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Assessment and Mapping of Wind Erodibility of Aridisols and Entisols in the Red Sea State, Sudan[*]

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Abstract: Wind erodibility of a soil (WE) is a major indicator of its susceptibility to wind erosion under a given climatic condition. This study is part of a national project for assessing and mapping wind erodibility of soils in Sudan. It was undertaken to generate WE data for the Red Sea State. Three replicate surface soil samples were collected, randomly, from twenty-eight geo-referenced farms spread in the State. Non-erodible soil particles (NEP>0.84mm) and selected soil properties were measured using standard procedures. The mean NEP values ranged from 17.0% to 57.2% with an overall mean coefficient of variation of replicate determinations equal to 4.7%. The equivalent WE ranged from 49.6 to 244.0 ton/ha. The results showed a highly significant ($P<0.001$) increase of NEP with increase of clay (C) and organic matter (OM), and decrease with increase of sand and sand plus silt (S+Si) expressed, successively, as ratios of clay, clay plus OM and clay plus $CaCO_3$. The reverse trends were obtained for the relations of WE and the various soil properties and their ratios. Clay, (Si+S)/C, (Si+S)/(C+OM) and (Si+S)/(C+$CaCO_3$) accounted for 80%, 81%, 81% and 82% of the variation of NEP, and 77%, 78%, 78%, and 79% of the variation of WE. Multiple regressions relationships of NEP or WE with clay, sand, $CaCO_3$ and OM gave coefficients of determinations equal to 81% and 80%, respectively. Thus, it was recommended that clay, (Si+S)/C, (C+OM), (C+$CaCO_3$) or multiple regression equations may be used for predicting NEP. However, (Si+S)/(C+$CaCO_3$) is recommended for predicting NEP, and in all cases the equivalent WE can be obtained from the standard table. A table for wind erodibility groups was developed for the State.

Key words: Soil erodibility; wind erosion; Red Sea State

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INTRODUCTION

The Red Sea State lies between latitudes 17º and 24º N and longitudes 33º and 39º E. It has an area of about 212 490 km^2. The most important land forms of the State are the coastal plain, the Red Sea Hills and the plateau stretching west of the hills. The coastal plain, between the sea and the hills, is a narrow strip, 20-30 km wide. The hills are intersected by seasonal watercourses draining east into the sea and west into the Nile. The agro-climatic zones of the State vary from desert to arid with a mean annual rainfall of less than 300 mm, which is highly variable. The mean annual rainfall of the coast ranges from 36 mm at Halaib to 164 mm at Suakin, with an overall mean of 111 mm The mean annual temperature is 30°C, and may reach ≥ 46°C at Port Sudan in July-August, in spite of the moderating effects of the Red Sea. Sandy and alluvial soils are found near the coast and in the alluvial plains and valleys and rocky soils in the hilltops and steep slopes. Near the sea coast the soils are saline and its salinity decreases with distance away from the coast (El-Wakeel 2007; Mohamed and Zahran 2010; Ahmed and Mustafa 2010). Sustainable biological production in the State is constrained by two desertification processes; namely, salinization and wind erosion.

Wind erosion depends on two main factors; namely, soil erodibility, referred to hereafter as wind erodibility of soil, and wind erosivity. The former is an indicator of the susceptibility of the soil mass to detachment into individual soil particles, and the latter is an indicator of the erosive energy of the wind to cause transport of the soil particles. Wind erodibility of soil (WE), as a major indicator of wind erosion, was used for the prediction of wind erosion by the soil loss equation (Woodruff and Siddoway 1965). In general, wind erodibility depends on many factors such as topographic position, slope steepness and soil management that cause detachment of the soil mass, e.g. tillage, but the most important factors are the soil properties (Morgan 1995). Previous research showed that WE was affected by, *inter alia*, particle-size distribution, structural stability, organic matter content, nature of clay minerals and chemical constituents (Harris *et al*. 1966; Lyles and Tatarko 1968; Wishmeier and

Mannering 1969; Romken *et al.* 1977; Black and Chanasyk 1989; Medani and Mustafa 2003; Mustafa and Medani 2004).

