Catena 187 (2020) 104388

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

A review of wind erosion models: Data requirements, processes, and validity

Mahboube Jarrah[a,*], Sonia Mayel[a], John Tatarko[b], Roger Funk[c], Katrin Kuka[a]

[a] Julius Kuehn Institute (JKI), Federal Research Centre for Cultivated Plants, Institute for Crop and Soil Science, Bundesallee 58, D-38116 Braunschweig, Germany
[b] USDA-ARS Rangeland Resources and Systems Research Unit, Fort Collins, CO 80526, USA
[c] Leibniz-Centre for Agricultural Landscape Research (ZALF), Institute of Soil Landscape Research, Eberswalder Str. 84, D-15374 Müncheberg, Germany

ARTICLE INFO

Keywords:
Wind erosion models
Model validity
Model database
Mechanisms of wind erosion

ABSTRACT

Wind erosion is a threat for numerous landscapes throughout the world, which can be promoted or suppressed by direct and indirect impacts. In recent years, great efforts have been made to determine magnitudes of wind-induced soil erosion under different environmental conditions and management practices. With the advent of wind erosion models, a better understanding of the dynamics and underlying mechanisms of wind erosion provides the basis for assessing not only soil erodibility, but also different conservation management practices with the aim of controlling soil erosion by wind. Different wind erosion models exist with varying degrees of complexity and specific capabilities as well as a range of spatial and temporal scales of application. Due to their uncertainties and limitations, their applicability to different regions and research questions is still under debate. This paper reviews several commonly used wind erosion models to compare the underlying concepts of wind erosion dynamics and provides some guidelines with respect to the models' applicability, expected validity, required databases, available outputs and future directions of modelling research.

1. Introduction

Over the past centuries, more than one third of the Earth's land surface has been faced with wind erosion, which is a natural process that mostly occurs under dry conditions and high wind velocity or on bare soils when plant biomass is sparse (Weinan and Fryrear, 1996). Anthropogenic pressures such as over-harvesting vegetation, monoculture systems, deforestation, overgrazing rangelands, abandoning farmland, or leaving cultivated lands fallow for a long time, accelerates the rates of soil loss (Chen et al., 2014; He et al., 2006).

Wind erosion is the movement of coarse and fine particles by wind across a landscape via different mechanisms whereby they enter the atmosphere, and subsequently are dispersed across the Earth's surface. The effect of released particles on the environment depends on the composition and size of the particles as well as the duration of their aerial trajectory, which may cause concern, both on-site and off-site (Goossens and Riksen, 2004).

Wind erosion is controlled by a set of factors such as wind force, soil wetness, surface roughness, soil texture and aggregation, soil organic matter, agricultural activities, vegetation cover, and field size (Bagnold, 1943; Chepil, 1945a; b; c; Chepil and Woodruff, 1963). Impacts and interrelationships of these factors are considered when assessing the rates of wind erosion (Blanco-Canqui and Lal, 2008b; Doetterl et al., 2016). Furthermore, the degree of soil aggregation and soil stability are indicators for evaluating the soil's susceptibility to wind erosion (Tatarko, 2001).

Measuring wind erosion can improve our insights into the mechanisms of the process, the assessment of the environmental effect of wind erosion, predicting its occurrence, and evaluation of conservation practices. Beginning in the 1940's, field and laboratory studies assessed the effect of individual factors on wind erosion (Fryrear et al., 1999), but due to the complex interactions of physical processes and human-environmental factors, monitoring these processes caused difficulties.

Wind erosion models are often employed, accompanied by field and laboratory measurements, to consider the influence of different wind erosion factors simultaneously. These models can provide varying levels of detailed information on wind erosion and soil particle movement at specific temporal and spatial scales (Bhuyan et al., 2002; Boardman and Poesen, 2006). Such essential knowledge can help land managers monitor and forecast how contributing factors affect wind erosion as well as for the implementation of conservation policies (Bhuyan et al., 2002). Wind erosion models vary in complexity, input data required, and model outputs generated. Therefore, model appropriateness depends on the objectives of the model users (Merritt et al., 2003). Additionally, other factors such as data requirements, model accuracy and validity, components of the model, and the required hardware can

* Corresponding author.
E-mail address: mahboube.jarrah@julius-kuehn.de (M. Jarrah).

https://doi.org/10.1016/j.catena.2019.104388
Received 22 March 2019; Received in revised form 30 October 2019; Accepted 21 November 2019

affect the choice of a model for a specific purpose. Every erosion model has limitations which cause a level of uncertainty in accuracy of the predicted results. Although initial wind erosion models suffered from a set of limitations and uncertainties including high input data requirements, unrealistic underlying assumptions, and inadequate test validation in different regions, these model approaches have been extended to provide more accurate estimates of wind-induced soil erosion and to suggest control managements.

Since the turn of the present century, the number of published papers on wind erosion models has increased considerably throughout the world (Stout et al., 2009). Therefore, it is a valuable effort to pool all these achievements and draw a review to comprehensively compare different aspects of models. This review evaluates some widely used wind erosion models with the following specific objectives:

(1) To describe model requirements, model components and basic approaches behind different types of wind erosion models;
(2) To investigate the specific ability, accuracy and limitation of each model for assessing wind erosion;
(3) To compare three main aspects of models, including validation/region, required input data, and representation of erosion processes; and
(4) To identify future research needs based on deficiencies in current approaches.

2. Wind erosion processes

Although soil wind erosion processes have been previously described in the literature, this section introduces the mechanisms and concepts used in a set of widely used models based on two standard descriptions by Lyles (1988) and Stallings (1951). Wind erosion consists of three distinct phases: (1) initiation of the soil particle movement (detachment or deflation), (2) soil particle transportation (suspension, saltation and surface creep), and (3) deposition of soil particles.

2.1. Initiation of soil particle movement

Wind forces exerted against the surface of the ground initiate soil movement, which is closely related to soil type and surface condition. The quantity of soil movement depends on the particle size, the cloddiness of particles, aerodynamic roughness, and wind velocity itself (Chepil and Woodruff, 1963). Threshold velocity is the minimum velocity required to initiate soil particle movement. For example, at 15 cm above the ground, the threshold velocity is 12–14 m per hour for small grains of soil, ranging between 0.1 and 0.15 mm in diameter (Stallings, 1951). The erosive force of wind causes detachment of fine soil grains from soil surfaces. When these particles are lifted by wind, and subsequently impact the surface, they may cause more grains to dislodge from soil aggregates (Shao, 2008).

