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Crop production and economic loss due to wind erosion in hot arid ecosystem of India

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ABSTRACT

Wind erosion is a severe land degradation process in hot arid western India and affects the agricultural production system. It affects crop yield directly by damaging the crops through abrasion, burial, dust deposition etc. and indirectly by reducing soil fertility. In this study, an attempt was made to quantify the indirect impact of wind erosion process on crop production loss and associated economic loss in hot arid ecosystem of India. It has been observed that soil loss due to wind erosion varies from minimum 1.3 t ha^{-1} to maximum 83.3 t ha^{-1} as per the severity. Yield loss due to wind erosion was found maximum for groundnut (*Arachis hypogea*) (5–331 kg ha^{-1} yr^{-1}), whereas minimum for moth bean (*Vigna aconitifolia*) (1–93 kg ha^{-1} yr^{-1}). For pearl millet (*Pennisetum glaucum*), which covers a major portion of arable lands in western Rajasthan, the yield loss was found 3–195 kg ha^{-1} yr^{-1}. Economic loss was found higher for groundnut and clusterbean (*Cyamopsis tetragonoloba*) than rest crops, which are about ₹ 191–12465 ha^{-1} depending on the severity of wind erosion. For mustard (*Brassica* spp.) and wheat (*Triticum* spp.) the economic loss was about ₹ 47–3181 ha^{-1}, whereas for pearl millet the economic loss was lowest (₹ 36–2294 ha^{-1}). In this calculation only indirect impact of wind erosion in terms of reduction in soil fertility was considered. There is need of future research work for assessing the direct damage on crops by wind erosion process, addition of which may lead to higher magnitude of losses.

1. Introduction

Soil erosion through water and wind is a major land degradation process and affects the soil productivity worldwide (Li et al., 2009; García-Ruiz et al., 2015). It has been estimated that about 75 billion metric tons of soil are removed by wind and water erosion each year (Pimentel et al., 1995) and most of these removal take place from agricultural land (Montgomery, 2007). However, the critics note that 75% of the eroded soils eventually deposit on another site and thus the soils are not truly lost from the landscape (Larson et al., 1983). But the source area of erosion e.g. the croplands are ultimately affected. About 80% of agricultural land in the world is affected by moderate to severe erosion whereas 10% suffers from slight to moderate erosion (Speth, 1994). Average soil erosion rate is as high as 40 tons ha^{-1} yr^{-1} in Asia, Africa and South America whereas in United States and Europe, it is about 17 tons ha^{-1} yr^{-1} (Barrow, 1991). Whereas, the rate of soil formation is about 2.5 cm topsoil in every 100–1000 years, which is equivalent to 0.4–4 tons ha^{-1} yr^{-1} (Pimentel et al., 1976; Brady and Weil, 1999; Verheijen et al., 2009). Therefore, it is quite clear that the soil losses through erosion far exceed the natural rate of soil formation. Impact of such losses on crop yield needs proper assessment, which will help in implementing suitable soil conservation and land management practices for mitigating the land degradation process. Several attempts have been made previously to establish the relationships between soil loss and crop yield and these are comprehensively described in few literatures (Lal, 1987; van Baren and Oldeman, 1998; Den Biggelaar et al., 2001; Pimentel and Burgess, 2013). Most of these previous studies quantified the impact of water erosion on crop productivity (Follet and Stewart, 1985; Lal, 1988; Larney et al., 1995; Larson et al., 1990; Alfsen et al., 1996; Sharda et al., 2010; Sharda and Dogra, 2013), whereas the studies related to wind erosion on crop productivity are limited (Lyles, 1975; Lyles, 1977; Larney et al., 1998; Zobeck and Bilbro, 2001, Nordstrom and Hotta, 2004).

Soil erosion affects the crop productivity through any of the following pathways: (i) removal of nutrient rich topsoil affecting soil productivity, (ii) reduction in topsoil thickness and thus restricts rooting depth, (iii) removal of organic matter and thus affects productivity, (iv) affecting soil water retention capacity since finer

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particles having higher water retention potential are removed, and (v) removal of soil biota and thus deteriorating soil health. The effect of wind erosion on crops is mainly manifested through blowing away of nutrient rich top soil leaving behind a coarser substrata which is poor in nutrients. Other effect includes crop damage by sand blasting or abrasion actions on tender stems and leaves, and crop burial by deposition of aeolian sediments. Effect of erosion on crop productivity is hardly visible since soil degradation is a slow process, implying relatively small annual changes whereas crop yields in any case vary considerably due to management, precipitation and other factors (Alfsen et al., 1996). Moreover, the technological interventions in crop production systems often mask the effect of erosion on crop productivity.

Since crop production is a function of several factors e.g. soil, weather, quality and quantity of inputs, management practices, pest and disease occurrence etc, it is also very difficult to isolate the sole effect of erosion on crop productivity (Frye, 1987; Stocking and Sanders, 1993; Littleboy et al., 1996). Therefore, it requires that all other factors determining the crop yield to be kept constant or controlled as much as possible while determining the effect of erosion on crop productivity. In case of water erosion, such controlled experiments on runoff plots are possible where degree of erosion is different across plots but is difficult for wind erosion study. However, such controlled experiments on wind erosion with unique designs have been conducted in few places which allowed the comparison of crop yields between eroded, non-eroded and deposited areas (Fryrear, 1981; Zobeck and Bilbro, 2001). Other than the controlled experiment, relating crop yield with topsoil thickness or percent reduction in crop yield with topsoil removal is often considered as the most viable approach of assessing the effect of erosion on crop productivity. The approach has been used in both water erosion (Alfsen et al., 1996; Larney et al., 1995) and wind erosion study (Lyles, 1975, 1977). Since the crop production does not only depend on the quantity but also on the quality and distribution of soil layers in the overall rooting zone, topsoil thickness is sometimes not considered as adequate measure of productivity (Hoag, 1998). Moreover, such relationship between soil depth and crop yield needs to be available for each soil category presents in the interested region of application, which are very limited. Hence, in this manuscript, a novel approach of relating soil test crop response (STCR) equations developed through long term experiments with nutrient removal through wind eroded soil loss is proposed to assess the crop production loss due to wind erosion. The approach is further tested in western Rajasthan, India. The crop production loss is further converted to economic loss using minimum support price of each crop of the region.

2. Materials and methods

2.1. Study area

In India, about 12.4 m ha area is affected by wind erosion (ICAR, 2010). The western part of India in Rajasthan which accounts for ~62% of hot arid regions of the country is mostly vulnerable to wind erosion, because of its vast sandy terrain and climatic characteristics. The study area in western Rajasthan consists of 12 States of Rajasthan and located between 69.47–76.12 °E and 24.6–30.2 °N (Fig. 1). About 48% area is occupied by sand dunes of various types and morphology and 76% area in this region is affected by wind erosion and deposition activities (Moharana et al., 2013; Kar et al. 2009). Over last five decades, human population in arid western Rajasthan has been increased by three and half fold whereas livestock population has been almost doubled. The region has experienced 32 moderate to severe droughts since independence. The land use statistics for the year 2005–06, showed that about 61.15% area in arid western Rajasthan is utilized for cultivation which includes 12.97% net irrigated area. An analysis of land use/land cover changes between 1982–83 and 2005–06 indicated an increase in net-irrigated area by 128%, and in double cropped area by 70% whereas a decline in culturable waste area by 7.70%. It indicates the quantum of population pressure on dryland environment of western Rajasthan. Such biotic pressures forced farmers to cultivate even semi-stabilized dunes for more crops and in the process, destabilize the soil surface and enhances the sand drifting and spread. Impacts of activated sand dunes or newly formed dunes cause serious problem to adjoining agricultural land, railway tracks, roads, irrigation networks and settlements, which are evident in many parts of the region.