Soil texture has the major impact on WE because it affects both the detachment and transport phases of the process. Under a given climatic zone, wind erodibility of soil is the main determinant of wind erosion. It is a good indicator for the prediction, assessment and mapping of wind erosion. For quick assessment of wind erosion, the concept of wind erodibility groups (WEGs) that classifies soils according to WE was proposed (Chepil and Woodruff 1963; Hayes 1965; Black and Chanasyk 1989).

A national project was developed to assess and map WE in Sudan. Since Sudan is a large country, the project was implemented State-wise to facilitate its use for wind erosion control in the studied States. The present research was undertaken in the Red Sea State. Its specific objectives are (i) estimation of WE of soil samples selected from different locations spread in the State, (ii) identification of appropriate soil indicators for WE, (iii) establishment of wind WEGs for the State and (iv) mapping of wind erodibility classes.

MATERIALS AND METHODS

Three replicate surface (0-3 cm) soil samples (1.0-1.5 kg) were collected at random from each of twenty eight small irrigated farms and traditional cultivation lands spread in the Red Sea State, starting from 17°36'N and 38°07'E and ending at 20°17'N and 35º49'E. The farms were geo-referenced using a GPS. The samples were carefully saved in bags to avoid fragmentation of natural aggregates. They were air-dried and stones and straw, if present, were removed. Wind erodibility of a soil was assessed by the dry-sieving method proposed by Chepil and Woodruff (1959). One kilogramme of each sample was sieved through 0.84 mm sieve, and the percentage of particles greater than 0.84, referred to hereafter as non-erodible soil particles (NEP), was obtained. A standard table developed by Woodruff and Siddoway (1965) was used to estimate

WE. The soil samples were‘ then, crushed, passed through 2-mm sieve and saved for physical and chemical analysis. Soil particle-size distribution was measured by the hydrometer method (Black *et al.* 1965) and the texture class of each sample was identified using USDA texture triangle. Saturated soil paste was prepared for each sample and the pH of the soil paste was measured. The electrical conductivity of the saturation extract (ECe) was determined using a conductivity metre. Calcium carbonate content was measured using a calcimeter. Calcium and magnesium were determined by titration against EDTA according to the method described by Chapman and Pratt (1961). Organic carbon was assessed by the dry-ashing method, proposed by Fredrick as reported by Ibrahim (1991), and organic matter (OM) was calculated. Sodium was determined using a flame photometer, and sodium adsorption ratio was calculated by the following equation: $SAR = [Na^{+}]/\sqrt{\{[Ca^{+2}+Mg^{+2}]/2\}}$, where the ionic concentrations were expressed in me/l.

The mean percentage of NEP values of each texture class was calculated and a table of WEGs was presented. Simple statistical parameters and the equations of trend lines were obtained using Microsoft Excel package. GIS was used to map the spatial variation of WE in the Red Sea State, Sudan.

RESULTS AND DISCUSSION

The mean clay percent of the soil samples ranged from 21.3% to 60.9% with an overall mean coefficient of variation of replicate measurements of each field (CVr) equal to 2.3%. The mean silt percentage ranged from 7.9% to 38.1% with a CVr equal to 2.9%. The mean sand percentage ranged from 11.0% to 68.0% with a CVr equal to 2.2%. The very low CVr values reflect a very high precision of replicate measurements of the three particle-size fractions. These primary particles are durable and not susceptible to significant change by management. Twelve of the surface soil samples were sandy clay loam, ten were clay, four were sandy clay, one was sandy loam and another one was clay loam.

The mean $CaCO_3$ percentage ranged from1.3% to 4.8% with a CVr equal to 2%. This compound is slightly soluble and relatively durable, and this explains why it has a very low spatial variation indicative of precision of replicate measurements.

The mean organic matter percentage in these arid-zone soils is low ranging from 0.05% to 0.68 with a CVr equal to 7.1%. The moderate spatial variation may be explained by the fact that OM is greatly affected by non-uniform soil and plant residue management.

The mean ECe values ranged from 0.3 to 26.1 dS/m with a CVr equal to 15.5%. The mean SAR values ranged from 0.5 to 40.0 $(me/l)^{1/2}$ with a CVr equal to 16.9%. The relatively high CVr values are due to the inherent high spatial variation of salts, which is profoundly affected by interactive effects of land micro-relief and natural and artificial field water management (Ibrahim and Mustafa 2001).