2.2. Transport

Sediment transport occurs when soil particles are lifted by airflow and moved along at various heights above the surface of the ground, often colliding with other particles (Cheng et al., 2017). Depending on the size and weight of the soil particles, the energy required to loosen and transport particles varies, with stronger winds carrying heavier particles (Stallings, 1951). The eroded soil particles are moved along the surface through three different types of movement: surface creep, saltation, and suspension (Blanco-Canqui and Lal, 2008b; Cornelis, 2006; Hagen et al., 1999; Lyles, 1988) (Fig. 1).

2.2.1. Surface creep

Particles ranging from 0.5 mm to 1 mm in diameter are too large to be lifted and carried into the air, and thus are moved by the process of surface creep. In this process, the particles receive energy for transport

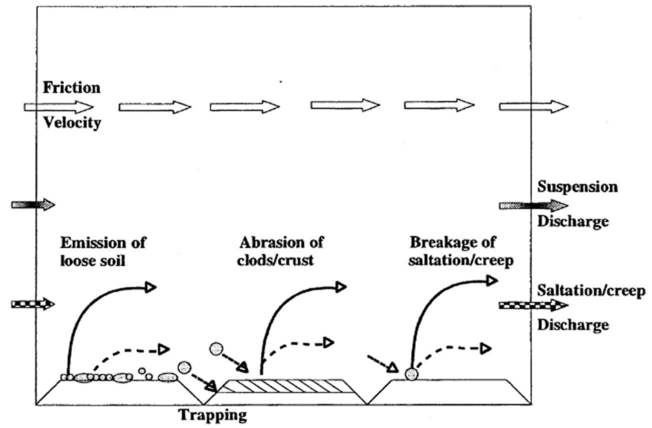

Fig. 1. Schematic of the phases of soil movement on bare soil (Dashed lines denote saltation/creep and solid lines denote suspension component.) (Hagen et al., 1999).

directly from the wind or from other particles striking the surface, as they move by saltation. Consequently, these particles creep or roll across the soil surface and can collide with or dislodge other particles (Stallings, 1951). This type of soil movement can transport soil only a few meters and contributes to loss and deposition within a localized area (Hagen et al., 1999; Lyles, 1988).

2.2.2. Saltation

A large proportion of middle-sized soil particles (0.1–0.5 mm in diameter) are transported by saltation in wind erosion (Lyles, 1988). Such particles are detached from the surface and emitted into the air, then drifted across the bed horizontally, but because of their weight they cannot be suspended (Stallings, 1951). The higher the grains jump, the more energy they derive from the wind. Because of this wind-derived energy, the impact of saltating grains initiates movement of larger grains and smaller dust particles that can be suspended in the air and carried great distances. Saltating grains collide with clods and cause their breakup, reducing roughness. Material carried in saltation can damage soil surface by breaking larger particles and crusts into smaller pieces. Saltation also damages young plants, threatening their survival and abrade vegetation cover as well (Lyles, 1988). Like particles under surface creep, saltating particles continue to move until the wind slows or they are trapped in sheltered areas.

2.2.3. Suspension

Suspension occurs when very fine dust particles (< 0.1 mm in diameter) such as very fine silt and clay particles and organic matter are lifted into the air through the effect of wind or other particles (Gillette, 1978; Gillette and Walker, 1977; Lyles, 1988). These particles can reach high altitudes and may stay in the atmosphere for a long time and travel long-distances until the wind velocity decreased or they are washed out by rainfall (Gillette, 1978). The finer sized suspension particles may cause health problems when inhaled. These particles are known as PM10, which are particulate matter of aerodynamic size less than 10 μm or smaller.

2.3. Deposition

Eventually the wind velocity decreases and soil particles are deposited. In-field deposition typically occurs in furrows or vegetated areas (Clow et al., 2016; Suter-Burri et al., 2013). Deposition also occurs along the edge of fields in ditches, fence rows, vegetation, or barriers such as windbreaks. For very fine particles, deposition may not occur until the particles have travelled hundreds or thousands of kilometers. As deposition continues, the original obstacle is buried with wind-deposited material and gets larger, consequently mounds are

Table 1
Overview of the selected wind erosion models considered in this review.

Model	Primary Reference	Model Type	Time Scale	Space Scale	Software Requirements	Software Source
WEQ	Woodruff and Siddoway, 1965	Empirical	Annual average, long term	Agricultural/non-agricultural field	MS Windows 3.1 or later, MS Excel.	Excel version: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/tools/weps/?cid=nrcs144p2_080201
RWEQ	Fryrear et al., 1998	Empirical/ process-based	Single-event to weeks	Agricultural/non-agricultural field	DOS, can be translated to PCRaster	Open source: https://www.csrl.ars.usda.gov/wewc/rweq/get_rweq.htm
WEPS	Hagen, 1991	Process-based	Daily to sub-hourly, long-term	Agricultural/non-agricultural field to region	Linux/Unix, Windows XP or newer and Java 8 or newer	Open source: https://www.ars.usda.gov/research/software
SWEEP	Tatarko et al., 2019	Process-based	Hourly to sub-hourly single-event	Agricultural/non-agricultural field	Windows XP or newer and Java 8 or newer	Open source: https://www.ars.usda.gov/research/software
EPIC	Williams et al., 1984	Empirical	Daily time-step, long term	Agricultural field to whole farm (multiple fields)	DOS, Windows, or Linux environment	Open source: https://epicapex.tamu.edu/epic/
APEX	Williams et al., 1995	Empirical	Daily time-step, long term	Agricultural field, small watersheds, landscape	DOS, Windows, or Linux environment	Open source: https://epicapex.tamu.edu/apex/
TEAM	Gregory et al., 1999	Process-based	Single-event	Different land segments	Windows 95, 98 or NT	Not publicly available
WEELS	Böhner et al., 2003	Process-based	Single-event	Multiple fields, user determined	SAGA-GIS, Windows, or Linux	Not publicly available