2.2. Crop production loss due to wind erosion

One of the commonly followed approaches to quantify the crop production loss due to wind erosion was suggested by Lyles (1975), in which removal of topsoil was related with crop yield reduction. Considering the core principle of this approach, a new procedure using soil test crop response (STCR) equations has been proposed in this study to assess crop production losses due to wind erosion process. This new approach involves the following steps: i) characterization of wind erosion severity category in the region, ii) collection of crop productivity data as per wind erosion severity categories, iii) collection of average soil loss rate in each wind erosion severity category iv) computation of nutrient loss through wind eroded soil v) application of region specific STCR equations for calculating the crop yield loss due to nutrient loss. Finally, economic loss due to wind erosion can be assessed by multiplying the computed crop production loss with minimum support price of respective crop. The STCR approach was applied in western Rajasthan to assess crop production loss due to wind erosion. In the following section, details of each step of STCR approach in western Rajasthan are described.

2.2.1. Mapping wind erosion severity categories in western Rajasthan

Wind erosion severity map of western Rajasthan was prepared by supervised classification of remote sensing images (Singh et al., 1992). First, different terrains with field indicators of erosion/deposition features were identified for different degree of wind erosion severity. At the second step ground truth observations on field indicators of erosion/deposition features were related with false colour composites (FCC) of remote sensing products e.g. images acquired by LISS-III and LISS-IV camera of IRS-P6 satellite as well as the google earth images.

Terrain properties and annual rainfall along with land surface conditions were grouped together to categorize a land unit into a single class out of four pre-identified severity classes e.g. slight, moderate, severe and very severe. Field indicators of erosion/deposition features for different terrains representing different wind erosion severity classes are given in Table 1.

The field indicators were further verified through visual interpretation of false color composites (FCC) of remote sensing images acquired during summer months (May-June). Characteristics erosion/deposition features and corresponding remote sensing signatures are mentioned in Table 2.

Using the above mentioned field indicators and remote sensing signatures; the wind erosion map of wind erosion severity was prepared at 1: 1 million scale. Detailed description of the map and the procedure followed to prepare it are available in Narain et al. (2000).

2.2.2. Average productivity of selected crops in western Rajasthan

Productivity of major crops in western Rajasthan was collected from agricultural statistics database of Government of Rajasthan during the period from 2001 to 2010 (http://www.krishi.rajasthan.gov.in/). Fifteen tehsils representing either irrigated or rainfed croplands were selected by overlaying land use/land cover (LU/LC) grid, wind erosion index layer, and wind erosion severity grid. The list of selected tehsils is given in Table 3 and its locations in western Rajasthan are depicted in Fig. 2. Crop productivity data of these selected tehsils were extracted from the database to assess the crop productivity under each wind erosion severity category.

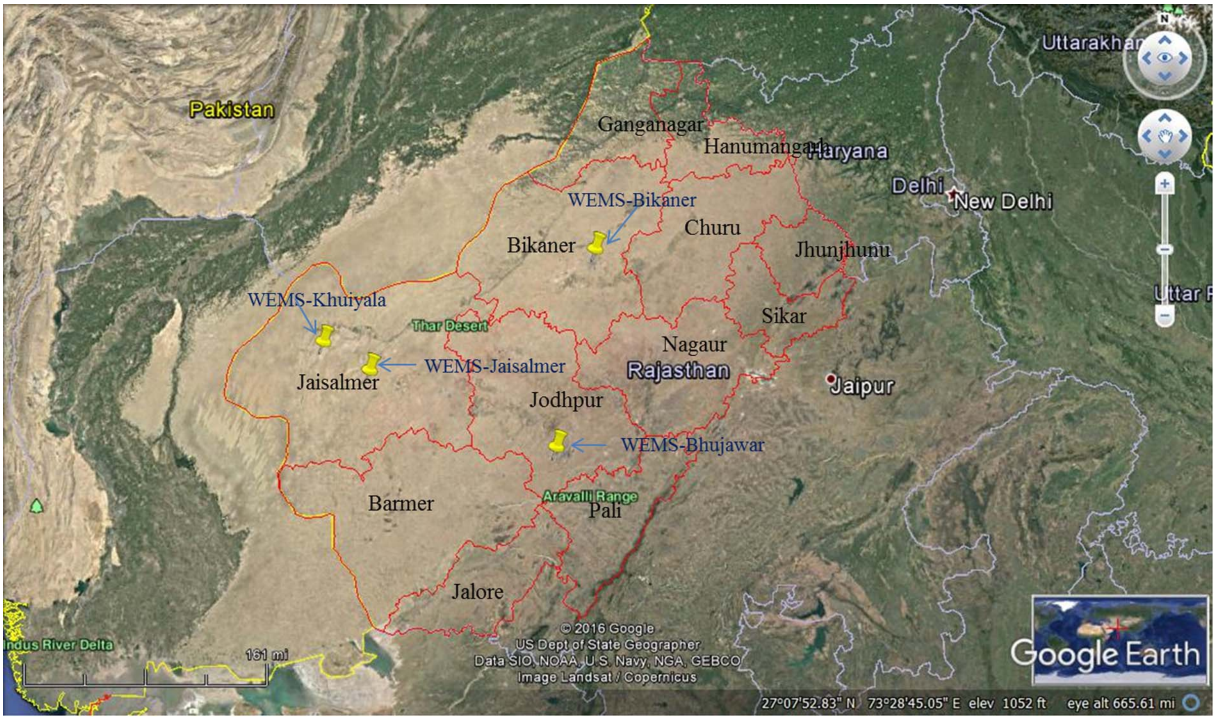

Fig. 1. Location of study area in western Rajasthan, India [boundaries of 12 States in western Rajasthan and the location of wind erosion measurement station (WEMS) are shown].

2.2.3. Average soil loss rate due to wind erosion in western Rajasthan

Annual soil loss data measured during 2009–2013 at different locations in western Rajasthan e.g. Khuiyala village in western part of Jaisalmer district, research farm of ICAR-CAZRI Regional Research Station at Bikaner and Jaisalmer and Bhujawar village in Jodhpur were compiled (Santra et al., 2010, Tewari et al., 2013; Soni et al., 2013; Santra and Varghese, 2015). Locations of these four wind erosion monitoring station (WEMS) are shown in Fig. 1 and they represents different wind erosion severity category e.g. WEMS-Khuiyala represents very severe, WEMS-Bikaner represents severe, WEMS-Jaisalmer represents moderate and WEMS-Bhujawar represents slight category of wind erosion severity. Wind eroded soil loss in these previous studies were measured either by using wind erosion sampler (Santra et al., 2010; Tewari et al., 2013; Santra and Varghese, 2015) or erosion pins (Soni et al., 2013), which are described here briefly.

Wind erosion samplers are generally placed at the centre of experimental field at four different heights from ground surface: 25 cm, 75 cm, 125 cm, and 200 cm (Fig. 3). These wind erosion samplers were freely rotating type and have a rectangular orifice of 10 cm^2, which could orient itself towards wind erosion direction. Details of the sampler are available in Santra et al. (2010).

Eroded soil masses were collected from samplers after dust storm events or at periodic intervals, which are mostly a week. Mass-fluxes of aeolian sediments at different heights were then fitted in power decay

Table 2
Image characteristics on FCCs for determining wind erosion /deposition features.

Erosion/deposition features	Signature on satellite FCCs
Sand sheets with few scattered fence line hummocks	Uniform whitish or light pale brown color
Fresh sand deposits on old and stable sand dunes	Bright white tone of reactivated sand and light yellow on stable surface
Closely spaced sandy hummocks and fresh sand deposits on sand ridges	Medium white tone with dull redness because of cultivation
Areas of drift sand, especially as fields of barchans	Bright white tone

Table 1
Field indicators of wind erosion in western Rajasthan.

