15-Jul-13	7 days	258	377
POWE-3	15-Jul-13 to 22-Jul-13	7 days	2202	3111
POWE-4	22-Jul-13 to 29-Jul-13	7 days	1934	2864
POWE-5	29-Jul-13 to 05-Aug-13	7 days	2430	3309
POWE-6	05-Aug-13 to 12-Aug-13	7 days	2370	3220
POWE-7	12-Aug-13 to 18-Aug-13	6 days	320	476
POWE-8	18-Aug-13 to 25-Aug-13	7 days	328	466
POWE-9	25-Aug-13 to 30-Aug-13	5 days	782	1033
POWE-10	30-Aug-13 to 08-Sep-13	9 days	1971	2254
POWE-11	08-Sep-13 to 15-Sep-13	7 days	1546	1893
POWE-12	15-Sep-13 to 22-Sep-13	7 days	1832	2086
POWE-13	22-Sep-13 to 29-Sep-13	7 days	1353	1510
POWE-14	29-Sep-13 to 05-Oct-13	6 days	436	508
POWE-15	05-Oct-13 to 12-Oct-13	7 days	1603	1816
POWE-16	12-Oct-13 to 19-Oct-13	7 days	984	1111
POWE-17	28-Dec-13 to 04-Jan-14	7 days	769	857
POWE-18	04-Jan-14 to 21-Jan-14	17 days	1114	1335
POWE-19	21-Jan-14 to 28-Jan-14	7 days	1318	1418
POWE-20	28-Jan-14 to 11-Feb-14	14 days	576	670
POWE-21	11-Feb-14 to 17-Feb-14	6 days	1325	1614
POWE-22	17-Feb-14 to 24-Feb-14	7 days	1521	1703
POWE-23	24-Feb-14 to 03-Mar-14	7 days	2084	2380
POWE-24	03-Mar-14 to 10-Mar-14	7 days	1443	1628
POWE-25	10-Mar-14 to 17-Mar-14	7 days	859	893

§Soil loss in suspension mode was computed within 0.25 to 2 m height, whereas total soil loss was calculated from very near to soil surface (0.01 m) up to 2 m height

DEPOSITION OF WIND ERODED SOIL

Deposition of eroded suspended soil particles either at local natural surfaces or surfaces far away from the source area is the final step of wind erosion process. Natural surfaces where deposition takes place frequently are plant leaves, grasslands, water bodies etc. In different literatures, deposition is also referred to as sedimentation, which is defined as 'the settling of solids from suspension in a fluid' (Evans, 2004). Several physical forces act on suspended particles in the process of sedimentation, among which gravitational force, turbulent force, electrostatic force, thermal force are important to mention. Relative importance of these forces depends on i) characteristics of the suspended particles e.g. grain shape, grain size, aggregation pattern etc., ii) the properties of the fluid in which particles are immersed (air is the fluid in this context) and iii) the nature of the sedimentation surfaces.

Most of the theoretical model considers the particle shape as sphere when calculating the sedimentation velocity. However, natural dust particles are not exactly rounded and may be flattened to some extent, which may create perturbations in the flow during deposition. Thus, a lower sedimentation velocity may be observed in case of flattened particles as compared to a completely rounded dust particle, although the size and density is same. Fine dust particles adhere with each other and form aggregates in most cases during the deposition process and thus again reduce the settling velocity. It may be thought that after aggregation of fine dust particles weight might be increased, which should have increased the fall velocity of aggregated particles, however, it is not the case. Aggregated particles increase the irregularity in shape and also decrease the density and thus lower the sedimentation velocity despite of its larger size and weight in comparison to a single grain dust particles. Apart from characteristics of suspended particles, the concentration of it affects the turbulence of fluid and thus influences the settling velocity. In most of natural environmental condition, the turbulence effect is usually small, however, in case of higher concentration it should not be neglected. The detailed discussion on turbulence effect of fluid on fall velocity may be found in Goosens (1985). The deposition of dust particles also largely depends on the type of sedimentation surface. Geometric properties of surface affect the characteristics of fluid close to it e.g. friction velocity, degree of turbulence, roughness length etc. and thus have a control on final deposition.

Whenever we discuss about deposition of wind eroded dust, it is important to distinguish the difference between deposition and accumulation. Deposition may be defined as the amount of sediment that impacts on a unit surface per unit time, whereas, accumulation refers to the amount of particles that remain on a surface after a particular time interval. More precisely, deposition is the sediment flux directed perpendicular towards the surface whereas accumulation is the sum of sediment flux and any other flux component directed away from the surface. The later flux is also called as re-emission or re-suspension of deposited particles. Deposition equals accumulation only in case of a perfectly absorbent surface, where re-emission flux or re-suspension flux will be zero. However, such perfectly absorbent surface is not available in nature. As erosion and deposition are simultaneously occurring process in environment, most of the field and laboratory measurements actually measure the accumulation, if special cares on depositional aspect are not considered. Accumulation may be positive or negative. In case of positive accumulation, surface is enriched with new sediments and sediment layer thickens, whereas, in case of negative accumulation sediment layer becomes thinner. Settling particles during deposition do not necessarily originate from the same surface, on which they are settle; they may have been eroded substantially upstream, upwind or upslope from a different substratum. More detailed discussion on deposition of wind eroded dust is available in Goosens (2005) and Goosens and Buck (2011).

Measurement of Deposition

Quantification of dry aeolian deposition is a very difficult issue in aeolian geomorphology. Several practical and theoretical methods are available in literature to calculate or measure deposition, a review on which is available in Seinfeld and Pandis (1998) and Goossens and Offer (2000). Based on dry deposition models for either of gas or particles as summarized in Businger (1986) and Wesley and Hicks (2000), techniques available for measuring deposition of eroded dust particles may be divided in to two major categories: direct and indirect (Seinfeld & Pandis, 1998).

In the direct approach, sediment flux to the surface is explicitly measured either by collecting the sediment deposited on the surface itself or by measuring the vertical sediment flux in the air near to it. Dust deposition on natural surface may be measured by collecting the amount of sediment deposited on plant leaves but is very difficult in open field condition. Instead of this surrogate surface may be used to collect deposited particles. Among different surrogate surfaces, water body, glass, metal (zinc), wide pans with marble layers are widely used. While measuring the deposited sands on surrogate surface in open environment, top of the surrogate should be leveled with ground surface otherwise shadow effect of wind may affect the deposition process. Moreover, such surrogate surface is very difficult to maintain in open environment because of human and animal disturbances. To avoid such disturbances, metal tower with surrogate surface of either glass or zinc metal at different heights may be placed to directly measure the vertical sediment flux, which then may be extrapolated up to surface. However, in case of metal tower, surrogate surface at different height should be placed carefully to avoid interference of one on another. In case of measuring the deposition through surrogate surface, strips of border surrounding the target surface needs to be placed. In most of the direct methods using surrogate surface, sediment amount is measured by weighing the surrogate surface before and after using analytical balance. In case of water body as a surrogate surface, water is to be evaporated first followed by weighing. In wind tunnel study with different surrogate surface, water body was found most effective to measure deposition, however, difficult to maintain in open environment due to high rate of evaporation and sometimes due to disturbances by birds and animals. Occurrence of rainfall events during measurement period is another important factor while measuring dust deposition in field.

In the indirect method, the deposition fluxes are derived by measuring secondary quantities, such as the mean concentration (or vertical gradients of the mean concentration) of the settling sediment, and relating these to the flux. There are main two approaches in indirect method: i) gradient approach and ii) inferential approach.