Model	Primary Input Parameters	Wind Erosion Output	Specific Goals
WEQ	**Soil erodibility, I** (aggregates > 0.84 mm); **Roughness, K** (ridge roughness); **Climate, C** (annual wind speed, precipitation, temperature); **Field length, L** (unsheltered distance); **Vegetation, V** (kind, quantity, orientation)	Average soil loss per area per year. Also available in tabular form (see source web site)	Estimate long-term average annual soil loss
RWEQ	**Erodible fraction** (aggregates > 0.84 mm); **Soil crust** (% clay and organic matter); **Soil wetness** (rainfall, irrigation, solar radiation); **Weather (**wind velocity, wind direction, rainfall, solar radiation, air temperature, snowfall**)**; **Tillage** (soil roughness); **Field geometry** (field size, shape, orientation, length); **Crop** (live canopy cover, residue height, stalk diameter, number); **Hills** (slope gradient, length)	Average soil loss per area per year or shorter period	Estimate annual or daily soil erosion at a field scale and within the field
WEPS	**Soil erodibility** (% sand, silt, clay, bulk density, soil layer thickness), **Surface cover** (rocks); **Soil surface condition** (random and oriented roughness, aggregate size distribution, surface moisture); **Climate** (wind velocity, wind direction); **Management** (tillage and crop operations)	Soil loss/deposition by direction and size class as saltation plus creep, suspension and PM_{10}	Simulate weather, field conditions, and wind erosion for soil conservation and environmental planning
SWEEP	**Soil erodibility** (% sand, silt, clay, bulk density, soil layer thickness); **Surface cover** (fraction of rock/crust, loose and erodible material on crust, flat/random biomass); **Soil surface condition** (random and oriented roughness, aggregate size distribution, surface moisture); **Climate** (wind velocity, wind direction)	Soil loss/deposition by direction and size class as saltation plus creep, suspension and PM_{10}	Simulate soil loss for a given date for site-specific planned surface conditions and control practices
EPIC	**Soil erodibility** (aggregates > 0.84 mm); **Roughness** (random and oriented); **Climate** (annual wind speed, precipitation, temperature); **Field length** (unsheltered distance); **Vegetation cover** (kind, quantity, orientation)	Process associated with wind erosion	Determine the relationship between soil erosion and soil productivity.
APEX	**Soil erodibility** (aggregates > 0.84 mm); **Roughness** (random and oriented); **Vegetation cover** (standing biomass, standing crop residue, flat crop residue); **Field length** (field dimensions and orientation); **Climate** (daily precipitation, maximum and minimum air temperature, solar radiation, daily wind speed, relative humidity)	Soil loss, process associated with wind erosion	Simulate agricultural management systems

(*continued on next page*)

Table 1 (*continued*)

Model	Primary Input Parameters	Wind Erosion Output	Specific Goals
TEAM	**Soil erodibility** (average % sand, silt, clay, rock cover); **Wind erosivity** (distance from windbreak, windbreak heights, windbreak density , wind speed); **Climate** (average hourly wind speed, relatively humidity); **Field geometry** (field size, shape, orientation, length); **Surface cover** (vegetation cover, residue)	Total soil loss, soil movement rate over field	Simulate detachment and maximum transport rate of soil and associated dust loading to the environment
WEELS	**Soil erodibility** (% sand, silt, clay, organic matter); **Wind erosivity** (wind barrier heights, wind barrier density, wind speed); **Roughness** (cultivation and crop type); **Land use** (crop rotation, land use scenarios and statistics); **Climate** (precipitation, air temperature, air humidity, global radiation, wind speed)	Hours of erosion and soil loss	Assess spatial distribution of wind erosion risks for changing management strategies

formed, and dunes develop. Most dunes are observed in sandy deserts or close to sandy beaches, which act as the source for the aeolian transport of sand (Jiang et al., 2017).

3. Description of wind erosion models

Modelling of wind erosion provides a good integration of erosion processes and factors and may be useful to evaluate the on-site and off-site effects of wind erosion at various spatial and temporal scales. They may estimate the rate of soil erosion from small-scale to larger geographic areas on a regional and national basis and assess appropriate erosion control strategies (Blanco-Canqui and Lal, 2008a). Most of the current models derive from the initial research on wind mechanics and dynamics for developing wind erosion models conducted by Chepil (1945a, 1945b, 1945c). Earlier research considered climate and soil surface properties as two main factors on wind erosion mechanics. Chepil (1959) proposed an equation (Eq. (1)) for expanding theoretical basis by focusing on main factors which affect wind erosion including: soil cloddiness (I), vegetative material (R), ridge roughness (K), soil abradability (F), wind barrier (B), field width (W), and wind direction (D).

$$E = \mathrm{IRKFBWD} \quad (1)$$

Models are continuously improved by further understanding influential factors which affect wind erosion (Blanco-Canqui and Lal, 2008a). Several wind erosion models with various prediction capabilities and utilities have been developed, and are classified into three categories: empirical, conceptual, and process-based (Merritt et al., 2003). Although most of the models reviewed in this paper have been discussed in previous studies, this review is conducted to identify the deficiencies in current approaches and achieve a view towards developing future models. There are numerous wind erosion models, which are not considered in this current review, however. Our focus is on models that are developed for a wide range of applications in various scales and regions. This review is to illustrate selected models in term of their model structure, input data, model outputs, and their scales of application. A summary of these models is provided in Table 1.

3.1. *WEQ and RWEQ*

3.1.1. *History of WEQ and RWEQ models*

In the 1960′s, the Wind Erosion Equation (WEQ) was the first empirical wind erosion model based on attempts by Chepil (1959) for assessing annual soil loss and was developed from wind tunnel and field measurements (Woodruff and Siddoway, 1965). With the advent of computer, WEQ became a highly sophisticated empirical model (Blanco-Canqui and Lal, 2008a; Fisher and Skidmore, 1970). At that time, WEQ was the model available for planning wind erosion control systems and has undergone continuous improvement and led to the development of the Revised Wind Erosion Equation (RWEQ) by Fryrear et al. (1998) to consider more information from agricultural fields. The RWEQ model was released to permit the short-term (i.e. daily and longer) estimation of soil erosion (Fryrear et al., 1998).