Terrain	Average rainfall (mm)	Major indicators for assessment of erosion/deposition features	Severity
Flat sandy plains with dominantly loamy sand to sandy loam soil	100–550	Fresh sand sheet up to 30 cm thick; few scattered new fence line hummocks and nebkhas up to 100 cm high	Slight
Moderately sandy undulating plains and sand dunes with loamy sand soils; thickly sand sheeted plains	Above 300	Presence of reactivated fresh sand of 50–150 cm thickness on stable dunes, sandy plains and fence line hummocks; many recently formed nebkhas	Moderate
Moderately sandy undulating plains and sand dunes with sand to loamy sand soils	Below 300	Reactivated and fresh sandy hummocks (nebkhas) and sand ridges of 90–300 cm height; sand sheets of 60–150 cm thickness between undulations; reactivated stable dunes with fresh sand deposits of 70–200 cm thickness; exposed plant roots to a depth of 40–100 cm in the sandy plains indicate erosion	Moderate
Moderate to strongly undulating sandy plains with closely spaced hummocks and high sand dunes with sand to loamy sand soils	100–550	Closely spaced sandy hummocks and sand ridges of 1–4 m height with fresh sand cover; sand deposits of 100–300 cm thickness usually present between undulations; highly reactivated sand dunes are covered by fresh sand and superimposed by crescentic bedforms of 2–4 m height	Severe
Barchan dunes and very thick sandy plains with loose sand throughout the profile	100–550	Areas of drift sand, especially as fields of barchans of 2–5 m height, which encroach upon roads, settlements and agricultural fields; also areas with very closely spaced nebkhas of 2–5 m height	Very severe

Table 3
List of selected tehsils for crop productivity assessment.

Croplands	Very Severe	Severe	Moderate	Slight	Negligible
Irrigated	–	Pokaran	Nawalgarh, Sanchore	Chirawa, Osiyan	Merta, Degana
Rainfed	Jaisalmer, Chohatan	Bikaner, Phalodi	Nokha, Shergarh	Jodhpur	Nagaur

mass-height profile, which was found the best model for the Indian Thar desert (Mertia et al., 2010) (Fig. 3b) and is shown in Eq. (1) below:

$$q(z) = az^{b} \tag{1}$$

where, q is the mass flux ($M\,L^{-2}\,T^{-1}$) of aeolian sediments at height z (L) from ground surface; 'a' and 'b' are empirical constant of the equation. Total aeolian mass transport rate ($M\,L^{-1}\,T^{-1}$) up to a standard height of 2 m has been computed through integration of Eq. (1) with lower limit of $z = 0.01$ m to upper limit of $z = 2$ m. The calculated mass transport rate was converted to soil loss (kg ha^{-1}) by dividing the aeolian mass transport rate with the fetch length (L) of from the sampling point and multiplying with the duration of wind erosion event (T).

While measuring the soil loss using erosion pins, properly marked iron pegs (100 cm × 1 cm) were installed at a distance of 6 meter in the form of squares. The pegs were buried in the soil in such a way that 60 cm of them are projected above the ground level and this level was taken as a reference point. Sand deposition or removal was monitored from the reference point of each peg (Gupta and Gupta, 1981).

2.2.4. Calculation of nutrient loss through wind eroded soil

Loss of soil nutrient along with eroded soil was calculated from measured soil loss data and the nutrient concentration in eroded soil. Observations from field experiments have revealed that nutrient content of eroded soil is generally richer than native soil (Santra et al., 2013). It is because of finer particle size composition of eroded soils consisting of fine sand, silt and clay. Data on major nutrient contents of native desert soils from several locations were compiled from published literatures (Kumawat et al., 2013; Soni et al., 2013; Praveen-Kumar and Agarwal, 1997; Kumar et al., 2011) and average contents were found as 113 kg N ha^{-1}, 20 kg P_2O_5 ha^{-1} and 281 kg K_2O ha^{-1}. Calculation of nutrient richness factor in eroded soil from the measured data on available N, P_2O_5 and K_2O content of eroded as well as native soil showed the factor values as 1.81, 1.68, and 1.42 for N, P_2O_5 and K_2O respectively (Soni et al., 2013). These nutrient richness factors and native nutrient soil nutrient contents were converted to nutrient content in eroded soil as follows:

$$\text{Nutrient content in eroded soil(kg/ton)} = \frac{\text{Nutrient content in native soil(kg/ha)} \times \text{nutrient richness factor}}{2.25 \times 1000}$$

After obtaining the nutrient content in arid soil, it was multiplied with the soil loss in each severity category to get the nutrient loss.

2.2.5. Crop yield loss estimation using STCR approach

For estimating the yield loss due to depletion of soil nutrients through wind erosion, STCR equations for arid regions of India were used (Dey and Gulati, 2013). Based on the targeted yield approach, the STCR equations can be represented in following general form:

$$F = b_1 Y + b_2 Nu \tag{2}$$

where F is amount of fertilizer required (kg ha^{-1}) to get the target yield

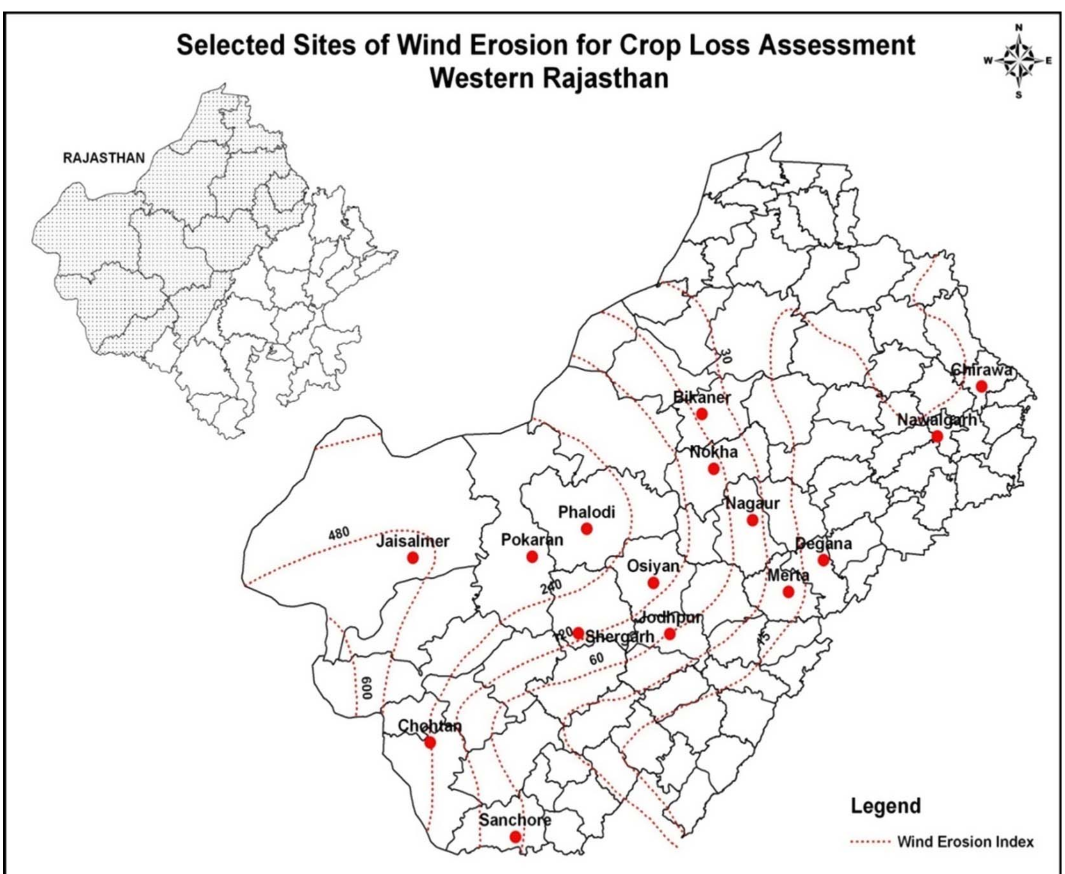

Fig. 2. Selected sites in western Rajasthan for assessing crop loss due to wind erosion.