In the gradient approach, vertical gradient of depositing dust concentration was measured and then the deposition flux is determined using gradient-transport theory. The deposition flux as per gradient theory is equal to (Seinfeld and Pandis, 1998):

$$F = K_A \frac{\delta C}{\delta z} \tag{13}$$

where, F is the deposition flux, K_A is the particle exchange coefficient, C is the dust concentration at an height z from surface. In most studies, it is assumed that C/z is constant and the concentrations are measured at only two heights (Gillette and Dobrowolski, 1993). When C/z is variable as a function of height (non-linear concentration profile), dust deposition profile curve was determined by calculating F at various heights z (Goossens *et al.*, 2001). The deposition at ground level can then be calculated from this profile.

The inferential method calculates the deposition flux F from the equation

$$F = v_D C \tag{14}$$

where, C is the particle concentration and v_d is the deposition velocity (Chamberlain, 1967). The velocity of deposition v_D, which is a function of particle size and shape and also depends on friction velocity (u^*) and roughness element (z_0), can be derived from standard graphs (Sehmel, 1980), or it can be calculated from theoretical models (Venkatram and Pleim, 1999).

Implications of Dust Deposition

The input of carbon and nitrogen from the deposition of dust storm sediments has an important fertilizing effect in arid and semiarid regions (Offer *et al*., 1996). It plays an important role in the nutrient cycle of natural ecosystems or low input agriculture, as shown for the Sahelian Zone (Bielders *et al*., 2002) and the Colorado Plateau (Reynolds *et al*., 2001). Also, the relevance of dust transfer at the intercontinental scale was shown for the influence of Sahara dust on the Amazon region (Swap *et al*., 1992).

Vegetation coverage is a crucial factor affecting wind erosion and airborne dust accumulation in semi-arid steppes. The grassland of the Xilingele steppe in the Eastern part of the Chinese province Inner Mongolia, has been shown to be a natural accumulation area for dust, sourced in the North and West Chinese drylands (Yanfen *et al*., 2004). It was reported that the natural dust fall in typical steppe areas reaches 35.2 t km^{-2} $month^{-1}$ in the Xilin River Basin of northern China (Wang *et al*., 2000). From the experimental data in grasslands, better correlation of deposited dust amount with vegetation height than to the vegetation coverage was observed. In rangelands of the Indian Thar Desert, deposition of wind eroded soil has also been found to enrich soil as observed from the good plant growth on freshly deposited aeolian surfaces. Measurements of wind eroded soil loss from a rangeland site at Jaisalmer region of the Indian Thar Desert also revealed a significant C and N in eroded soil. Average C and N contents in eroded soils was observed as 4 g C kg^{-1} and 0.77 g N kg^{-1}, respectively. Cumulative loss of C and N for a period of 3½ months from the middle of June to the end of September was 46 kg C ha^{-1} and 4 kg N ha^{-1}.

ENVIRONMENTAL EFFECTS OF ERODED SOILS

Eroded soil mass commonly known as dust, emitted during wind erosion events over desert area throughout the world, remains in atmosphere for a long time as suspended particles. These suspended particulate matters in atmosphere have an adverse effect on respiratory and cardiovascular activity of people and thus are considered as health hazard. Furthermore, eroded soils carries lot of carbon and nutrients along with it and thus reduces the soil fertility in source areas and enrich the nutrient contents in unwanted places through dust deposition like in water bodies etc. Moreover, these suspended particulate matters mix with other minute particles of the atmosphere e.g. carbon soots, smoke, salts etc. and produce a blanket of haze, an aerosols and known environmental hazard. A brief detail on environmental impact of wind erosion in western Rajasthan is available in Mertia and Santra (2012).

Particulate Matter in Eroded Soil

Particle size analysis of collected aeolian samples during a dust storm event of 15th June, 2009 showed that particulate matter having size less than 10 µm (PM_{10}) was 30% in eroded aeolian mass, whereas the same for desert surface was only 7.5%. Particle size distribution of eroded soil along with the same for surface soil is presented in Fig. 14. It clearly revealed that fine sized particles that contribute to aerosol load in atmosphere were more in eroded soils than on land surface.

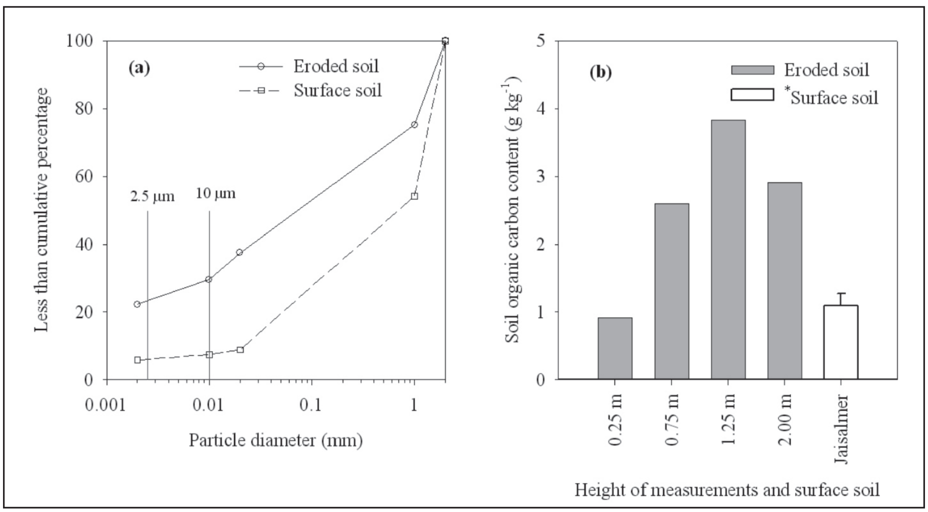

Fig. 14. Particle size distribution and soil organic carbon content of eroded soils during dust storm event on 15th June, 2009 and the same for surface soil in the Indian Thar Desert at Jaisalmer.

Nutrient Contents in Eroded Soil

Soil organic carbon (SOC) content of eroded aeolian mass measured through Walkley and Black method during dust storm event on 15th June, 2009 was on an average 2.6 g kg^{-1} and was highest in eroded soils collected at 1.25 m height from surface. In contrary, average SOC content of surface soil at Jaisalmer is 1.1 g kg^{-1}, which is the average SOC content of surface horizons for six major soil series of Jaisalmer district published by National Bureau of Soil Survey & Land Use Planning, Nagpur, India. These data indicate that a major portion of SOC pool may be lost through a single and short duration dust storm event. For example, total SOC loss during dust storm event on 15-06-2009 was calculated as 3 kg ha^{-1}.

C and N content of each collected sample was also analyzed using Foss Heraeus CHN-O-rapid elemental analyzer and are presented in Fig. 15. The average contents of C and N in eroded soils from the experimental site were 4 g kg^{-1} and 0.37 g kg^{-1}, respectively (Santra *et al.*, 2013).

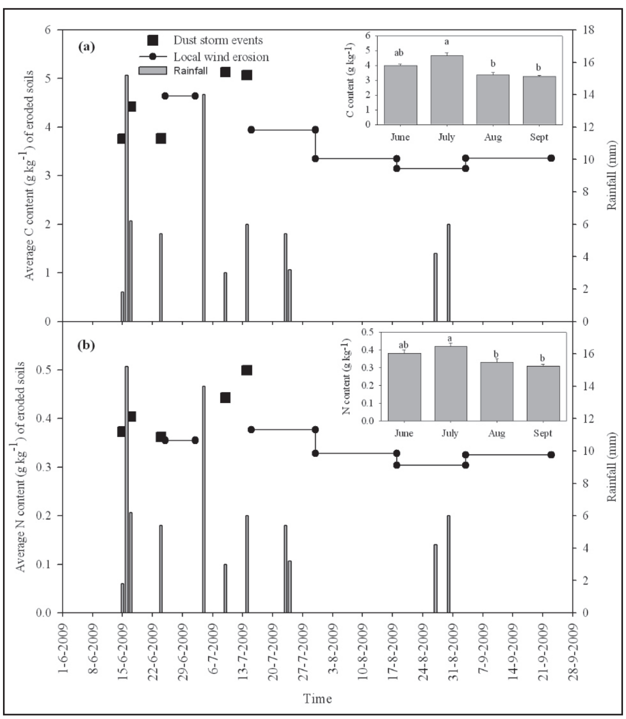

Fig. 15. Periodic variation of carbon (C) and nitrogen (N) content of eroded soils; (a) C content and (b) N content; Values with the same letters above the bars are not significantly different (P<0.05, Tukey test).