3.1.2. *Structure of WEQ and RWEQ models*

WEQ predicts average wind erosion (E) along a line-transect across a wide, unsheltered, isolated, bare, smooth, non-crusted surface in mass per unit area per year (Fryrear et al., 1999; Woodruff and Siddoway, 1965).

In the WEQ model, different factors are considered to predict the potential annual wind erosion from a field (Woodruff and Siddoway, 1965):

$$E = f(I, K, C, L, V) \quad (2)$$

where E (Mg ha^{-1} yr^{-1}) is the average annual soil loss, I the soil erodibility factor, K the soil ridge roughness factor, C the climatic factor, L the length of field factor which can adjusted for any wind protection (i.e., wind barriers), V the equivalent vegetative or residue factor (Woodruff and Siddoway, 1965). The term f indicates that WEQ is a function of the factors and their interactions.

The I value is related to the percentage of non-erodible aggregates (AGG), which are proposed in a table by Woodruff and Siddoway (1965) and included knoll erodibility (i.e., soil topography) where fields with greater slopes could have increased wind velocity (Woodruff and Siddoway, 1965).

$$I = 525(2.718)^{(-0.04AGG)} \tag{3}$$

C is an annual climate parameter in an integrated form and has been produced as *iso*-C value maps which is determined as follow (Lyles, 1983; Skidmore, 1986; Woodruff and Siddoway, 1965).

$$C = \frac{1}{100}\sum_{i=1}^{i=12} \mathrm{U}^3\left(\frac{\mathrm{ETPi} - \mathrm{Pi}}{\mathrm{ETPi}}\right)\mathrm{d} \tag{4}$$

where, U is mean monthly wind velocity at a height of 10 m (m s^{-1}), ETPi is monthly evaporation (mm), Pi is monthly precipitation (mm), and d is number of days in the considered months.

The ridge roughness factor (K) is calculated based on the ratio of ridge height to ridge spacing, in which the K value for a flat, bare, and smooth field is equal to 1. In practice, K values can be adjusted by implementing some management activities on fields surface such as ridges and furrows (Tatarko et al., 2013). The total distance across a given field is the L factor, measured along the prevailing wind erosion direction and adjusted for any barriers present. The equivalent vegetative cover factor (V) is an input data that comes from complex graphs that relates various vegetation types, quantity and crop orientation to a flat, small-grain (e.g., winter wheat) equivalent.

All these input data are derived from maps, tables, and graphs to make an estimation of soil erosion with a graphical solution to simplify input relationships. A computer program of the WEQ model simplifies its use (Fisher and Skidmore, 1970).

The RWEQ model is based on WEQ and contains both empirical and process-based components with the ability of describing physical wind erosion processes by combining field datasets with a computer model for the prediction. Thus this model is not completely a physically-based model (Blanco-Canqui and Lal, 2008a; Fryrear et al., 1999).

RWEQ includes a weather factor (WF), soil crust factor (SCF), erodibility factor (EF), roughness (K), and vegetation/residue crops on ground (COG), a field parameter for size and orientation of the field, and wind speed which depends on slope and height of the hills (Youssef et al., 2012). This model's inputs are based on both field and laboratory studies (Fryrear et al., 1999). As with most wind erosion models, wind plays a key role as the basic driving force in this model.

The model estimates the amount of sediment flux (Q(Z) in kg m^{-1}) for specified periods based on a single-event, to a height of 2 m at a downwind distance (Z in m) for a specific field length based on the balance between wind erosivity and soil erodibility (Fryrear et al., 1998; Youssef et al., 2012).

$$\mathrm{Q(Z)} = \mathrm{Qmax}(1 - \mathrm{e}^{(\mathrm{Z/S})2}) \tag{5}$$

where Qmax (kg m^{-1}) is the maximum transport capacity, and s (m) is the critical field length at which 63% of the maximum transport capacity is reached. These two factors are calculated as:

$$Q_{max} = 109\ (\mathrm{WF}\ .\ \mathrm{EF}\ .\ \mathrm{SCF}\ .\ \mathrm{K}\ .\ \mathrm{COG}) \tag{6}$$

$$s = 150.71(\mathrm{WF}\ .\ \mathrm{EF}\ .\ \mathrm{SCF}\ .\ \mathrm{K}\ .\ \mathrm{COG})^{-0.3711} \tag{7}$$

The weather factor (WF in kg m^{-1}) is based on input weather parameters such as wind, snow, and soil wetness and calculated as:

$$WF = \mathrm{W}f\frac{\rho}{\mathrm{g}}(\mathrm{SW})\mathrm{SD} \tag{8}$$

where Wf is the wind factor (m^3 s^{-3}) derived from Eq. (9), ρ is air density (kg m^{-3}), g is acceleration due to gravity (m s^{-1} s^{-1}), SW is the soil wetness factor (Eq. (11)) and SD is the snow cover factor determined as 1 – probability of snow depth > 25.4 mm.

Wf and SW are determined as:

$$Wf = \frac{\mathrm{W}}{\mathrm{N}}\mathrm{Nd} \tag{9}$$

where W is a wind value (m^3 s^{-3}), N is the number of wind speeds used in the period (minimum of 500), Nd is the number of days in the simulation period (e.g., 15 days for a half month). W is calculated as:

$$W = \sum_{i=1}^{i-n} U_2(U_2 - U_t)^2 \tag{10}$$

where, U_2 is wind velocity at 2 m (m s^{-1}), and U_t is the threshold wind velocity at 2 m height equal to 5 m s^{-1}.

$$SW = \frac{\mathrm{ETp} - (\mathrm{R} + \mathrm{I})\frac{\mathrm{Rd}}{\mathrm{Nd}}}{\mathrm{ETp}} \tag{11}$$

where ETp is potential relative evapotranspiration (mm day^{-1}) as calculated in Eq. (12), R is the amount of rainfall (mm), I is the cumulative irrigation (mm), and Rd is the number of rainy and/or irrigated days in the simulation period.

$$ETp = 0.0162\left(\frac{\mathrm{SR}}{58.5}\right)(\mathrm{DT} + 17.8) \tag{12}$$

where, SR is total solar radiation (J m^{-2} day^{-1}), DT is mean temperature (°C).