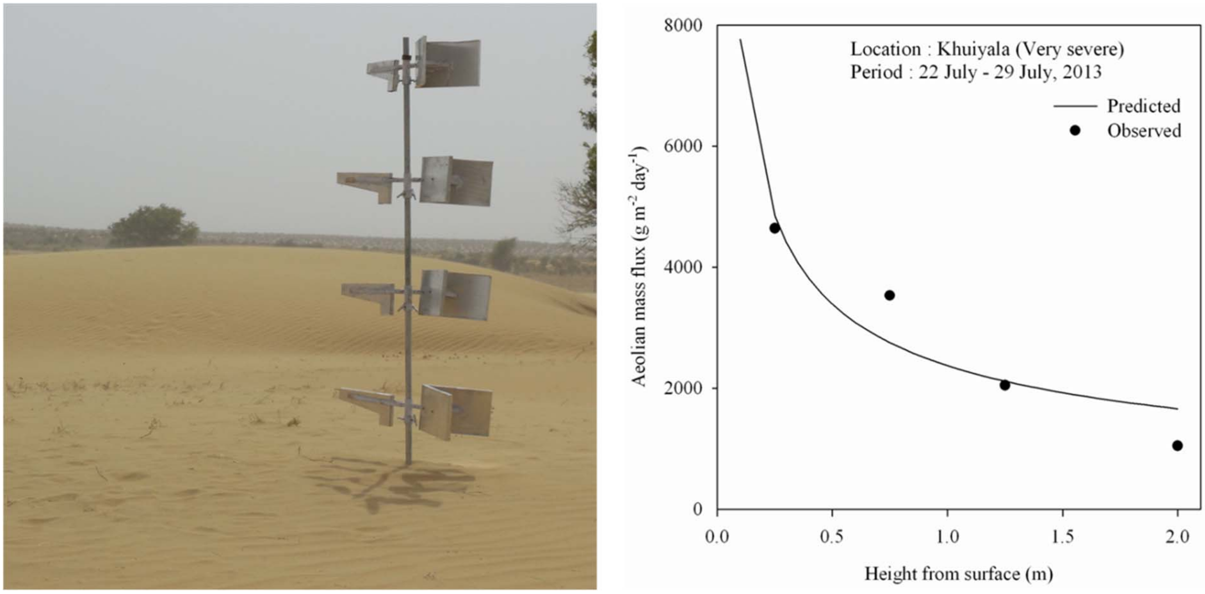

Fig. 3. Measurement of wind eroded soil loss in field (a) installed wind erosion sampler in field (b) mass-height profile of eroded mass flux.

Table 4
Soil test crop response (STCR) equations developed for arid region using targeted yield approach by All India Coordinated Research Project (AICRP) on STCR.

Crop	Fertilizer required (kg ha^{-1})	Coefficient of STCR equations			
		Target yield (kg ha^{-1})	Soil N content (kg ha^{-1})	Soil P_2O_5 content (kg ha^{-1})	Soil K_2O content (kg ha^{-1})
Bajra	N	1005	−0.89		
	P_2O_5	602		−1.66	
	K_2O	820			−0.52
Mustard	N	2725	−0.969		
	P_2O_5	2211		−5.69	
	K_2O	2154			−0.59
Wheat	N	854	−0.63		
	P_2O_5	693		−3.72	
	K_2O	721			−0.55
Groundnut	N + 0.18 ON	182	−0.26		
	P_2O_5 + 0.6 OP_2O_5	208		− −1.48	
	K_2O + 0.33 OK_2O	243			
Moth bean	N	861	−0.29		
	P_2O_5	891		−1.66	
	K_2O	1758			−0.53
Cluster bean	N	538	−0.46		
	P_2O_5	507		−2.46	
	K_2O	486			−0.34

ON = Nitrogen through organic sources, OK_2O = Potash through organic source, OP_2O_5 = Phosphate through organic source.

of Y (q ha^{-1}) if the nutrient present in soil is Nu (kg ha^{-1}), b_1 and b_2 are coefficients. STCR equations for selected six crops for this study were given in Table 4

In this approach, for calculation purpose, two situations were assumed for which the amount of fertilizer applied in two cases are similar (F) but the nutrient contents are different (Nu_1 and Nu_2) due to depletion of soil nutrient through wind erosion, which ultimately lead to different yields (Y_1 and Y_2). These two situations can be represented by Eqs. (3) and (4), respectively.

$$F = b_1Y_1 + b2Nu_1 \tag{3}$$

$$F = b_1Y_2 + b_2Nu_2 \tag{4}$$

where, Y_1 and Y_2 are crop yields under soil nutrient concentrations of N_1 and N_2, respectively. Subtracting Eqs. (3) and (4) following rearrangements will lead to

$$b_1(Y_1-Y_2) = -b_2(Nu_1-Nu_2) \tag{5}$$

$$Y_1-Y_2 = -b_2/b1(Nu_1-Nu_2) \tag{6}$$

Yield loss (kg ha^{-1}) = $-(b_2/b_1)$ × nutrient loss (kg ha^{-1})

Following the above equation (Eq. (6)), corresponding factor (b_2/b_1) for N, P_2O_5 and K_2O content under each selected crop has been calculated.

2.3. Calculation of economic loss due to wind erosion

Economic loss due to wind erosion was computed by multiplying the yield loss with corresponding minimum support price (MSP) for the year 2012–13. For cluster bean and moth bean, MSP values were not reported and hence were estimated from the market price of the same crop at the time of harvest. Total economic loss in western Rajasthan has been estimated by averaging the economic loss per hectare for each crop multiplying with area under cultivation for the year 2011–12.

3. Results and discussion

3.1. Wind erosion severity in western Rajasthan

Wind erosion severity map of western Rajasthan is presented in Fig. 4. The map depicts five severity categories of wind erosion: very severe, severe, moderate, slight and negligible. It has been observed that western part of the study area mostly covering Jaisalmer district is very severely affected by western boundary whereas at eastern part mostly covering Jodhpur, Jalore and Pali district are negligibly affected by wind erosion. The prevalent wind erosion direction in the study area is the South of South West and hence a clear diagonal area from South West corner to North East corner of the map covering Barmer, Phalodi, Churu etc shows patchy areas severely affected by erosion. Area under each severity category in western Rajasthan is presented in Table 5. Overall, 50.33% of the study area is moderately to very severely affected by erosion.