In general, both C and N contents were higher during regional dust storm events than during local wind erosion events. Overall, the C and N contents ranged from 3.01 to 5.44 g kg^{-1} and 0.30 to 0.51 g kg^{-1}, respectively. In comparison to C and N content of eroded soil mass, the average contents of C and N of surrounding top soils of the experimental site were 5.01 and 0.44 g kg^{-1}, respectively. Although nutrient enrichment through dust deposition was not directly measured in our study, however, may be indirectly approximated from several measured data on C content. Mean SOC content of 78 soil samples covering 8 different land use system at Jaisalmer was observed < 2 g kg^{-1}. In addition, SOC content in a cultivated farm of 76 ha at Jaisalmer was observed to range from 1.06 to 2.13 g kg^{-1} (Santra *et al.*, 2012). Therefore, overall SOC content of soils from Jaisalmer region may be considered < 2 g kg^{-1}. With the application of suitable conversion factor (Krishnan *et al.*, 2009), this average C content of Jaisalmer as per CHN-O analyser will be about < 3 g kg^{-1}. In comparison to this, C content of surface soil at the experimental rangeland site was slightly higher (5.01g kg^{-1}). Moreover, average C content of eroded soil was observed as 4.0 g kg^{-1}, which is lower than parent soil. This indicated that apart from dust emission, deposition of eroded particles in the rangelands is common, which finally led to enrichment of top soils. However, continuous overgrazing associated with severe drought situations in the desert may lead to rapid loss of top fertile soils.

It was observed that the C and N content of eroded soil did not vary significantly with height both during dust storm and local wind erosion events ($p<0.05$). This disproved the general notion that C content in soils at top most sampling height will always be higher due to its light weight. However, it was found that during extreme wind erosion events C and N content of eroded soil slightly increased with height. For example, during the severe local dust storm event on 9 July 2009, C content increased with height from 4.73 g kg^{-1} at the sampling height of 0.25 m to 5.44 g kg^{-1} at the sampling height of 2 m. Similarly, N content of eroded soils during supra-regional dust storm event on 15 June 2009 increased from 0.34 g kg^{-1} at the sampling height of 0.25 m to 0.48 g kg^{-1} at the sampling height of 2 m. However, during local wind erosion events, C and N content did not vary with height.

Aerosol Extent in The Indian Thar Desert

Dust emitted during wind erosion events over desert area throughout the world is contributing significantly towards atmospheric aerosol. Such type of aerosol, in association with other aerosol products like sulphate aerosol, carbonaceous aerosol, sea salts etc. produces a vast blanket of haze in upper atmosphere, specifically in troposphere. These tropospheric aerosols have both direct and indirect effect on net radiative forcing, which can be defined as change in net downward flux of shortwave radiation due to presence of any substances in atmosphere. Several reports from different parts of the world have shown that atmospheric aerosols have a negative net radiative forcing and hence a cooling effect unlike of greenhouse gases. Dust aerosols generated during wind erosion events in the Thar Desert create dust haze over a large area and even carried over towards Indo-Gangetic plains in severe dust storm events (El-Askary *et al*., 2004, Deepsikha *et al*., 2006). Regional transport of dust aerosol is clearly viewed in MODIS image obtained during 10th June, 2005 as depicted in Fig. 16. This figure also shows the intercontinental dust transport from Sahara desert of Africa to Thar Desert of Asia.

Dust aerosol generated through wind erosion process was monitored through MODIS atmospheric products. Aerosol optical thickness (AOT) at 0.47 micrometer over Indian Thar Desert was mapped during severe dust storm events. It was found from AOT maps that dust aerosol was more active in western part of Jaisalmer and nearby areas (Fig. 17).

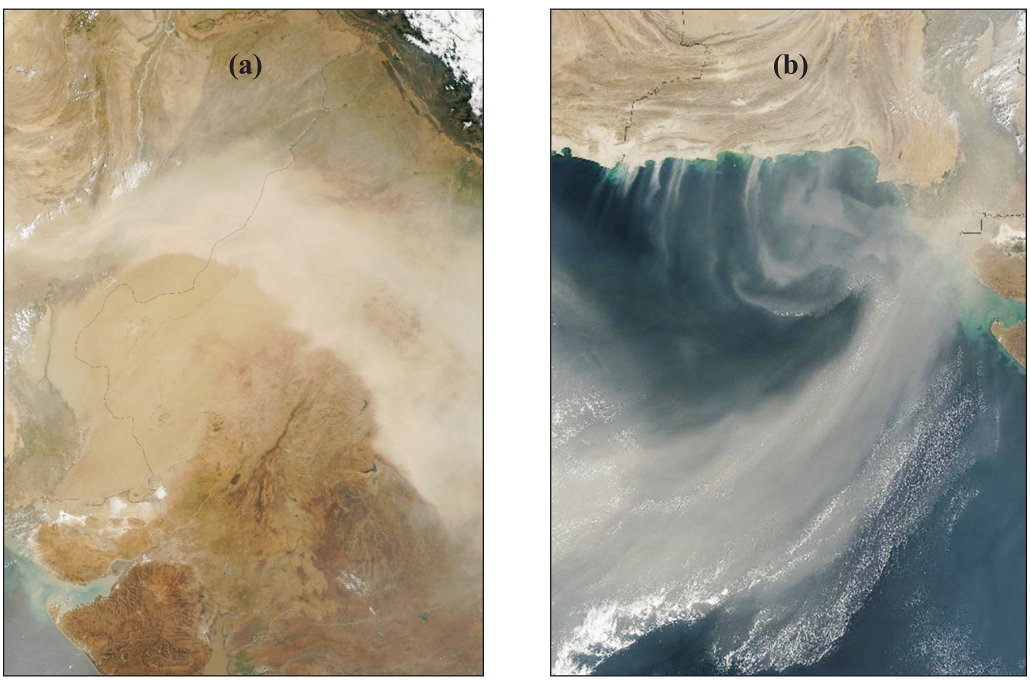

Fig. 16. MODIS image of dust transport from source region of Thar Desert to Indo-Gangetic Plains and intercontinental dust transport (a) 10th June, 2005, (b) 14th December, 2003.