The mean NEP values ranged from 17.0% to 57.2% with a CVr equal to 4.7%. The CVr values are low because NEP is constituted from durable primary soil particles. The equivalent WE ranged from 49.6 to 244.0 ton/ha.

Relationships between NEP and soil properties

The data show a highly significant ($P<0.001$) linear increase of NEP with increase of clay ($r=0.8944$) and OM ($r=0.6184$), and quadratic decrease with increase of sand ($r=-0.8097$) (Table 1). They also show significant logarithmic ($P=0.05$) increase of NEP with increase in ECe ($r=0.3784$, $P<0.05$) and SAR ($r=0.4598$, $P<0.05$). Both the clay platelets or domains and derivatives of organic matter acted as cementing agents, promoted soil aggregation and consequently increased NEP. Salts indicated by ECe promoted clay flocculation and hence promoted aggregation and increased NEP. The effect of SAR was an indirect effect of ECe because SAR was expected to cause dispersion. This was evidenced by the highly significant ($r=0.9684$) linear increase of SAR with increase of ECe. The results also gave a non-significant quadratic increase of NEP with increase of $CaCO_3$. The effect of silt was not significant. Sand, being inert, had a dilution effect on the impact of the cementing agents and hence reduced NEP. Clay, sand, OM, ECe and SAR accounted for 80%, 66%, 38%, 14% and 21% of variation of NEP, indicating the overriding impact of clay. However, the lack of perfect accountability in the case of clay and other soil properties may be attributed to the interactive effects of variables other than the one in question. This is an inherent limitation of regression analysis when other variables are not separated.

Table 1. Parameters of trend lines showing the relationships between non-erodible soil particles (NEP, %) or wind erodibility of soil (WE, ton/ha) as a function of some soil properties

Property (%)	Trend line #	a	b	c	r^2	r*
			NEP			
Clay	Linear	1.157	-7.4980	-	0.8001	0.8944
Sand	Quad.	-0.011	0.1800	53.480	0.6556	-0.8097
OM	Log.	9.439	55.8280	-	0.3824	0.6184
ECe	Log.	3.788	34.3750	-	0.1432	0.3784
SAR	Log.	4.050	32.2590	-	0.2114	0.4598
			WE			
Clay	Linear	5.324	343.8500	-	0.7733	-0.8794
Sand	Quad.	0.057	-1.3659	69.341	0.6874	0.8291
OM	Log.	-42.185	55.0720	-	0.3486	-0.5904
ECe	Log.	-15.802	150.4600	-	0.1138	-0.3374
SAR	Log.	-17.826	160.1600	-	0.1869	-0.4323

Trend lines: Linear: $Y = aX + b$; Quad. (Quadratic): $Y = aX^2 + bX + c$; Log. (Logarithmic): $Y = a \ln X + b$

* Level of significance: $r_{0.05} = 0.3746$; $r_{0.01} = 0.4793$; $r_{0.001} = 0.5887$

Attempts were made to correlate NEP with compound indicators that express non-cementing agents as a ratio of cementing/flocculating agents (Abdelwahab *et al*. 2009). Fig. 1 shows highly significant quadratic decrease in NEP with increase of (Si+S)/ C, (Si+S)/ (C+OM) and (Si+S)/(C+$CaCO_3$). The three successive compound indicators accounted for 81%, 81% and 82% of the variation of NEP. It is evident that these compound indictors slightly improved the accountability of clay alone. Thus, for this State clay or (Si+S)/(C+$CaCO_3$) ratio may be used as indicators of NEP. However, we recommend the use of the compound indicator because it incorporates the three primary particles and the slightly soluble $CaCO_3$. The use of $CaCO_3$ is in agreement with the criteria used for delineating WEGs (Black and Chanasyk 1989). This agrees with the conclusion of Abd Elwahab *et al.* (2009) for the Northern State and Hassan and Mustafa (2011) for the Nile State.