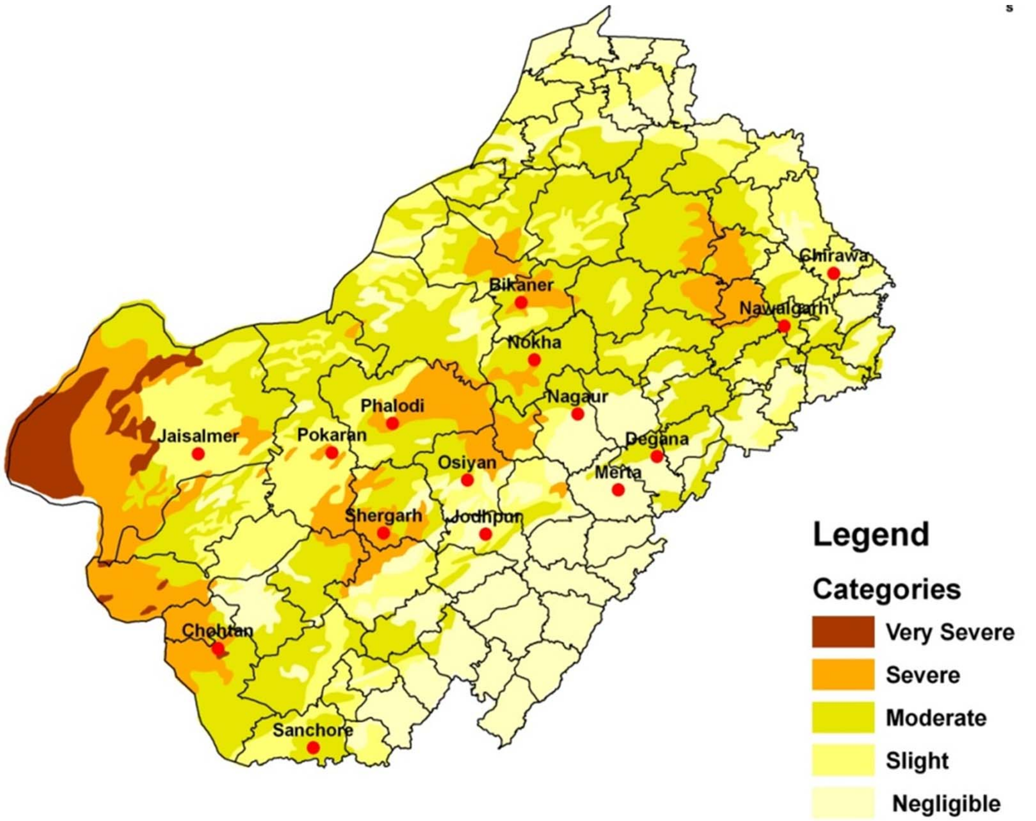

Fig. 4. Wind erosion severity map in western Rajasthan.

Table 5
Wind erosion severity in western Rajasthan.

Erosion/deposition class	Area (km^2)	Percentage of total area
Very severe	5800	2.78
Severe	25540	12.23
Moderate	73740	35.32
Slight	52690	25.24
Negligible	50981	24.43

3.2. Crop productivity in western Rajasthan

Productivity of selected major crops in western Rajasthan under each severity class is presented in Table 6. Decrease in productivity with increasing in severity of wind erosion was observed from the table. It was also observed that the average crop yield in areas affected by very severe category of wind erosion was 50–80% lower than the crop yield in areas where wind erosion is negligible. The reduction in very severely affected areas was found highest (82%) for pearl millet and lowest for gram (51%). The yield reduction in slightly affected areas was also highest for pearl millet (54%) as compared to negligible.

Table 6
Productivity of major crops in western Rajasthan under different wind erosion severity category.

Crops	Crop productivity (kg ha^{-1}) and wind erosion class				
	Very severe	Severe	Moderate	Slight	Negligible
Pearl millet (*Pennisetum glaucum*) [local name: Bajra]	118	142	277	300	658
Wheat (*Triticum aestivum*)	565	1029	1533	1783	2032
Chick pea (*Cicer arietinum*)	540	–	692	732	1112
Kharif pulses*	147	159	173	201	342
Rapeseed and Mustard (*Brassica* sp.)	435	704	970	1076	1440
Groundnut (*Arachis hypogea*)	336	612	712	862	1089

* Kharif pulses include Moth bean (*Vigna aconitifolia*), Mung bean (*Vigna radiata*) and Clusterbean (*Cyamopsis tetragonoloba*); Productivity data of Sanchor has not been included because only mung bean is cultivated in the tehsil.

3.3. Soil loss due to wind erosion in western Rajasthan

Difference in soil loss between very severe and moderate categories of wind erosion has been presented in Fig. 5. Aeolian mass transport has been observed as high as 7 kg m^{-1} day^{-1} for very severe category, whereas it was around 4 kg m^{-1} day^{-1} for severe category. Aeolian mass transport rate ($M L^{-1} T^{-1}$) 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. Characteristically, wind erosion was most severe during July-August (Julian day 180–240) at both sites. It has also been observed that wind erosion process was active throughout the year at very severely affected area, whereas it was active during summer months at moderately affected areas.

Computed annual soil loss rate due to wind erosion for four wind erosion categories are given in Table 7. It was found that annual soil loss rate varies largely with severity, e.g. it was as high as 83.3 t ha^{-1} yr^{-1} under very severe category and as low as 1.3 t ha^{-1} yr^{-1} under slight category. Fetch length in field surrounding the sampler plays a critical role in calculation of annual soil loss rate by wind erosion. For example, at Jaisalmer the fetch length was roughly estimated as 150 m as per the field situation and prevailing wind erosion direction. However, if we consider fetch length < 150 m e.g.

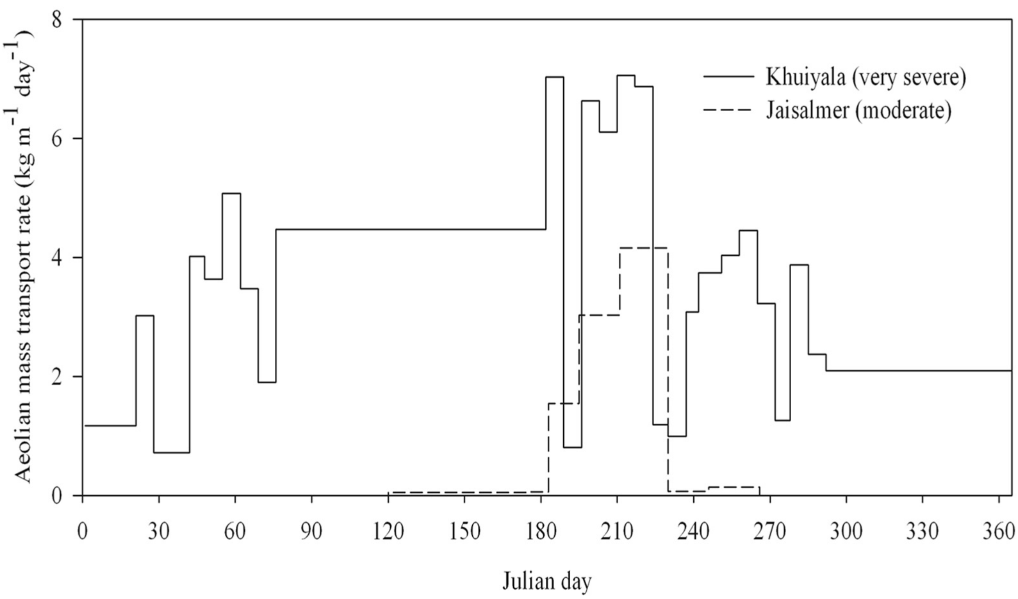

Fig. 5. Aeolian mass transport rate (kg m^{-1} day^{-1}) at very severely (Khuiyala) and moderately (Jaisalmer) affected areas in western Rajasthan.

100 m or 125 m, which are lesser than the fetch length considered in the above site, the calculated soil loss will be 49% and 20% higher, respectively. Whereas, if we consider fetch length > 150 m e.g. 175 m or 200 m, the calculated soil loss will be 14% and 25% lower than the calculated soil loss at Jaisalmer site. Therefore, one must be critical in getting a good estimate of fetch length while calculating soil loss from field measurements. Conversion of these soil loss rates into equivalent loss of soil depth resulted into a loss of 5.27 mm yr^{-1} and 0.08 mm yr^{-1}, respectively in very severe and slight wind erosion severity category. As compared to these soil loss rates in western Rajasthan, average annual potential soil loss rate due to wind erosion as reported in several literatures from different locations in the world are also mentioned in Table 7. Soil loss rate in western Rajasthan is slightly lower than in West Africa, Niger and higher than in UK, Germany and USA. Wind erosion rate at China is comparable with the present study.

3.4. Soil nutrient loss due to wind erosion

Considering the nutrient richness factor of eroded soil as 1.81, 1.68 and 1.42 for N, P_2O_5 and K_2O, respectively, average nutrient loss through wind erosion was found 0.09 kg N ton^{-1}, 0.01 kg P_2O_5 ton^{-1} and 0.18 kg K_2O ton^{-1} of eroded soil. Average loss of nutrients through wind erosion under each wind erosion severity category is given in Table 8.