Eqs. (13) and (14) are used to determine the erodible fraction (EF) and soil crusting factor (SCF):

$$EF = \frac{29.09 + 0.31\mathrm{Sa} + 0.17\mathrm{Si} + 0.33\frac{\mathrm{Sa}}{\mathrm{Cl}} - 2.59\mathrm{SOM} - 0.95\mathrm{CaCO3}}{100} \tag{13}$$

$$SCF = \frac{1}{(1 + 0.0066(\mathrm{Cl})^2 + 0.21(\mathrm{SOM})^2)} \tag{14}$$

where, Sa is sand content (%), Si is silt content (%), Sa/Cl is the ratio of sand to clay, SOM is soil organic matter content (%), and CaCO3 content (%).

The roughness factor (K) is calculated as follows:

$$K = \mathrm{e}^{(1.86\mathrm{KrRc} - 2.41\mathrm{KrRc}^{0.934} - 0.124\mathrm{Crr})} \tag{15}$$

where, Rc is a correction for wind direction, Kr is the ridge roughness factor (m), Crr is the random roughness (Saleh and Fryrear, 1999).

The crops on ground factor (COG) describe the impact of crop canopies, plant orientations, and crop residues on wind erosion and is computed as:

$$COG = \mathrm{e}^{(-0.0438(\mathrm{SC}))} + \mathrm{e}^{(-0.0344(\mathrm{SA}^{0.6413}))} + \mathrm{e}^{(-5.614(\mathrm{CC}^{0.7366}))} \tag{16}$$

where SC is the percent of land covered by crop residue, SA is the standing stem area index (m^2 m^{-2}), and CC is the percent soil surface covered by crop canopy.

The average soil loss S_L in (kg m^{-2}) at a specific point from the non-erodible border (Z, m) of the field is calculated as:

$$S_L = \frac{2.\ Z}{\mathrm{S}^2}\ \mathrm{Q_{max}}\mathrm{e}^{-(\mathrm{Z/S})^2} \tag{17}$$

3.1.3. Limitations and applications of the WEQ and RWEQ models

The weather, soil, vegetation and roughness are the main factors of both the WEQ and the RWEQ models. Manipulating one parameter relative to each of the other factors can identify the impacts of each single parameter on the rate of soil loss. This in turn makes it possible for users to know which parameter primarily impacts soil loss, which can be applied to management decisions for erosion control.

Potential limitations with the WEQ and RWEQ models are noted in

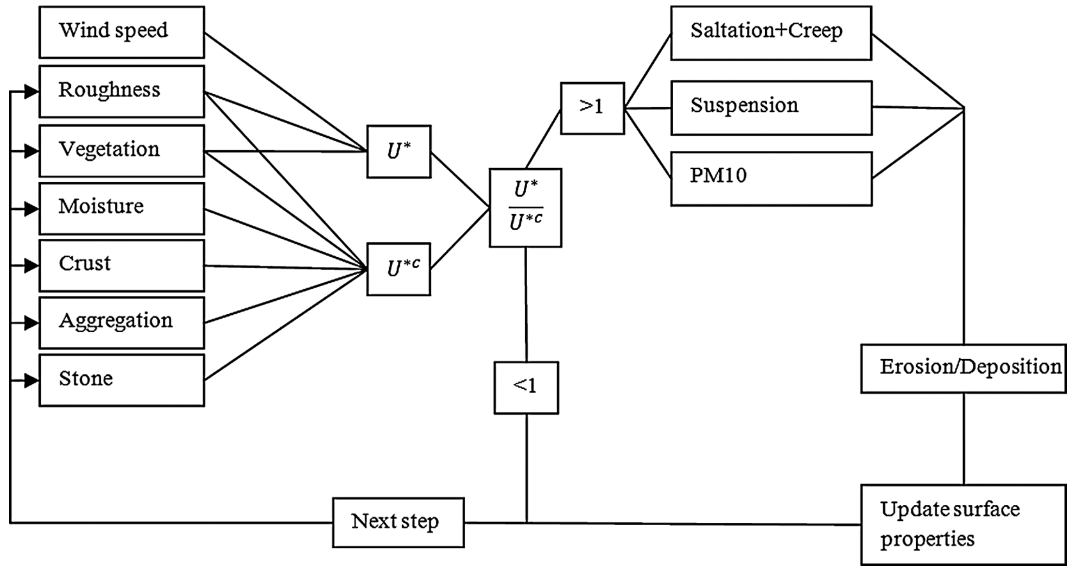

Fig. 2. Graphical scheme of the WEPS model where U^* is friction velocity (m s^{-1}) and U^{*c} is the dynamic threshold friction velocity (m s^{-1}); modified from Visser et al. (2005b).

previous literature and are summarized here. WEQ is empirical and based on 3 years of field wind tunnel data at Garden City, Kansas, USA and thus is not able to predict wind erosion accurately where climate and surface strongly deviate from this location (Fryrear et al., 1999; Tatarko et al., 2013). Determining input values is difficult due to varying surface conditions throughout the modelled year (Cole, 1983). In general, RWEQ can be applied for small rough surfaces with low wind velocities, however it does not work in highly and medium rough surfaces (de Oro et al., 2016).

The effects of all interactions between management activities and climate conditions are not accounted for in WEQ (Hagen, 1991). For example, wind and precipitation variations from the average are not supported. Woodruff and Siddoway (1965) considered a normal distribution of wind velocity in WEQ, so wind magnitude, duration, and direction are not reflected in wind input data, thus observed and predicted erosion are not well correlated (Van Pelt and Zobeck, 2004). In regions with extreme rainfall patterns (i.e., very low or very high), WEQ is not able to predict the accurate rate of soil loss in comparison with the field measurements. In conditions with high precipitation, WEQ estimates lower than measured loss while in low precipitation conditions, overestimation has been observed. Furthermore, for extremely large fields, WEQ overestimates wind erosion while it underestimates extremely narrow fields (Fryrear et al., 1999).