Regression analysis yielded a highly significant ($P<0.001$, $R=0.9001$) correlation between NEP and multiple soil variables as shown in the following empirical relationship:

$$NEP = - 6.06 + 1.10\ clay\% - 0.67\ sand\ \% - 2.68\ OM\% + 1.23\ CaCO_3\%$$

According to this relationship, the four soil properties account for 81% of the variation of NEP. The negative sign of the coefficient of OM may be attributed to the empiricism of the equation. It is evident that clay alone or the compound indicators gave nearly similar accountability as the four properties expressed in this relationship.

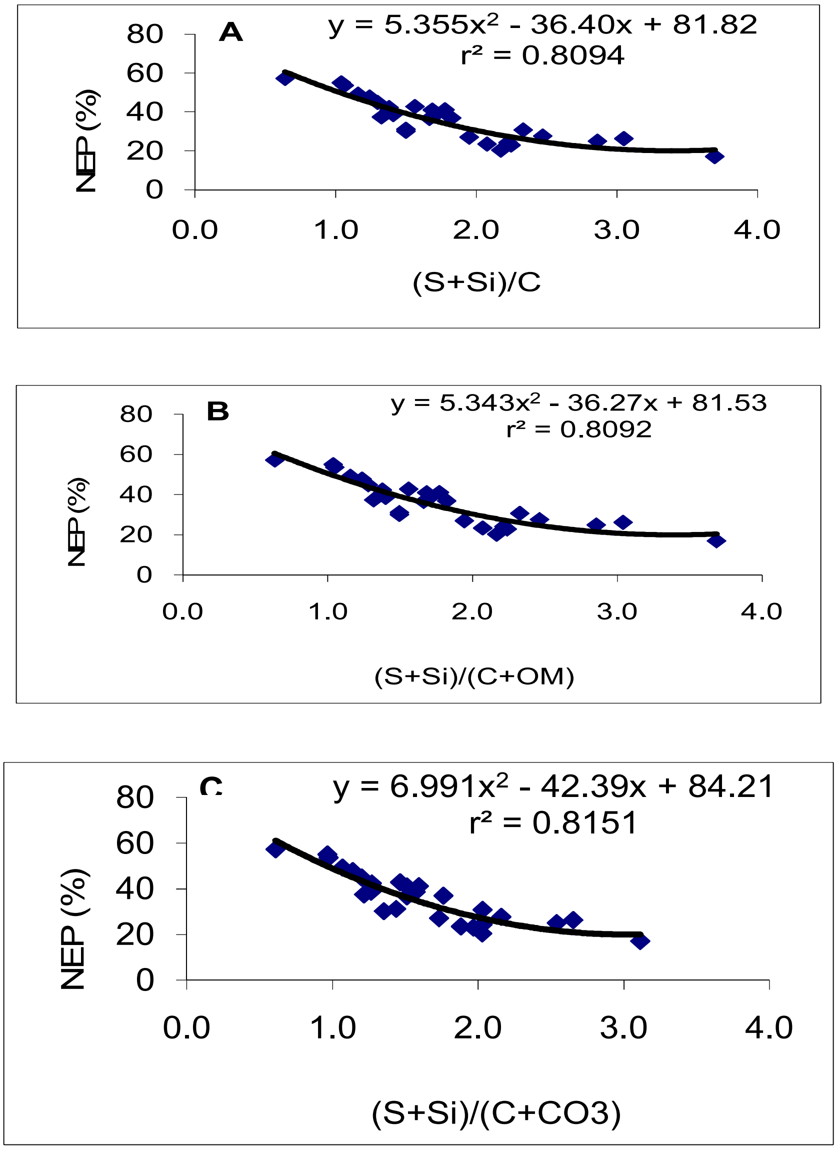


Figure 1. Non-erodible soil particles (NEP) as a function of (A) (Si+S)/C (B) (Si+S)/(C+OM) and (C) (Si+S)/(C+CO_3)

Relationships between WE and soil properties

The results show highly significant ($P<0.001$) decrease in WE with increase of clay ($r=-0.8794$), and OM ($r=-0.5904$) and increase with increase of sand ($r=0.8291$) (Table 1). These single soil properties, in sequence, accounted for approximately 77%, 35%, and 69% of the variation of WE. The soil properties that promoted aggregation and increased NEP reduced WE and *vice versa*. Both ECe and SAR reduced WE, but the effect was not significant for ECe, but significant for SAR ($r=-0.4323$) with very low accountability for the variation of WE.