Table 7
Annual soil loss rate at different wind erosion severity categories in western Rajasthan.

Sr. No	Country	Year of measurements	Location	Wind erosion category	*Annual soil loss rate (t ha^{-1} yr^{-1})	Source
1	India	2013–2014	Khuiyala, Jaisalmer	Very severe	83.3	Present study
		2010–2013	CAZRI farm, Bikaner	Severe	50.0	
		2009–2011	CAZRI farm, Jaisalmer	Moderate	12.2	
		2011–2013	Bhujawar, Jodhpur	Slight	1.3	
		1980	Bikaner	Severe	1449	Gupta and Agarwal (1980)
2.	China	1905–2000	Inner Mongolia, Beijing, Shangdong, Shanxi, Shanaxi, Qinghai, Xinjiang	–	7.44–349.5	Shi et al. (2004)
3.	Germany	–	East Angila	–	21	Groβ and Barring (2003)
		1981–1993	Gronhein	–	0.43 (Maximum:10)	Böhner et al. (2003)
5.	UK	1970–1998	Barham	–	1.56 (Maximum:15.5)	Böhner et al. (2003)
		1999–2000	Moor house in the North Pennines	–	0.46–0.48	Warburton (2003)
6.	USA	1975	Great Plains of USA	–	15.8–262.3	Lyles (1975)
		1977	Great Plains of USA	–	4.74–674.7	Lyles (1977)
		1982	Corn Belt, Lake States, Mountain, Northern Plain, Pacific, Southern Plains	–	3.3 (0.9–9.9)	NRCS NRI (2007)
		2007	Corn Belt, Lake States, Mountain, Northern Plain, Pacific, Southern Plains	–	2.1 (0.2–6.2)	NRCS NRI (2007)
7.	West Africa, Niger	–	Sahel region	–	190	Buerkert et al. (1996)
		–	Sahel region	–	521.4	Michels et al. (1995)
		–	Banizoumbou	–	15–21	Bielders et al. (2000)
		–	Sahel region	–	48.5	Chappell et al. (1998)
		–	Sadore	–	34	Sterk et al. (1996)

* Soil loss rate of 1 mm yr^{-1} is equivalent to 15.8 t ha^{-1} yr^{-1}.

Table 8
Soil nutrient loss due to wind erosion under different severity categories.

Wind erosion severity	Loss of soil nutrients (kg ha^{-1} yr^{-1})		
	N	P_2O_5	K_2O
Very severe	7.58	1.25	14.79
Severe	4.55	0.75	8.87
Moderate	1.11	0.18	2.16
Slight	0.12	0.02	0.23

Table 9
Yield loss of major crops in western Rajasthan due to wind erosion under different categories.

Crop	Yield loss (kg ha^{-1} yr^{-1})			
	Very severe	Severe	Moderate	Slight
Pearl millet (*Pennisetum glaucum*)	195	117	29	3
Mustard (*Brassica* spp.)	100	60	15	2
Wheat (*Tritticum* spp.)	236	141	34	4
Groundnut (*Arachis hypogea*)	331	198	48	5
Moth bean (*Vigna aconitifolia*)	93	56	14	1
Clusterbean (*Cyamopsis tetragonoloba*)	229	137	33	4

3.5. Crop yield loss due to wind erosion using STCR approach

Estimated yield losses of major crops in western Rajasthan are given in Table 9. It has been observed that the loss was highest under very severe category of wind erosion for all crops. With decrease in severity, the yield loss was also decreased. Comparison of losses revealed that yield loss under very severe category was very larger in comparison to the loss under slight category.

Among cereal crops, wheat yield loss due to wind erosion varied from 4 kg ha^{-1} yr^{-1} under slight wind erosion to 236 kg ha^{-1} yr^{-1} under very severe category. Similarly, yield loss of pearl millet grain due to wind erosion was 195 kg ha^{-1} yr^{-1} under very severe category and 3 kg ha^{-1} yr^{-1} under slight wind erosion category. As compared to these yield losses, loss of wheat and sorghum grain yield in the Great Plains of USA was reported as 0.8–118.3 kg ha^{-1} yr^{-1} in wheat-fallow rotation and 3.6–204 kg ha^{-1} yr^{-1} in wheat-sorghum-fallow rotation, respectively (Lyles, 1975; Lyles, 1977). Larney et al. (1995) reported an average loss of 11 kg ha^{-1} grain yield of spring wheat per 1 mm of topsoil loss for a simulated erosion study in Alberta. Among oilseed crops, yield reduction was higher for groundnut (5–331 kg ha^{-1} yr^{-1}) than mustard (2–100 kg ha^{-1} yr^{-1}). Among pulses, yield losses were higher for clusterbean (4–229 kg ha^{-1} yr^{-1}) than moth bean (1–93 kg ha^{-1} yr^{-1}). In a previous study by Poonia and Singh (2005) in India on the effect of wind erosion control technology on crop yield in Bikaner showed improvement in clusterbean yield from 208.5 kg ha^{-1} in bare plot to 348.5 kg ha^{-1} in controlled plot. The yield loss of clusterbean reported by this study found similar with the yield loss of clusterbean at severely affected areas (137 kg ha^{-1}) as calculated by the STCR approach in this study.

In this study, yield loss of wheat under very severe and severe wind erosion category was observed as 236 kg ha^{-1} yr^{-1} and 141 kg ha^{-1} yr^{-1} against an average soil loss rate of 5.27 mm yr^{-1} and 3.16 mm yr^{-1}, respectively. The effect of topsoil thickness on wheat yields at USA was reported as a yield reduction of 102 kg ha^{-1} per inch of topsoil (Lyles, 1975). Application of this relationship in western Rajasthan resulted in wheat yield loss of 22 kg ha^{-1} yr^{-1} and 13 kg ha^{-1} yr^{-1}, respectively under very severe and severe wind erosion category, which is lower than the loss calculated through STCR approach. Even, the estimated yield loss in western Rajasthan by applying the crop yield-soil loss relationship of 11 kg ha^{-1} per 1 mm topsoil removal as reported by Larney et al. (1995) also resulted in lower estimate in yield loss. Since these relationships between topsoil thickness and yield were developed at Great Plains USA or Alberta Canda, which are quite different in soil type, climate and crop varieties than the present study region in western Rajasthan India, it is difficult to apply these relationships in other regions of the world. However, the average yield loss of millet of about 172–422 kg ha^{-1} in Niger, West Africa as reported by Bielders et al. (1997) was found higher than the present study region.

The gap in productivity of selected crops in different wind severity categories were also calculated by comparing it with yield at negligibly affected areas as given in Table 6, which was considered as the reference yield for each crop. Simultaneously, yield loss in terms of percentage of the reference yield for each crop was also calculated. Both these data on productivity gap and yield loss due to wind erosion as calculated through STCR approach are presented in Fig. 6. It is clear from the figure that out of 82% productivity gap of pearl millet yield in very severely affected areas, 30% was contributed by wind erosion and rest was affected by other production factors in the region e.g. rainfall amount and distribution, temperature regimes, length and intensity of dry spells etc. It is also observed that the productivity gap followed the decreasing trend with decrease in wind erosion severity. The gap in productivity of pearl millet was 54% in slightly affected areas, out of which only 0.46% was contributed by wind erosion. Comparison of productivity gap and yield loss due to wind erosion for each crop revealed that cluster bean yield is mostly affected by wind erosion whereas, wheat and mustard yields are least affected.