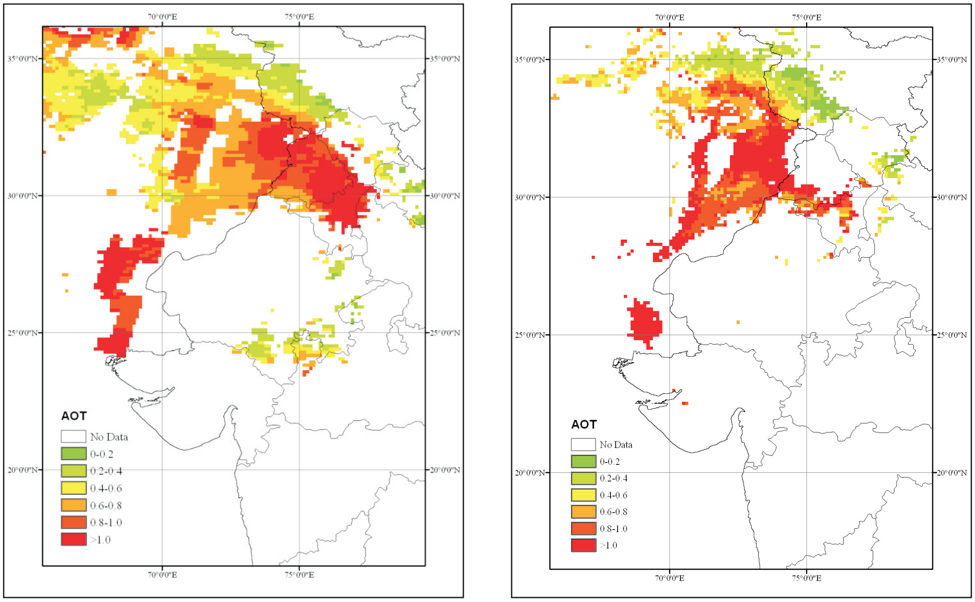

Fig. 17. Aerosol optical thickness near Jaisalmer and nearby areas during (a) 8th July, 2009 and (b) 9th July, 2009; more is the value of AOT denser is the dust aerosol cloud in atmosphere (Data source: MODIS aerosol level 2 product, MOD04_L2).

MANAGEMENT AND CONTROL OF WIND EROSION

Wind erosion can be controlled by two major ways: either by decreasing the erodibility of soil or by reducing the erosive energy of wind by erecting barriers. This can be accomplished through the use of various conservation practices: (i) reduced field width, (ii) providing vegetative cover on soil surface, (iii) utilization of stable soil aggregates or clods for wind resistance, (iv) by constructing ridge or contours, and (v) by levelling of land surface (Harsh *et al*., 1991). Basic principles to control wind erosion may be found in Chepil and Woodruff, (1963), Tibke (1988) and Li and Sherman (2015). Fundamental design aspects of wind barrier or wind fences are depicted in Fig. 18. The sheltered distance created by a barrier on the leeward side depends on its height (H), length (L) and porosity (β). Optimum designing of barrier may lead to a sheltered distance of 20-25 times of barrier height (X/H). Wind barriers of different porosities are presented in the figure starting from solid barrier (A) to highly porous barrier (F). Barrier type C and D represents mixture of different porosities and may be created by different compositions of plant canopy, shrub and grass vegetation.

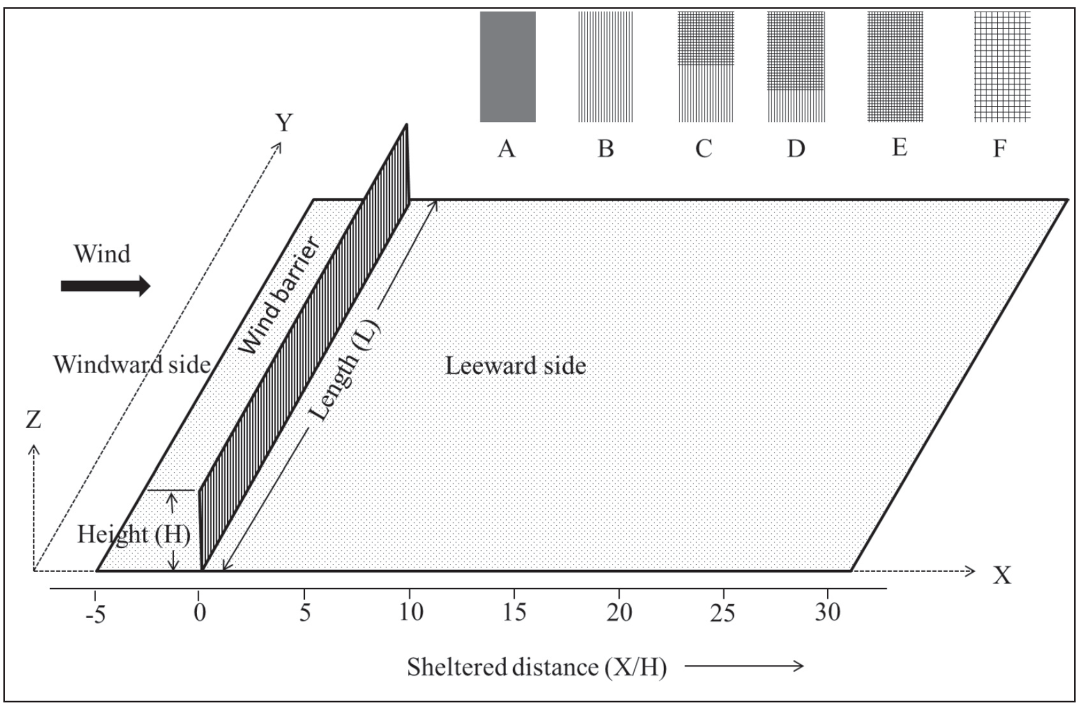

Fig. 18. Design of wind barrier to control wind erosion

In this document five major control measures are discussed: i) sand dune stabilization, ii) surface cover iii) wind breaks and shelterbelt, iv) tillage and v) crop management e.g. mixed cropping, intercropping strip cropping etc. All these five control practices are designed to either take some of the wind force or to trap the eroded soil.

Sand Dune Stabilization

For control of wind erosion in the Indian Thar Desert several research efforts were made in past (Muthana, 1982; Gupta *et al*., 1984; Kaul, 1985; Mann, 1985; Mertia, 1992; Kar and Joshi, 1995; Venkateswarlu and Kar, 1996; Narain and Kar, 2007). Most of these works reported the sand dune stabilization by vegetation cover in checkerboard method, which became a popular wind erosion control technology in the region (Fig. 19). Planting suitable vegetations on denuded dune surface results in decreasing surface wind speed, prevention of scouring action and amelioration of soil conditions, which ultimately lead to improved micro-climatic condition of the area. In view of the limited water, high percolation, high ambient temperature and more evapotranspiration in arid region, it is important to select such plants having adaptive edge to survive in such demanding situations. Of many criteria, the ones to be taken care of in sand dune stabilization are that these should be able to survive in (i) extremes temperature condition, (ii) a variety of salinity conditions, (iii) variable speed and direction of wind, (iv) severe sand storm events, (v) very low soil moisture condition, and (vi) biotic stress situations.

Fig. 19. Wind erosion control on dunes through checkerboard method.

In order to be able to have above mentioned adaptive qualities, the selected plant species should be

i) Able to put out root system rapidly

ii) Succession facilitator

iii) Able to multiply rapidly over time and space

iv) Enhance and ameliorate soil conditions

v) Be able to grow after grazing or complete leaf removal or leaf fall

vi) Be prolific seeder so that it builds seed bank

vii) Possess staggered dormancy and longer duration viability of the seeds

viii) Be able to grow both as commensals and as a nurse plant

ix) Have some economic value

x) Be resistant to pest and diseases

Detailed study of sand dunes have revealed that lower depths of unstabilized sand dunes have considerable moisture (2-5%) even in the peak evaporation months of May-June (Gupta, 1979) due to low capillarity and formation of surface crust that further prevents evaporative loss. Thus, this offers a conducive moisture zone underneath for root growth ensuring success of the plantation.

Agrofrestry for sand dune stabilization

The sand dune stabilization involves following steps (Harsh and Tiwari, 1997):

1. Fencing-either mechanical or vegetative such as *P. juliflora*, *Euphorbia caducifolia*

2. Establishing micro windbreaks in checker board pattern or parallel rows across wind to stop surface creep and save saplings from sand abrasion by way of brush wood from *Ziziphus numularia*, twigs of *Prosopis cineraria*, *P. juliflora*, *Crotolaria burhia*, *A. persica*, *L. pyrotechnica* and *Calotropis procera*. Of late, live plants of *C. angustifolia* have emerged successful as micro windbreaks.