Fig. 2 shows highly significant quadratic increase in WE with increase of (Si+S)/C, (Si+S)/(C+OM) and (Si+S)/(C+$CaCO_3$). The three successive compound indicators accounted for 78%, 78% and 79% of the variation of WE. The results were nearly similar to those obtained for NEP. However, the accountability of the compound indicators for the variation of WE were slightly lower than that for NEP, because determination of WE included the additional error inherent in the standard table. In view of the lower accountability, it is recommended to predict NEP from knowledge of clay percentage or (Si+S)/(C+$CaCO_3$) and then read the equivalent WE from the standard table.

Regression analysis yielded a highly significant ($P<0.001$, $R=0.8918$) correlation between WE and multiple soil properties as shown in the following empirical relationship:

$$WE = 318.48 - 4.92\ clay\% + 0.62\ sand\% + 31.02\ OM\% - 6.73\ CaCO_3\%$$

The four soil properties accounted for 80% of the variation of WE. This level of accountability was similar to those given by clay alone or (Si+S)/(C+$CaCO_3$).

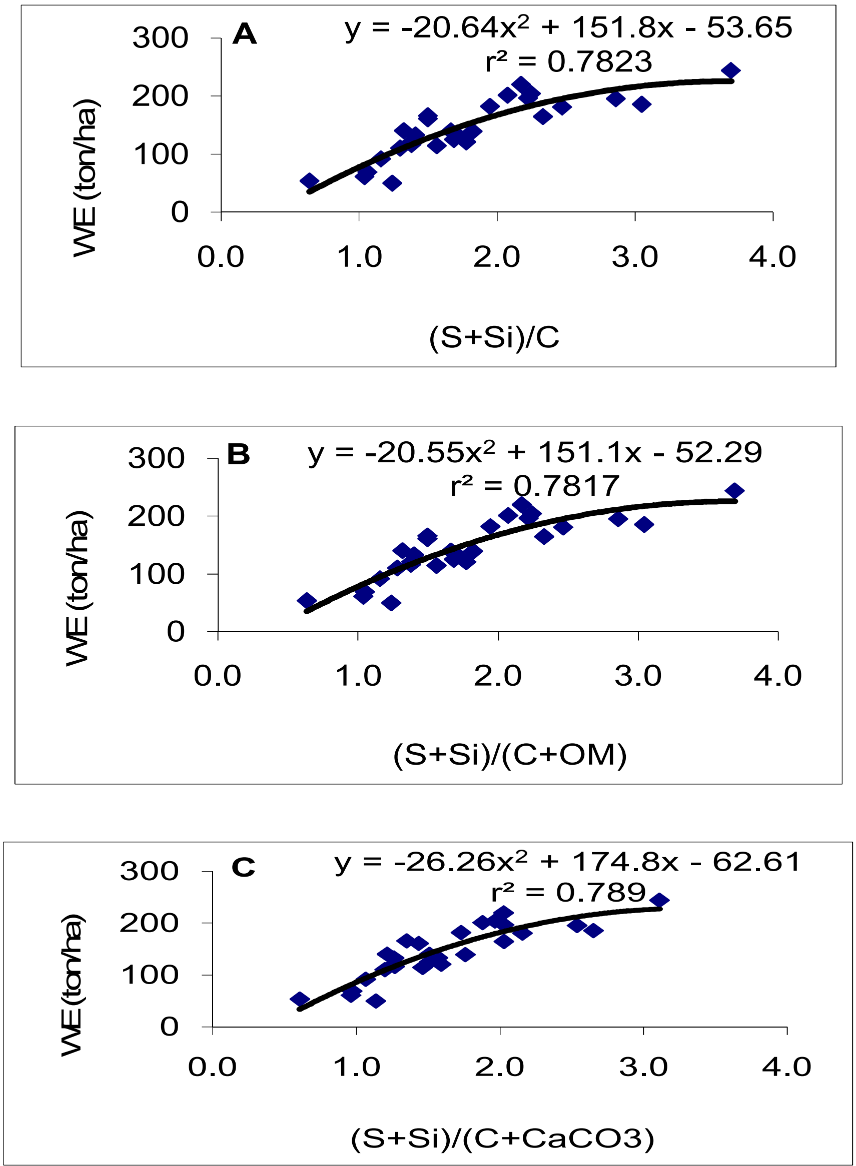


Figure 2. Wind erodibilityof soil (WE) as a function of (A) (Si+S)/C (B) (Si+S)/(C+OM) and (C) (Si+S)/(C+CO_3)

Wind erodibility groups

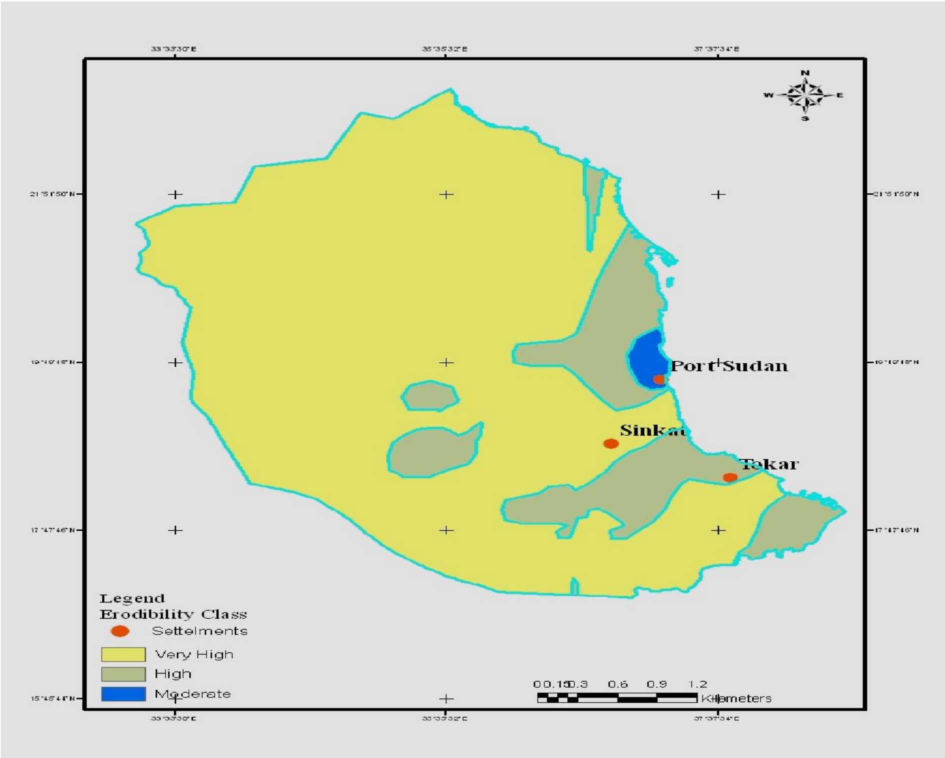