Highest effect of wind erosion on crop productivity was observed on clusterbean followed by pearl millet. These two crops are mostly grown in the region as rainfed crop just after summer season from April to July during and during the summer period wind erosion process remains most active. The effect of wind erosion on crop yield was low for mustard and wheat crops, which are generally grown in the region as irrigated crop during winter season from November to March. Effect of irrigation masks the wind erosion effect on these two crops. The percentage reduction in crop yield due to wind erosion in western Rajasthan as stated above is comparable with yield reduction reported by Zobeck and Bilbro (2001). They reported 34% lower cotton boll weights and 40% lower lint weights in eroded areas than non-eroded areas from a controlled field experiment on wind erosion at Southern Great Plains of west Texas, USA. Fifty-eight per cent lower grain yield of grain sorghum in eroded areas than non-eroded areas was also reported by them. Larney et al. (1998) reported 11% reduction in canola (*Brassica* sp.) yield in eroded area as compared to deposited area. Therefore, it is quite clear that wind erosion causes a significant reduction in yield specifically in severe affected areas, which are often not visible. Moreover, due to the perceptible wind erosion hazards in very severely affected areas, farmers do not cultivate much in these degraded lands.

3.6. Validation of STCR approach for assessing yield loss due to wind erosion

The STCR approach of estimating crop yield loss due to wind erosion was further validated by comparing it with observed yield gap of the crop across different categories of wind erosion. It is noted here that the yield gap under a severity class was calculated by subtracting the average yield for that class from the average yield under negligibly affected areas. Calculated yield loss and the observed yield gap of four major crops are plotted in Fig. 7. Significant relation between calculated yield loss and observed yield gap was observed for all crops as indicated by higher R^2 value (0.89–0.99) of linear regression between them. It may be noted from these plots that slope of the regression line represents the contribution of wind erosion in yield gap across severity classes. For example, the slope was found 0.9 for pearl millet, which indicates a loss of 90 kg ha^{-1} due to wind erosion if the yield gap is 100 kg ha^{-1}. The slope was found low for mustard and wheat (0.15 and

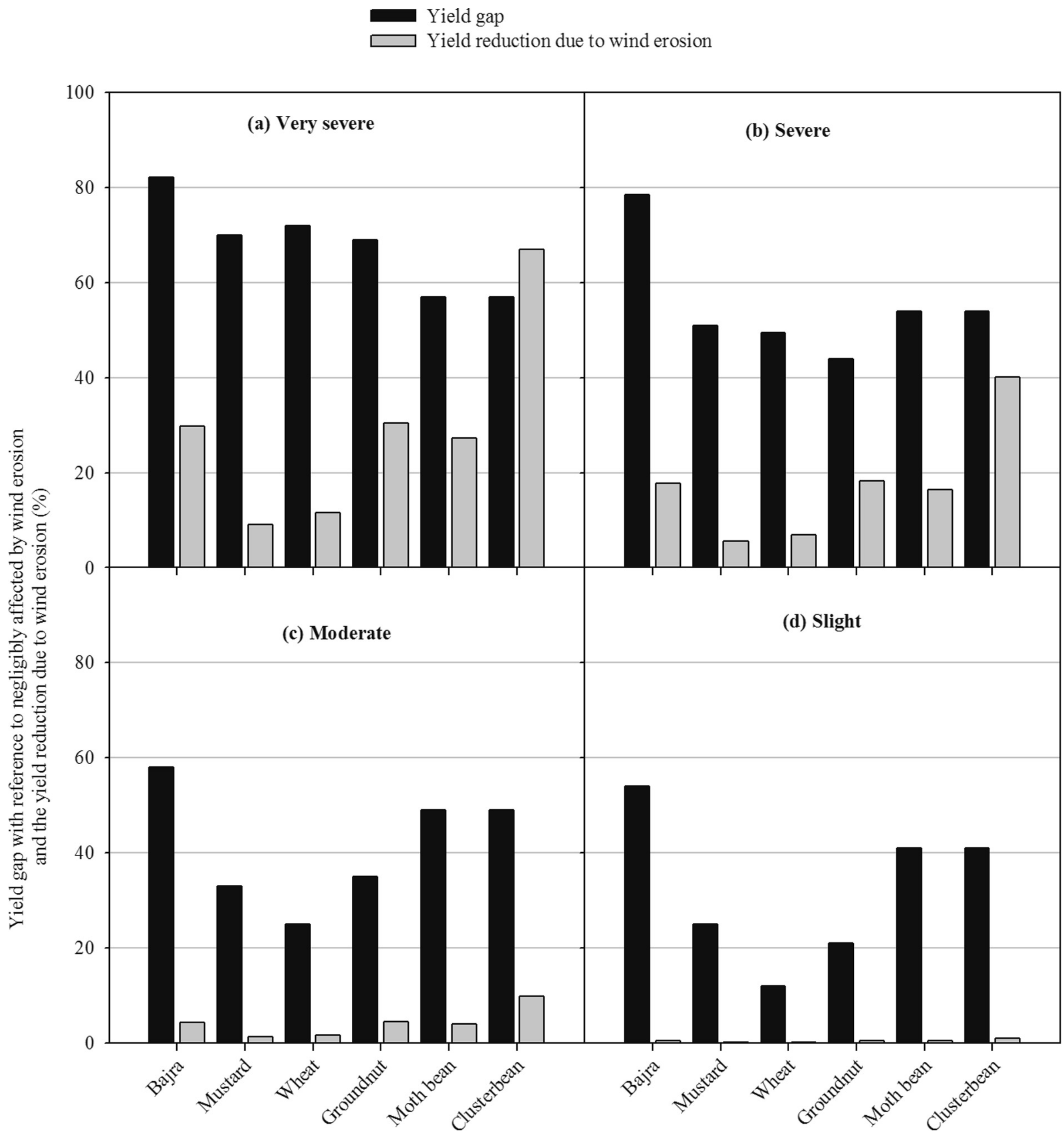

Fig. 6. Productivity gap and yield loss in different categories of wind erosion affected areas as compared to areas with negligible effect of wind erosion in western Rajasthan.

0.19) as these are irrigated crops and grown during winter months from November to March. For groundnut, the slope is in between these values (0.65) because it is irrigated but cultivated during summer months of pre-*kharif* or *kharif* season.

3.7. Economic loss due to wind erosion

Economic loss of wind erosion on the basis of minimum support prices of recent years (2012–2014) is presented in Fig. 8. It is to be noted here that ₹ 1 is equivalent to 0.015 US $. It is very clear from the figure that for groundnut and cluster bean, the economic losses were higher and about ₹ 12241 ha^{-1} and ₹ 12465 ha^{-1}, respectively in very severely affected areas as compared to other crops. This is because the price of these two commodities in market was quite higher than rest crop produces. With decrease in severity, the economic loss also decreased. In slightly affected areas, the economic loss was lowest for pearl millet (₹ 36 ha^{-1}) and highest for clusterbean (₹ 194 ha^{-1}). For mustard, wheat and groundnut, the economic loss in very severely affected areas ranged from ₹ 2986 ha^{-1} to ₹ 3500 ha^{-1}, whereas in slightly affected areas it ranged from ₹ 47 ha^{-1} to ₹ 55 ha^{-1}. The economic loss was lowest for pearl millet in each severity category and was ₹ 2294 ha^{-1}, ₹ 1376 ha^{-1}, ₹ 336 ha^{-1} and ₹ 36 ha^{-1}, respectively in very severe, severe, moderate and slightly affected areas. Considering the recent five year average acreage of the crops in western Rajasthan and the average economic loss per hectare for a particular crop, about ₹ 25.6 billion total economic loss was estimated per year for the selected six crops (see Fig. 8). The loss was highest for clusterbean, which was about ₹ 15.09 billion per year. It was followed by pearl millet with an economic loss of ₹ 3.98 billion per year. Lowest loss was estimated for groundnut (0.99 billion per year) because it has been cultivated in scattered areas in arid zone of western Rajasthan, where intensive irrigation source is available. For moth bean, mustard and wheat, total economic losses were found ₹ 2.00 billion, ₹ 1.27 billion and ₹ 1.27 billion per year, respectively.