Daily changes in weather and management activities such as freezing/thawing and soil roughness in the RWEQ model are not supported (Blanco-Canqui and Lal, 2008a). RWEQ uses the mean of weather data for predicting the rate of soil loss from homogenous units for a specific period. However, weather conditions change continuously so that average weather does not account for temporal changes of the weather factors (Youssef et al., 2012). This model also has limitation in estimating the rate of soil loss in suspension (Fryrear et al., 2000). The performance of RWEQ was found to improve after calibration for local condition, otherwise, the RWEQ model underestimates erosion (Buschiazzo and Zobeck, 2008; Pi et al., 2017; Van Pelt et al., 2004; Visser et al., 2005a; Youssef et al., 2012).

3.2. WEPS and SWEEP

3.2.1. History of the WEPS and SWEEP models

The Wind Erosion Prediction System (WEPS) model was developed by the Agricultural Research Service of the United States Department of Agriculture (USDA) beginning in 1985 in response to user requirements for more accurate predictions than WEQ and RWEQ (Hagen, 1991; Tatarko et al., 2016). Because of their empirical and complex nature, WEQ and RWEQ were not easily adapted to conditions or climates different from the US central Great Plains (Hagen, 1991). However, WEPS represents new technology and does not represent simply a new and improved version of the WEQ model (Wagner, 2013). Like WEQ, the most important customer of the WEPS model is the USDA Natural Resources Conservation Service (NRCS) who uses the model for conservation planning and controlling wind erosion (Tatarko et al., 2019). This model is able to calculate total, creep plus saltation and suspension loss, and estimate PM-10 emissions (particulates < 10 μm in aerodynamic equivalent diameter) from a field (Wagner, 2013) and computes soil losses for one day rather than one year intervals (Tatarko et al., 2013). Thus, this model is applicable for planning soil conservation systems and evaluating offsite impacts of wind erosion on cultivated agricultural fields under specified management rotations.

The Single-event Wind Erosion Evaluation Program (SWEEP) is a standalone version of the WEPS's erosion submodel (Tatarko et al., 2016). This model was developed to estimate potential soil loss for a single storm (i.e., ≤24 h) given user supplied surface and wind conditions (Tatarko et al., 2016).

3.2.2. Structure of the WEPS and SWEEP models

The WEPS model is a process based, continuous, and daily time-step model that has the ability to simulate total wind erosion for the field as well as by direction and size class (Tatarko et al., 2019). This model has a modular structure (i.e., submodels) for predicting soil loss by incorporating a set of mathematical equations based on the conservation of mass and momentum principles (Wagner, 2013).

A simple graphical scheme is shown in Fig. 2 to illustrate the main structures/concepts of this model. The WEPS model consists of three main components including a science model, the WEPS interface, and databases (Wagner, 2013).

The WEPS science model is used to simulate the surface state of soil and vegetation through five submodels that simulate surface processes and resulting surface state. If conditions are susceptible and winds are strong, then the wind erosion loss is calculated (Wagner, 2013). Submodels that simulate the surface state include: hydrology, soil, management, crop growth, residue decomposition. These submodels provide and update parameters dynamically and supply the erosion submodel information needed to calculate soil loss. A summary of the structure of these submodels are given in Table 2.

Table 2
Structure of the WEPS submodels.

Submodel	Parameters/Processes Simulated	Simulates	References
Erosion	Detachment, transport, and deposition by particle size class and by direction; surface rearrangement	Wind erosion	Hagen, 1995
Soil	Wetting/ drying, freezing/ drying, freezing/ thawing, precipitation amount and intensity, and time	Change in soil properties	Hagen et al., 1995
Management	Changes from physical disturbance of the soil, crop, and residue	Change in soil properties caused by farming operations	Wagner and Fox, 2013
Plant Growth	Water and temperature stress	Growth of crops and plant communities	Retta and Armbrust, 1995
Residue Decomposition	Temperature, soil moisture and the decay rate of plant material	Decrease in residue biomass	Steiner et al., 1995
Hydrology	Daily precipitation, snow melt, runoff, infiltration, evapotranspiration	Surface wetness, change in soil water content, and soil temperature	Durar and Skidmore, 1995

The WEPS interface queries the user for field conditions (i.e., location, field geometry, soil parameters, and management operations). The weather generators (CLIGEN and WINDGEN) calculate daily weather (i.e., precipitation, temperature, solar radiation, etc.) to drive the processes for the WEPS science model. Consequently user friendly outputs are provided by the science model through the user interface (Wagner, 2013).

The Erosion submodel calculates soil loss and deposition based on friction velocity as affected by the surface condition, such as soil surface roughness, vegetation status (i.e., leaf area index, flat and standing biomass orientation), distribution of soil aggregate size, soil moisture, the amount of erodible material and the amount of crust and rock on the surface (Tatarko et al., 2019). During erosion, WEPS simulates different wind erosion processes of saltation plus creep, suspension, and PM10 emission separately in response to wind speed, wind direction, field geometries, and surface conditions, which provide useful assessments for estimating on- and off-site impacts of wind erosion (Feng and Sharratt, 2007; Hagen, 2004). Since input wind data are simulated for a specific direction for a day, erosion losses are also provided by direction for each process. WEPS treats the simulation field as two-dimensional grid with uniform-sized rectangular cells. Based on the size and shape of the simulated region, the size and shape of each cell will vary from the minimum 7 m × 7 m to the maximum greater than 200 m by 200 m (Wagner, 2013). The surface state is dynamically updated in each cell proceeding erosion events. WEPS calculations are made on a daily basis and users can specify the output intervals ranging from single events to multiple years. Five databases contain historical weather records for CLIGEN and WINDGEN, as well as other parameters for soil, management and wind barriers. However, the WEPS model can be configured to apply user supplied measured weather and soil data if available, depending on the needs of the user.

The SWEEP model is a single event model that utilizes the same erosion submodel science and computer code as that in WEPS. In addition to the WEPS erosion submodel, SWEEP has a graphical user interface (GUI) to provide easier access to inputs and outputs (Tatarko et al., 2019) and works independently of the WEPS model. SWEEP input parameters are grouped based on (1) field geometry (field length, width, orientation, and barriers if present); (2) plant material (flat dead biomass, biomass height, and leaf and stem area index); (3) soil layers (particle and aggregate size distribution, volume of rocks, and aggregate density, and stability); (4) soil surface (crust and loose material cover, crust stability, ridge and random roughness, and surface soil wetness); and (5) wind parameters (speed and direction) with average speed intervals available ranging from 5 to 60 min (Feng and Sharratt, 2009; Tatarko et al., 2016). SWEEP simulates all the same erosion processes as WEPS for a single day given user specified surface conditions and provides sub-hourly results if desired (Tatarko et al., 2016, 2019).