Table 2 shows that the NEP of the WEGs of the studied soil samples gave significant simple linear correlation coefficient with those of N. Dakota (r= 0.9248) and Khartoum (r=0.8244).

Mapping of wind erodibility

The studied soil samples were classified according to their WE values. Four classes were delineated according to the following WE class limits: <76 ton/ha (moderate), 76-140 ton/ha (high), 140-278 ton/ha (very high). The spatial variation of WE was mapped according to GIS (Map1)

Table 2. The mean percentage of measured non-erodible soil particles (NEP) for the various wind erodibility groups (WEG) compared with equivalent values obtained from N.Dakota and Khartoum State

WEG	No. of samples	NEP		
		Measured	N. Dakota	Khartoum
Clay	9	47.6	60.8	77.3
Clay loam	1	36.9	45.0	63.8
Sandy clay	5	36.2	40.0	-
Sandy clay loam	12	28.1	40.0	55.2
Sandy loam	1	26.2	25.0	45.3
Correlation coefficient			0.9248	0.8244



Map 1. The classes of wind erodibility of soils in the Red Sea State

CONCLUSIONS AND RECOMMENDATION

1. NEP of a soil from the Red Sea State may be predicted from knowledge of clay using the following equation:
   NEP% = 1.157 Clay% - 7.498 (r^2 = 0.800)
2. NEP may also be predicted from knowledge of (Si+S)/C, (Si+S)/ (C+OM) or (Si+S)/ ($C+CO_3$), using the relevant empirical relationship.
3. WE may be predicted from the multiple regression equation.
4. WE should be looked out from the standard table from predicted NEP values.