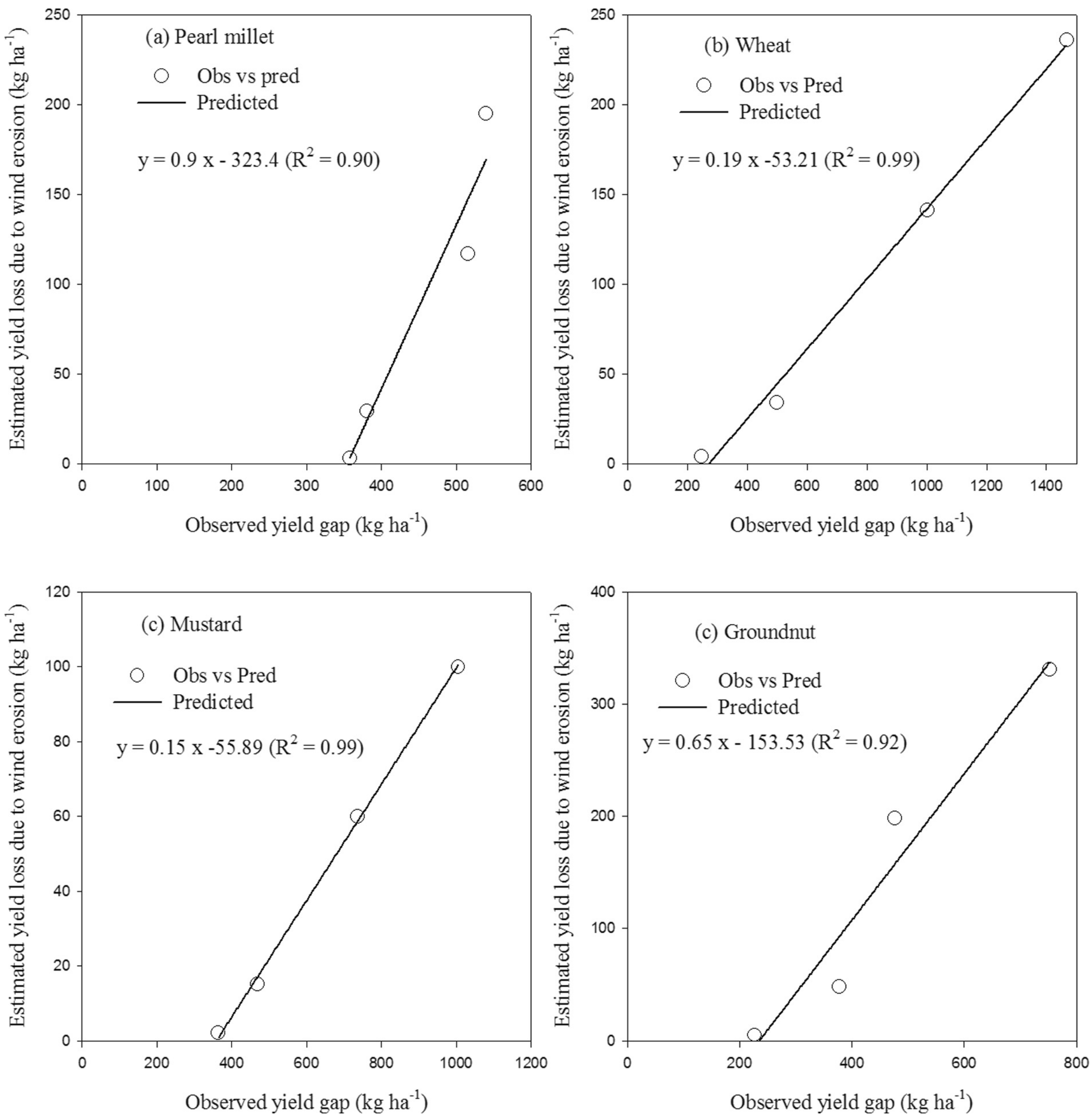

Fig. 7. Observed yield gap and estimated yield loss due to wind erosion for selected crops in western Rajasthan.

4. Conclusion

Crop production losses and corresponding economic losses due to wind erosion in western Rajasthan have been calculated in this study through STCR approach. It has been found that the yield gap of major crops at very severely affected areas varied from 57 to 82%, of which about 9–67% was contributed by wind erosion. The STCR approach was further validated with observed crop productivity data of selected crops across different wind erosion severity categories. The contribution of wind erosion to total yield gap was found highest for pearl millet and lowest for wheat and mustard. Yield reduction due to wind erosion was found 195 kg ha^{-1} yr^{-1} for pearl millet in very severe affected areas whereas for moth bean and cluster bean it was 93 kg ha^{-1} yr^{-1} and 229 kg ha^{-1} yr^{-1}, respectively. Soil loss rate in very severe wind erosion category was observed as 5.27 mm yr^{-1} whereas in severe category it was 3.16 mm yr^{-1}. Economic loss due to wind erosion depends both on the magnitude of yield loss and minimum support price of the particular crop. For example, economic loss was observed minimum for pearl millet (₹ 2294 ha^{-1}) although the yield loss was higher for pearl millet than other crops. This is because of the low support price for pearl millet in comparison to other crops. Economic losses were observed higher for groundnut (₹ 12241 ha^{-1}) and clusterbean (₹ 12465 ha^{-1}) because of its high support price. Here, it is to be noted that the yield loss in this study has been estimated based on the loss of nutrients through erosion process. Considering the direct damages of wind erosion on crops, e.g. abrasion actions of blown sands, deposition of fine dust particles on leaf surface and thus affecting photosynthesis or complete / partial burial of crop stands etc, the above estimated yield loss may be higher than reported here. However, to quantify these direct damages of wind erosion, field experiments at selected locations are required to be carried out.

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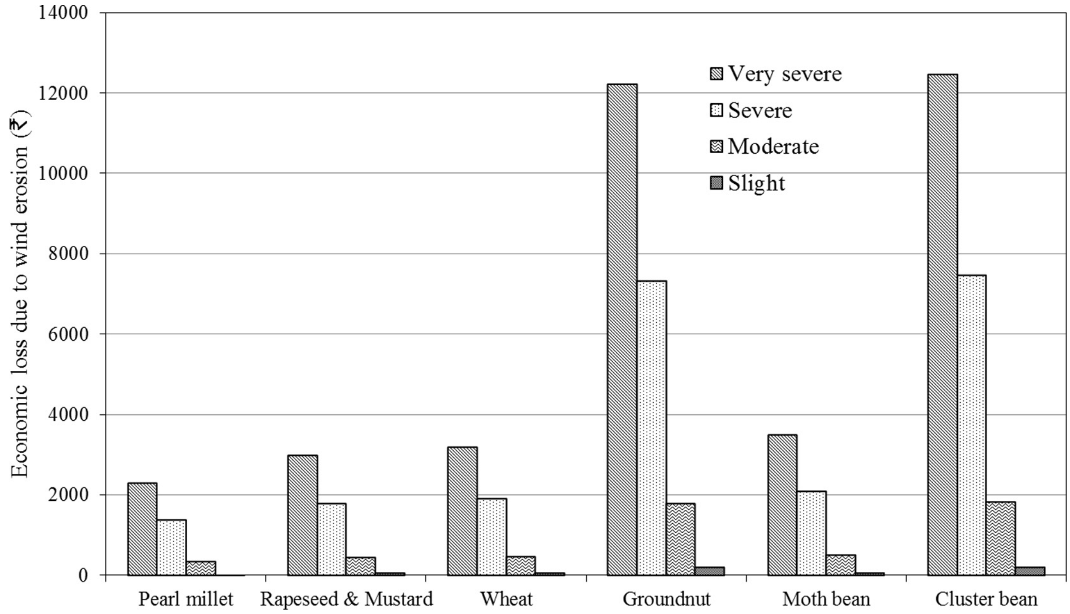

Fig. 8. Economic loss due to wind erosion through loss of crop yield (₹ 1 = 0.015 US $).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aeolia.2017.07.009. These data include Google maps of the most important areas described in this article.

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