3.2.3. Limitations and applications of the WEPS and SWEEP models

A current limitation in WEPS is that it has not been adapted to rolling terrain, which become increasingly important as one tries to extend wind erosion models to other areas such as range lands. Part of the problem involves the difficulty in developing the large topographic databases needed for convenient general applications. WEPS requires detailed input data about the study areás weather, soil surface conditions, vegetation, and management, which may not be easy to obtain even for a small area (Tatarko et al., 2019). WEPS has been noted for under prediction of both small and large erosion events. Feng and Sharratt (2009) tested the WEPS erosion submodel (i.e., SWEEP as well) for very small storms and found that the model underestimated erosion by overestimating the threshold friction velocity. Other researchers have also reported that WEPS underestimates the occurrence of small storms (Feng and Sharratt, 2007; Funk et al., 2004). Hagen (2004) found a similar response for small storms but attributed this to surface spatial variability where portions of the field had higher erodibility than the "average" surface (Tatarko et al., 2019). It can be noted that the erosion submodel in WEPS is not called until winds exceed the static surface threshold. Once that threshold is exceeded, the dynamic threshold is used in continuing the erosion. This was a deliberate choice to save computation time by reducing the number of times the erosion submodel is called for customers that are often making runs that simulate 50 or more years. Thus, the model may give zero for events with "trivial" erosion amounts. For such trivial amounts the practical decision response by the user is the same – no control action required. An exception may be if one is simulating a toxic, highly contaminated site. But, in this case onsite instrumentation should be used to assess the particulate matter leaving the site. There are very few large events studies to judge whether the model or the surface inputs are not correct when the erosion has been measured. But even when loss for large storms is underestimated, the decision is the same – control action is required.

WEPS is considered a unique wind erosion model due to its determination of the susceptibility of the soil surface to wind erosion using more detailed information on a daily and sub-daily basis, while other wind erosion models, are not able to determine the surface state (Wagner, 2013). The performance of WEPS was tested in different regions throughout the world by different researchers and acceptable results are documented. Thus, according to previous literature, WEPS can be used with confidence for wind erosion estimation for historic and future climates (Sharratt et al., 2015). Tatarko et al. (2019) provide an extensive review of studies where WEPS has been applied.

3.3. EPIC and APEX

3.3.1. History of the EPIC and APEX models

Improvements in the WEQ model led to the emergence of the EPIC model, originally called the Erosion Productivity Impact Calculator, designed "to determine the relationship between soil erosion and soil productivity throughout the U.S." (Williams et al., 1984). EPIC was one of several comprehensive cropping system models that were developed in the United States at the time (Cole et al., 1983; Williams et al., 1984;

Skidmore and Williams, 1991). The EPIC model is an empirical computer-based model that includes the prediction of soil loss rate from wind and water on a daily basis in response to management decisions that is also able to assess the relation between soil erosion and soil productivity in more detail (Williams et al., 1984).

The amount of soil loss in wind and water erosion can be simulated by the EPIC model, however this model is not used widely for wind erosion estimations due to the lack of field testing of the model (Potter et al., 1998). The EPIC model has been improved and further developed and is now known as the Environmental Policy Integrated Climate model for use in whole field or farm management. Improvements were made to not only simulate water quality, nutrient cycling, grain yields, climate change, and the effects of atmospheric carbon dioxide, but also evaluate runoff and erosion from snowmelt by inserting new algorithms (Puurveen et al., 1997; Toure et al., 1995).

The Agricultural Policy/Environmental eXtender (APEX) model is an extended version of the EPIC model developed by Texas A&M University as a flexible and dynamic tool in order to simulate agricultural management strategies and land use impacts for whole farms and small watersheds (Gassman et al., 2009). EPIC and APEX models apply the same algorithm for simulating wind erosion (Wang et al., 2012). Currently, APEX is being used in the USDA-NRCS Conservation Effects Assessment Project (CEAP) for the Cropland National Assessment of the effectiveness of conservation practices (Plotkin et al., 2013).

3.3.2. Structure of the EPIC and APEX models

One of the EPIC capabilities is simulating potential wind erosion for long periods based on a daily time-step by considering four main components including a soil erodibility factor, soil surface roughness, biomass status, field distance and wind direction, which is used to adjust field length along the wind direction (Potter et al., 1998). EPIC continuously simulates the processes associated with erosion for time intervals specified by the user (Puurveen et al., 1997) based on wind energy and soil surface properties with following equation (Skidmore, 1986):

$$YWR = C\left(\frac{\rho_a}{g}\right)\left[u_0^2 - u_\tau^2 - 0.5\left(\frac{sw}{wp}\right)^2\right]^{1.5} \tag{18}$$

where, YWR is the mass flow rate (kg m^{-1} s^{-1}), C is an empirical parameter ≈2.5, ρ_a is air density (kg m^{-3}), g is acceleration of gravity (m s^{-2}), u_0 is friction velocity (m s^{-1}), u_τ is threshold friction velocity (m s^{-1}), sw is actual water content of the surface soil layer, wp is 1500 kPa water content of the surface soil layer, and sw/wp ratio is surface water parameter. More information and discussion about the EPIC model can be found in (Potter et al., 1998).

The Wind Erosion Stochastic Simulator (WESS) is a stand-alone version of the wind erosion module of EPIC, which is designed to simulate single wind events (Van Pelt et al., 2004). In this model, users apply local and stochastic wind speed distribution or 10-minute average wind speeds, accompanied with soil surface characteristics such as aggregate size distribution, texture, roughness, soil water content, crop residue (Potter et al., 1998; Van Pelt et al., 2004).