3. Transplantation of suitable trees and shrubs species like *A. trotilis*, *P. cineraria*, *P. juliflora*, *C. polygonoides*, *A. nubica*, *Cordia rothi*, *P. cineraria*. Intervening species are planted/seeded with grasses like *C. ciliaris*, *Panicum turgidum*, *Lasiurus sindicus*, *Citrullus colocynthes* and *Saccharum benghalense*.

Attempts have also been made to do direct seeding of sand dunes through air craft. A mixture of seeds of trees, shrubs and creepers along with grass seeds in soil pellets were aerially broadcasted on sand dunes in Bikaner during post-monsoon season of 1982-83. The germination and growth of *Acacia tortilis* and *Lasiurus sindicus* was maximum (Kumar and Sankarnarayana, 1988). The risk involved in this exercise was (i) drifting of seeds by wind during the broadcast (ii) falling of seeds and its trapping in the existing bushes and being lost (iii) roling of seeds on the slope resulting in uneven distribution of saplings (iv) burial of seeds under sand thus preventing its germination (v) loss of seeds by zoochory and (vi) grazing of emerging saplings by both wildlife and livestock of villages. Despite so many risks, aerial seeding can be extremely useful in areas receiving low rains and are inaccessible for ground based human assisted rehabilitation of sand dunes. The pellets of soil (clay + FYM + sand) in the above exercise were replaced with a polymer called 'Jalasakti' in a separate experiment. Seeds were treated with 'Jalasakti' @ 2 kg/100 kg seeds of different species. The survival in Jodhpur conditions after three years was 25% in *Colophospermum mopane*, 20% in *Acacia tortilis*, 15% in *A. bivenosa*, and 5-10% in all other species. The untreated seeds showed 1-10% survival. Thus, polymer treated seeds in direct broadcast for dune stabilization do have a potential (Harsh and Tewari, 1993). Such stabilization of dunes not only prevents sand drift, it can also be turned in to an economic activity by way of providing 15-20 t ha^{-1} of wood after five years of plantation (Kaul, 1985). Benefit in terms of fuel wood yield and pods in different plantation densities at different locations have been summarized by Harsh and Tewari (1997), while a B:C ratio of 1.83 to 3.58 has been estimated depending upon locality (Kalla, 1977). Such plantation of dune by *C. mopane* was shown to improve soil organic carbon (SOC) from 0.03 to 0.10%, total N from 0.007 to 0.012%, available N from 87.5 to 190 kg ha^{-1}, available P_2O_5 from 5.85 to 11.70 kg ha^{-1} and available K_2O from 200 to 220 kg ha^{-1}.

Surface Cover

Use of surface cover to control wind erosion may be of two types, vegetative and non-vegetative. Protection of land surface through vegetative surface cover of grasses or crops are perhaps the most effective, easy and economical. Grasslands of *Lasuirus sindicus* and *Cenchrus ciliaris* and maintenance of cover crops like *Citrullus colocynthis* have a large role in reduction of soil loss from sandy plains due to wind erosion. In addition to the standing vegetation, crop residues often are placed artificially on the soil to provide temporary cover until establishment of permanent vegetation. It was further reported that in case of residue application, better control of wind erosion may be obtained if the residues are well anchored to the surface.

Other than vegetative covers, various surface films such as resin-in-water emulsion (petroleum origin), rapid curing cutback asphalt, asphalt-in-water emulsion, starch compounds, latex in water emulsion (elastomeric polymer emulsion), by-products of the paper pulp industry and wood cellulose fibre were used to control wind erosion (Woodruff *et al*., 1972), which mainly aim to decrease soil erodibility. Diouf *et al.* (1990) tried an inexpensive technology to control wind erosion by adding kaolinite and bentonite clay to fine sands. Sand or pebble (>2 mm) mulch are often used to control erosion. However, these types of materials as surface cover are mainly used in non-agricultural lands where it is not feasible to obtain cover by growing and managing vegetation.

The effectiveness of vegetative or non-vegetative covers depends on type of covers and other several factors. Permanent grass covers in rangelands are thought to be more effective than crop covers, which exists in the field for short period. Among crops, dense row crops and creeping crops are highly favorable. After the plants complete their crop growth, residues become the primary cover. The decay of leguminous residues is faster than of cereal or other crops and thus is less durable in field to control wind erosion. Moreover, more erect, finer and the denser is the residue, the smaller is the amount of wind erosion. Maintenance of grass cover in rangelands is very important to control wind erosion and hence it is always better to adopt controlled grazing practices in rangelands so as to maintain the primary productivity as well as to provide sufficient protective grass covers. From a field experiment at two grazing situations in Jaisalmer region of the Indian Thar Desert had revealed that the aeolian mass transport rate was almost three times higher at the overgrazed site than at the controlled grazing site during mid of June to mid of July (Mertia *et al*., 2010).

Wind Break and Shelterbelt

Shelterbelts are barriers of trees or shrubs that are planted to reduce wind speed and, as a result, prevent wind erosion; they frequently provide direct benefits to agricultural crops, resulting in higher yields, and provide shelter to livestock, grazing lands, and farms. Shelterbelts have been consistently reported in literature as barrier to prevent wind erosion and wind damage (Skidmore and Hagen, 1977; Kort, 1988). For establishment of shelterbelt, the design aspect was reported in detail by Mohammed *et al*. (1996) and Cornelis and Gabriel (2005). Few fundamental aspect of shelterbelt is presented in Fig. 20. Plant species of trees, shrubs and herbs to be used in shelterbelt need to be suitably chosen as per its height and canopy porosity for obtaining effective shelter effect.

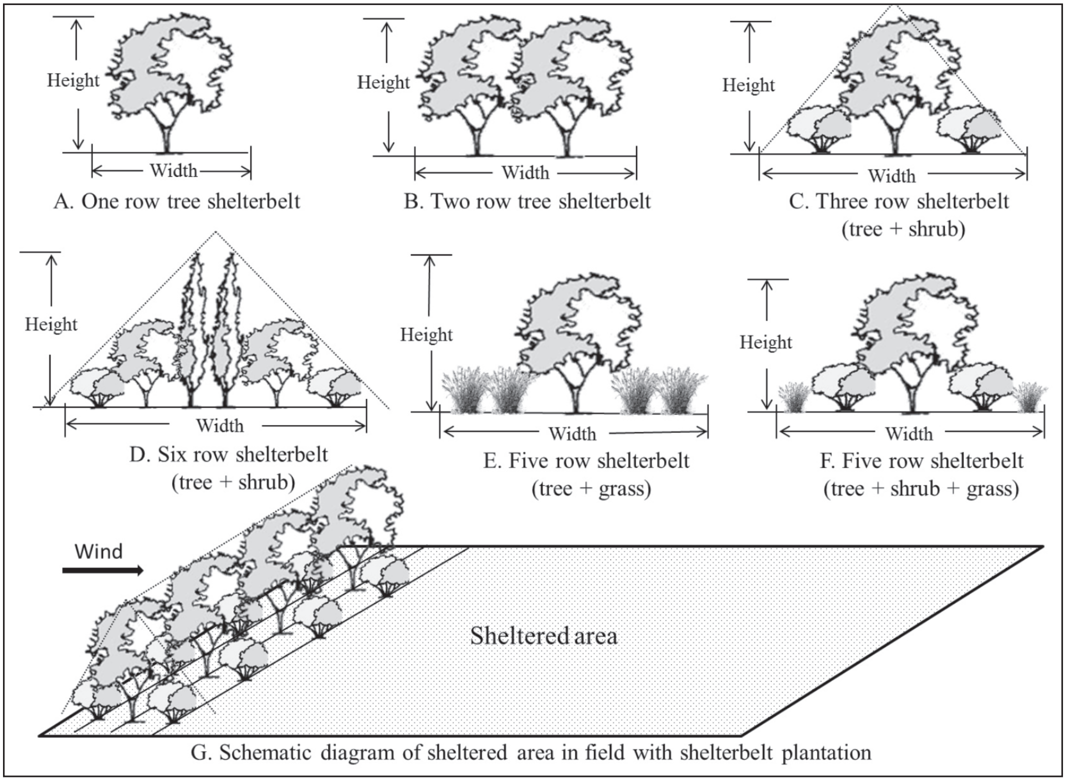

Fig. 20. Basic design of shelterbelts composing of trees, shrubs and grass.