5. The use of compound indicator $(Si+S)/(C+CO_3)$ is recommended, because it proved to be the best indicator for other States and because $CaCO_3$ was incorporated in the criteria used for delineating WEGs in some other countries.
6. For quick assessment, the wind erodibility groups or the erodibility map may be used.

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تقدير وتخريط تعريية الرياح لترب الأريديسولز والإنتيسولز في ولاية البحر الأحمر ، السودان*

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المستخلص: تعتبر تعريية الرياح المؤشر الرئيسي لقابلية التربة للتعرية الريحية تحت ظروف مناخية معينة . يكوّن هذا البحث جزءاً من مشروع وطني صمم لتقدير وتخريط تعريية الرياح فى السودان ، ويهدف لجمع بيانات تعريية الرياح لولاية البحر الأحمر . جمعت ثلاثة مكررات لعينات تربة سطحية عشوائيا من ثمانية وعشرون مزرعة ، منتشرة فى مختلف أنحاء الولاية ، وحدد موقع كل منها باستخدام نظام المعلومات الجغرافية . تم قياس حبيبات التربة غير القابلة للتعرية (قطرها> 0.84 مم) وبعض خواص التربة الأخرى بإستخدام طرق تحليل التربة القياسية . تراوحت نسب الحبيبات غير القابلة للتعرية بين 17% و 57.2% وبمتوسط نسبة معامل تباين لقيم مكررات القياس يساوي 4.7%، كما تراوحت قيم تعريية الرياح المكافئة بين 49.6 و 244.0 طن/هـ. أوضحت النتائج زيادة معنوية عالية (P<0.001) للحبيبات غير القابلة للتعرية نتيجة لزيادة النسبة المئوية لكل من الطين والمادة العضوية ، كما دلت النتائج على انخفاض هذه الحبيبات نتيجة لزيادة نسبة الرمل أو نسبة (السلت+الرمل)/ الطين أو نسبة (السلت+الرمل)/ (الطين+المادة العضوية) أو نسبة (السلت+الرمل)/ (الطين + كربونات الكالسيوم) . وأعطت خواص التربة الأساسية ونسبها علاقات عكسية مع تعريية الرياح . ودلت النسبة المئوية للطين ونسبة (السلت+الرمل)/ الطين ونسبة (السلت+الرمل)/ (الطين+المادة العضوية) ونسبة (السلت + الرمل)/ (الطين+كربونات الكالسيوم) على 80%

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و81% و 81% و 82% على التوالى من تباين الحبيبات غير القابلة للتعرية . كما دلت على 77% و 78% و 78% و79% من تباين تعريية الرياح . كما أعطت علاقة الانحدار متعددة المتغيرات بين الحبيبات غير القابلة للتعرية أوتعريية الرياح وخواص التربة الأربع الأساسية معامل تقدير يساوي 81% و80% ، على التوالي . لذلك تدل نتائج هذه الدراسة على إمكانية استخدام محتوى النسبة المئوية للطين أو نسب (السلت+الرمل)/ الطين أو (السلت+الرمل)/ (الطين+المادة العضوية) أو (السلت+الرمل)/ (الطين+كربونات الكالسيوم) أو المعادلة متعددة المتغيرات للتنبؤ بنسبة الحبيبات غير القابلة للتعرية. ولكن توصي الدراسة باستخدام نسبة (السلت+الرمل)/ (الطين+كربونات الكالسيوم) للتنبؤ بنسبة الحبيبات ومن ثم تستخرج كمية تعريية الرياح المكافئة من الجدول القياسي . ولقد تم تحضير جدول لمجموعات تعريية التربة .