Shelterbelt when planted across the wind direction and on the field boundaries, it effectively protects crops as well as controls sand drifting (Ganguli and Kaul, 1969). The effectiveness of shelterbelt in reducing wind speed depends on wind speed and direction at windward side and the shape, width, height and density of tree component.

All wind barriers provide maximum percentage reductions in wind velocity at leeward locations near the barrier with a gradual decrease downwind. In case of rigid barriers, the percentage reduction remains constant for different wind speeds. However, in case of flexible barriers i.e. tree shelterbelts, the degree of wind erosion control will be greater for low velocity winds than for high velocity winds. The direction of wind influences both the size and location of the leeward protected area. The area of protection is greater for wind blowing at right angles to the barrier length and is smallest or almost nil for wind blowing parallel with the barrier direction. The shape of windbreaks characterizes the outer perimeter or outer surface, which is in contact with the airstream. Abrupt vertical height of the barrier is less effective than the sloped triangular outer surface. Therefore, tree shelterbelt with pyramidal cross section will be more effective and such cross section may be obtained by planting tall trees in middle central rows followed by shrub of 2 rows at the outer ends with decreasing height. Porosity is other important factor influencing the effectiveness of wind breaks. It was observed from several studies on aerodynamics of shelterbelt that dense barriers provide large reduction of wind speed but for a short leeward distances whereas a porous barrier provide smaller reduction in wind speed but for an extended leeward distances (Bhimaya and Chowdhari, 1961; Raheja, 1963; Ganguli and Kaul, 1969; Vora *et al*., 1982). Therefore, a certain level of porosity is always desirable; however, large openings in barrier may be avoided because of air jetting through large opening may cause serious erosion in the leeward zone. Height of the barrier is another important factor influencing the effectiveness of barrier. Expressed in multiple of barrier height (H), the influence of a wind barrier may be up to 40 H to 50 H at leeward direction. For complete control of wind erosion in field wind breaks or tree shelterbelts need to be placed at close intervals as per the barrier height. Different aspects of wind barrier and sand fences and their effect on wind speed reduction in sheltered area are given in detail in Li and Sherman (2015).

Trees for shelterbelt are generally planted at right angles to the prevailing wind direction. However, if wind direction changes frequently a checkerboard pattern of plantings is required. Otherwise only parallel lines are needed. From 2-5 rows of fast growing trees of different heights should be planted to prevent any possible breaks in single rows, which would create a tunneling action with high and dangerous wind velocities. Tree shelterbelts with different species composition suitable for Indian Thar Desert and their effect on wind speed reduction are reported in Mertia *et al*. (2006). The shelterbelt technology is adopted well in areas of Indian Thar Desert where water resource is available either through tubewell command area (e.g. Lathi series at Jaisalmer) or IGNP command area. Selection of tree species for establishement of shelterbelt should be done after considering the following criteria: (i) tree species should be adopted to the site, (ii) the height and crown density should be sufficient to provide adequate protection, (iii) species should be drought tolerant, (iv) the should have deep tap root system, and (v) should also have a tendency to develop erect or drooping branches. For arid conditions in the Indian Thar Desert, Kaul (1959) suggested five row shelterbelt with a pyramidal shape having one row of tall trees (e.g. *Acacia tortilis*, *Tamarix articulata*, *Azadirachta indica*) followed by two rows of smaller trees (e.g. *Acacia senegal*, *Prosopis juliflora*, *Parkinsonia aculeata* etc.) and then followed by two rows of shrubs [e.g. *Aerva javanica (Syn. A. tomentosa)*, *Ziziphus spinachristi* and *Calligonum polygonoides*] at the edge in flank rows. Tree species suitable for different purposes in the Indian Thar Desert is mentioned in Table 6.

Table 6. Design and species for shelterbelt plantation

Purpose	Design	Suitable species
Road side	3 to 5 staggerred rows	*Acacia tortilis*, *Albizia lebbek*, *Azadirachta indica*, *Dalbergia sissoo*, *Prosopis juliflora*, *Tamarix articulata*
Railway side	6 rows	*Parkinsonia aculeata*, *P. juliflora*, *T. articulata*
Canal side	6 rows	*Acacia nilotica, Eucalyptus spp., Tecomella. undulata, A. tortilis, P. juliflora, D. sissoo, P. cineraria, A. nubica*
Farm boundary (rainfed)	1/2/3 rows	*Acacia tortilis*, *A. lebbeck*, *A. indica*, *D. sissoo*, *P. aculeata*, *P. juliflora*
Farm boundary (irrigated)	2 rows	*A. tortilis*, *A. lebbeck, Dicrostachys cinerea, P. juliflora*

Source: Mertia *et al*. (2006).

Control of wind erosion through shelterbelt plantation was well adapted in tube well command area especially in Lathi series located at Jaisalmer as well as in IGNP canal command areas (Mertia *et al*., 2006). A major portion of farmers in villages from Lathi series planted tree shelterbelts along farm boundaries and the preferred species are *A. tortilis, E. camaldulensis, D. sissoo, A. nilotica, T undulata, Cordia myxa* and *Z. mauritiana*. The latter two species provide fruit yield in addition to protection of crops from speedy winds.

The species like *E. camaldulensis* has been planted at closer spacing of 2 m apart in single row. The other species like *A. tortilis, A. nilotica* and *D. sissoo* are planted either 3 or 5 m apart in the rows. In double row shelterbelts, the rows are spaced 4 to 5 m apart. The species like *Cordia myxa* and *Z. mauritiana* are planted along the shelterbelt plantations in leeward side. In some cases 2-3 rows of ber are planted in leeward side near the belt. In IGNP command, most of the farmers have planted *D. sissoo* as shelterbelt either along water channel or on field bund. Few farmers have planted *E. camaldulensis, T. undulata* and *Z. mauritiana* as shelterbelt. Planting of *D. sissoo* is done 5 m apart in single-row belt while rows are placed closer (4-5m apart) in double-row shelterbelts. In some fields, staggered planting was observed in double row shelterbelts.

Performance of shelterbelt in tube well command area at Lathi and in IGNP canal command area at Mohangarh is presented in Table 7. In general, it has been observed that different shelterbelts had varying effects on reduction of wind speed at leeward side of the belt. The maximum reduction in wind speed was observed at 2H distance from shelterbelt in leeward side, where H is the height of shelterbelt. Two row shelterbelt was found more effective in reduction of wind speed than one row shelterbelt, however, the distance of protection at leeward side was found higher in case of one row shelterbelt plantation of *E. camaldulensis*. To obtain maximum effectiveness of tree shelterbelts in field, those tree species are preferred which grows fast and attain maximum height within a short period. The height of shelterbelt plays an important role in reduction of wind speed at leeward side. If the height of shelterbelt is short, then it creates a ridge of deposited sands at about 6H to 8H distances from tree belt, which is generally observed during initial stage of shelterbelt development. Therefore, tree shelterbelts needs to be planted in field with 6H to 8H spacing between two rows to obtain optimum results. The length of the shelterbelt is also an important factor and it has been observed that if the length is short then high wind speed was observed at both ends of the row, which again intensifies the wind erosion. From field data, it was observed that length of shelterbelt should be 10-12 times of the height of shelterbelt for better efficiency and effectiveness in controlling wind borne hazards. Other than these, canopy structure and porosity of tree shelterbelt play key role in controlling wind erosion.

Table 7. Performance of tree shelterbelt in western Rajasthan

Type of shelterbelt	Direction and number of rows	Age (yrs)	Length (m)	Mean height (m)	Mean GBH (m)	Per cent reduction in mean wind speed				
						2H	5H	10H	15H	20H
Tube well command, Lathi series (November 2005)										
Acacia tortilis	S-W/2	18	116	8.9	112.6	29.6	24.5	10.7	3.3	0
Eucalyptus camaldulensis	S-W/1	20	66	15.5	116	24.6	18.6	12.5	9.4	7
Dalbergia sissoo	S-W/2	6	85	7.8	58.6	32.4	17.9	5.5	1.5	0
IGNP command, Mohangarh (June 2006)										
Dalbergia sissoo	S-W/1	10	100	6.2	61.6	21.5	14.2	6.2	3.2	0.2
Dalbergia sissoo	S-W/2	15	73	8.8	70.3	36	28.7	12.2	1.4	0
Tecomella undulata	S-W/1	20	75	10.2	93.4	24	19.7	9.7	3.5	2

Source: Mertia *et al*. (2006).

Once a shelterbelt is established, the height, density and cross sections of the shelterbelt changes with time, which greatly affect the structure as well as efficiency of the shelterbelt. Therefore, suitable management practices are required to maintain the optimum structure of a shelterbelt (Harsh *et al*., 1991). Pruning of innermost rows of tree species facing the leeward side is essential to facilitate cultivation of crops. Pruning is also required for damaged trees by wind, insects and pests. Unwanted stems and branches of shelterbelt tree species should be removed to maintain optimum porosity. Thinning is also necessary to provide extra space for crown expansion and can be accomplished by removal of one or two complete rows or the individual tree. Moreover, when the tree species in a shelterbelt attained its maximum growth or dying off, the shelterbelt should be renewed and can be done by (i) by removing the half of shelterbelts and replanting the new seedlings (ii) planting new belts midway between the existing plantation.

Mechanical wind barrier

Mechanical wind barrier in the form of rock piles are often used by farmers in the Indian Thar Desert. Other than shelterbelt, various non-vegetative structures were also tested as wind barrier throughout the world. Date-fronds mat fence may be used as mechanical barrier to control wind erosion, which was successfully tested in Arabian desert by Murai *et al*. (1990) and Al-Afifi *et al*. (1990). Technical textiles may also be used as wind screen for reducing the wind speed, which was successfully tested in Belgium (Dierickx *et al*., 2001). Gravel sand barrier is another option to control wind erosion, the basic design of which was developed and tested in Tibet by Zhang *et al*. (2007). Even, the porous fence made of stainless steel may be an option to shelter the saltating sand particles, which was reported by Zhang *et al*. (2010) from a wind tunnel study.

Study on dual mechanical barrier is also in progress at CAZRI, which can generate wind energy and simultaneously reduces the wind speed in leeward side of the barrier. From all these literatures, it is comprehended that engineering structures are most economical and scientific system to combat wind-blown sand at initial stage of wind erosion control until the tree shelterbelts mature. Dual purpose mechanical barrier of fibre composites made from native grass species e.g. *Leptodenia pyrotechnica* along with low height vertical axis wind turbine (VAWT) in between two running barrier units was proposed by Santra (2012).

Micro shelterbelt

Wind erosion in agricultural field may also be controlled through micro shelterbelts of high crops (Fig. 21). In this method, few rows of high crops e.g. pearl millet (*Pennisetum* *glaucum*), sesame (*Sesamum indicum*) are sown in 15-20 m distance to give shelter effect to low height crops like mung bean (*Vigna radiata*), cluster bean (*Cyamopsis tetragonoloba*), groundnut (*Arachis hypogaea*) etc. In tube well command areas of Lathi series, the farmers adapted the micro shelterbelt technology to protect their crops. In farmers field, micro shelterbelt consisted of strip (4-6m wide) of fodder crop like millet and sorghum, which are usually sown at least 1-2 months in advance of sowing of main crop to which they are supposed to provide protection from winds. By and large, strips of micro windbreaks are created at a distance of regular intervals of 15H (H is the average height of micro windbreak i.e. 2 m) distance against the direction of blowing winds. Sometime the whole field is encircled by raising 3-4 m wide strips of micro windbreak along the field bund to ensure safety and security of those crops, which are highly sensitive to hot or cold winds and damaged by the wild animals. Most of the vegetable crops are provided with such windbreaks. The studies conducted at Central Arid Zone Research Institute, Jodhpur from 1976-1981 by Gupta *et al*. (1984) revealed that 3 rows of pearl millet as shelterbelt has increased the yield of cowpea and okra crops in order of 21 and 44% over unsheltered crop in summer season. In addition to increase in vegetable yield, the sheltered field provides an additional income from bajra fodder.

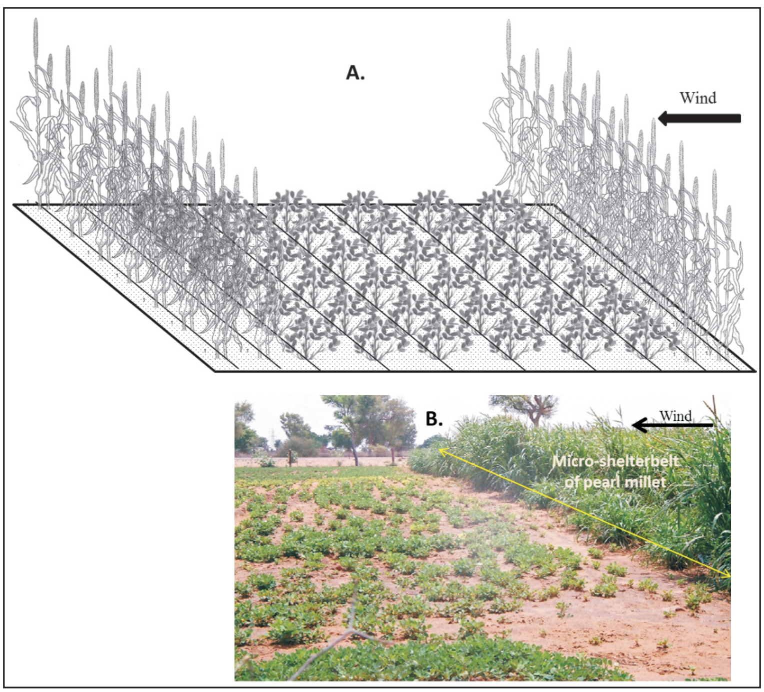

Fig. 21. Design and field view of micro-shelterbelt plantation to control wind erosion.

Tillage

Tillage operation in arid lands control wind erosion mainly through creating rough surface and by bringing the clay rich subsoil to the surface and thus increasing the clods. Normal tillage practices makes ridge and furrow in the field and thus create the rough surface. However, roughening the surface is effective only when the roughness elements are non-erodible clods. During tillage operation, it is always better to orient the ridge and furrow across the prevailing wind direction. Repeated or excessive tillage pulverizes the soil, which is more prone to erosion and hence may be avoided in drylands. The timing of tillage is also a very important factor because soil moisture content at the time of tillage operation decides the degree of soil pulverization. More clods are produced if the soil is either extremely dry or extremely moist than if it is at intermediate moisture content. Emergency tillage or deep tillage to provide rough cloddy surface is a temporary measure and is applied in extreme cases of vegetation depletion due to excessive grazing or drought etc. Emergency tillage should be accomplished at a depth which brings up compact clods, usually 10-15 cm. If sufficient amount of clay compacted clods are not available at subsurface, then it is recommended not to practice emergency tillage.

Crop Management

In general, crops grown at close spacing are more effective to control wind erosion than at wider spacing. The direction of crop rows with reference to prevailing wind direction has effect on wind erosion. It is recommended to align the crop rows perpendicular to wind direction so as to protect the top soils from inter-row areas from erosion. (Fig. 22). It was reported from field experiments that the wind erosion may be six times higher in cases when crops are planted along the wind direction rather than across the wind direction. Different type of cropping practices and their effect on wind erosion are discussed in following sections.

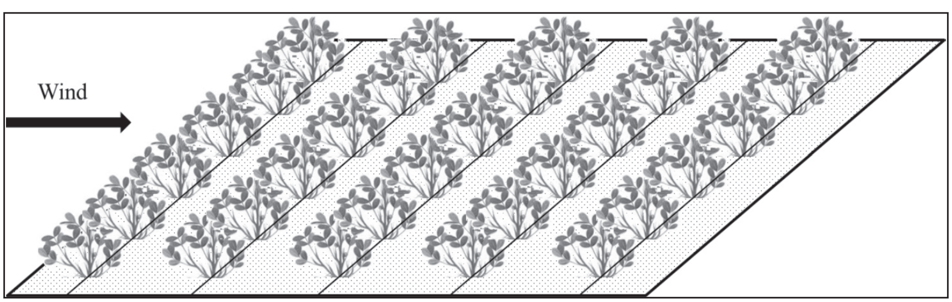

Fig. 22: Orientation of crop rows to control wind erosion

Intercropping

It mainly involves planting the crop with minimum tillage in a field having left over stubbles of previous year crop. Experiments by Mishra (1964) at CAZRI Bikaner revealed that leaving a pearl millet stubble of 15 cm, 30 cm, 45 cm and whole stalk height decreased the wind eroded soil loss by 28.6, 46.5, 54.6 and 63.5%. The cumulative loss of soil during 75 days was reduced to 22.5 t ha^{-1} from fields covered with 10-15 cm stubbles of pearl millet (Gupta and Aggarwal, 1980).

Mixed cropping

Farmers normally adopt a practice of agro-horti silvipastoral system in Indian arid zone. A mixed crop of pearl millet, moth/mung/clusterbean, cucurbitaceous twiners and scattered tussocks of *Lasiurus sindicus*, *Cenchrus ciliaris*, bushes of *Ziziphus numularia*, *Calligonum polygonoides* as well as trees of *Prosopis cineraria*, *Acacia nilotica*, *Tecomella undulata* is a common sight in the hinterland. While such a system may appear to be a primitive farming system, it has potential ecological and economic advantages. Ecologically, the perennial component neither competes with crop, nor has a phenology that adversely affects crop. In fact shade of these scattered tussocks, bushes and trees considerably ameliorates the ambient environment by lowering the temperature by as much as 4-10˚C. Further, the naturally placed geometry of these plants in a particular staggered way does prevent wind erosion as they act as live mulch. In fact a modelling exercise is needed to optimize the geometry of these perennial components in the mixed cropping system and their consequent impact on wind erosion control.

Strip cropping

It is an improved version of mixed cropping, where in alternate strips of cultivated crops and close growing crops are sown in the same field. This system helps in preventing soil avalanching by (i) physical protection against wind laden sand and (ii) limiting the soil removal to a distance equal to width of a strip (Gupta *et al*., 1997). In view of above, narrower strips are more effective in reducing wind erosion. The erodibility of soil as determined by its sandiness and the type of crop determine the width of strips, which varies from 6 m in sand to 30 m in sandy loam (Gupta, 1993).

Earlier experiments by Misra (1971) revealed that strips of perennial grass *Lasiurus sindicus* and *Ricinus communis* planted at right angle to wind direction significantly reduced wind speed, checked wind erosion and enhanced crop yields in the intervening strips. Mung and moth bean and grass in strips width of 6:1 ratio were found optimum. In another study, it was found that 18-20 years old cover of such perennial grasses like *Lasiurus sindicus*, *Cenchrus biflorus* and *P. turgidum* at Bikaner completely checked the soil erosion by providing surface cover, formation of soil crust and binding sand particles (Gupta, 1993)

More recent experiments in Bikaner involved growing of crops (moth bean) in the year 2004 in the intervening strips alternated by *Aloe vera* and *Cassia angustifolia* strips across wind direction. *Aloe vera* emerged as a plant that stopped wind eroded sand and recorded deposition of soil up to 179 t ha^{-1} compared to soil loss of 248 t ha^{-1} from bare sand and 8.8 t ha^{-1} under *Cassia angustifolia.*

Soni *et al*. (2013) have reported that in Bikaner, strip cropping of *C. cilliaris* with clusterbean in 5:15 meter row width ratio reduced soil loss from 67.5 and 33.5 t ha^{-1} in sole cropping in 2006 and 2007 to a mere 7.5 t ha^{-1}. Net loss of SOC was reduced by 3-6 folds under strip cropping as compared to sole cropping whereas NPK removal was reduced by 5-7 folds.

Alley cropping

It involves growing trees (including shrubs) and row crops side by side in strips or alleys. Crops are normally cash crops and match well with selected tree species in terms of requirement of light, water and nutrients. This also diversifies the whole system, reduces risk, controls erosion and optimizes niche use. The width of alleys varies depending on agroclimatic situations. Such alleys of a number of trees with a lot of crops, fruit crops with field crops and grass have been experimented for the last 20 years in the integrated farming system experiment in 8 ha area in CAZRI Jodhpur. While complementarity of component crops and trees have been studied in detail to find out reasons of enhanced productivity, it remains to be investigated in terms of its value as wind erosion control.

CONCLUSION

Wind erosion is a major land degradation process in both hot arid and cold arid regions of the world. The mechanism of wind erosion process mainly includes four basic steps: initiation of movement of soil particles by wind force, transport of moving particles basically in three modes (suspension, saltation and surface creep), sorting of transported particles, and the abrasion by moving soil particles, which further induce the erosion process. All the particles initially carried out by wind are deposited at distant places thus affecting the source area by depleting its soil fertility and creating environmental hazards in deposited areas. Sometimes, the deposition of nutrient enriched eroded soil particles in places away from the source region increased the fertility. Computed soil loss from field measurements revealed annual soil loss rate of 12.2 t ha^{-1} in Jaisalmer lying under moderate category of wind erosion whereas it was as high as 83.3 t ha^{-1} in Khuiyala village at Jaisalmer lying under very severe category. However, at Bhujawar village, Jodhpur, which lies under slight category of wind erosion, annual soil loss rate has been observed as 1.3 t ha^{-1}. There are main five factors affecting the wind erosion process, which are climatic factor, soil erodibility factor, roughness factor, field length factor and vegetative factor. Considering these causative factors different control measures have been formulated, which mainly aim either to decrease the erosive energy of wind or to decrease the erodibility of soil by altering the surface soil characteristics or surface cover or roughness. Among different control measures, well-anchored surface vegetative cover is the most applicable method to control wind erosion, which may be achieved through maintaining permanent grass cover in rangelands. Tree shelterbelt is also a suitable option to control wind erosion in those places of desert where water resource is available for its initial establishment.

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