The APEX model assesses a wide range of land management operations such as ploughing, conservation managements, crop rotation, and fertilizer management (Gassman et al., 2009). It focuses on both soil properties, water supply, weather conditions, plant competition, and pests, as well as soil erosion, economics, and soil productivity and sustainability (Williams et al., 2010). APEX runs on a daily time-step and has the ability to continuously evaluate for the long-term for either single or multiple fields based on soil characteristics and field geometry (Gassman et al., 2009; Wang et al., 2012). The APEX model contains 12 submodels, which include climate, hydrologic balance, crop growth, soil erosion, carbon cycling, nutrient cycling, pesticide fate, management operations, soil temperature, vegetation control, economic budgets, and water routing (Gassman et al., 2009).

The APEX wind erosion submodel simulates erosion in which wind speed and soil water content are the most sensitive parameters in this model (Wang et al., 2006). APEX needs a large number of input parameters such as daily weather, soil, field management, and site information, which include information about plant status, fertilization, plough management, and pesticides. Furthermore, many equation coefficients, s-curve information, and other parameters are set in a parameter file (Wang et al., 2006). In addition to wind erosion loss, the APEX model can simulate management affected water yield (including surface runoff, lateral subsurface flow, and return flow from groundwater, which contributes to stream flow), soil loss by water, soluble P and N loss in runoff, particulate P and N loss, soil organic carbon change, and crop grain yield, as well as pesticide dynamics, and soil conditions (Plotkin et al., 2013; Wang et al., 2006).

By using the following equations, the APEX model simulates soil wind erosion (Williams et al., 2008):

$$SL = SEF \times SRF \times VCF \times FLF \times \int_0^t \frac{ER}{WL} dt \tag{19}$$

$$SF = SEF \times SRF \times VCF \times FLF \times \int_0^t ER dt \tag{20}$$

In these equations, SL and SF are soil loss (kg m^{-2}) and soil discharge (kg m^{-1}) respectively, where SEF is the soil erodibility factor, SRF is the surface roughness factor, VCF is the vegetative cover factor, FLF is the field length factor, ER is the potential erosion rate (kg m^{-1} s^{-1}), WL is the mean distance of wind traversing a field (m), and t is the duration (s). These equations are applied when the friction velocity (u_0) is higher than the threshold friction velocity (u_t). The model equations and parameters of the APEX model are given in Pi et al. (2017).

The Wind Erosion Continuous Simulation (WECS) is a subset of the APEX wind erosion model and requires daily wind speed distribution and the dominant wind direction for estimating potential wind erosion in smooth and bare soils on daily time-step. However, the actual erosion is affected by factors of soil characteristics, soil surface conditions, biomass status, and the field length through which wind is blown (Gassman et al., 2009).

The following equation simulates the daily wind speed probability distribution (Williams and Izaurralde, 2006).

$$u10 = a1.\ U10(-\ln(f))^{a2} \tag{21}$$

where u10 is simulated wind speed at a 10 m height, U10 is daily mean wind speed, f is the fraction of daily wind speed, a1 and a2 are fitting parameters. A detailed description of WECS equation can be found in (Williams and Izaurralde, 2006).

3.3.3. Limitations and applications of the EPIC and APEX models

EPIC currently has a capability to compare different management operations and also their effects on nutrient cycles, pesticides and sediments (Williams et al., 2010). The original wind erosion component of the EPIC model was converted from the WEQ model (Woodruff and Siddoway, 1965) and from annual to daily prediction. However, soil erodibility and climate factors remained constant for each day of the year and other variables are subjected to daily changes by EPIC (Cole et al., 1983). Skidmore and Williams (1991) stated that converting relative field erodibility to average annual soil loss is accompanied with uncertainties. The relationship between field erodibility and individual wind storms is ignored and is a main limitation of the EPIC model (Skidmore and Williams, 1991).

APEX has various features, one of which is the ability to subdivide farms or fields by soil characteristics, location on the landscape, surface hydrology, management practices, and crop diversity within a field or farm. Application of APEX includes determining the effects of different managements, climate change, CO2 atmospheric concentration, animal feeding facilities, and bio-energy production systems (Wang et al., 2011). APEX can simulate events on a daily time-step, in which some processes are simulated on hourly or sub-hourly time-steps. This model accounts for changes in daily weather and considers different management practices based on simulation of physical, biological and environmental processes. An APEX simulation can be run for different time periods (i.e., one year or hundreds of years, if necessary) and the results can be examined daily, monthly, yearly, or with multi-year analyses (Wang et al., 2011). According to Pi et al. (2017), although measured and simulated soil loss in the APEX wind erosion model have an acceptable relation, the effect of vegetation cover factor may be overestimated for soil erosion simulation. This may be because of the simplified vegetative cover factor, which is applied for total biomass but not plant tissues (i.e., leaf or stem area) that affect wind shear at the surface (Pi et al., 2017).

3.4. TEAM

3.4.1. History of the TEAM model

The Texas Erosion Analysis Model (TEAM) model was developed to address the need to understand wind erosion processes and conserve valuable natural resources to protect human health and environment. TEAM attempted to model wind erosion for both pure sands as described by Bagnold (1943) and agricultural soils as modelled by Chepil and Woodruff (1963). This model was developed using a systems approach to apply the current state of knowledge and mathematical modelling. Beginning in 1985, the Wind Engineering Research Centre at Texas Tech University in Lubbock, Texas, USA assembled data and the basic equations and the mathematical modelling to produce TEAM (Gregory et al., 1999). TEAM is able to simulate the rate of soil detachment and maximum transport as well as dust loading to the environment and provide protocols to design wind erosion controls (Gregory et al., 2004). TEAM was later expanded to predict dust concentrations and visibilities with height onsite and offsite downwind from the erosion source. Surface cover and soil descriptions were incorporated for both wind and water erosion prediction to facilitate the integration of a water and wind erosion model in the future.

3.4.2. Structure of the TEAM model

TEAM can describe wind erosion processes individually and assess the on-site and off-site impacts of wind erosion by inserting environmental conditions and human activities as inputs (Gregory et al., 1999; Gregory et al., 2004). The TEAM model contains two main functions for describing the mechanism of wind erosion and dust generation. The first function is maximum-transport component that is highly sensitive to wind speed, vegetative cover, surface residue, soil aggregate cover, soil particle size distribution, and soil moisture. The other function is a length factor, which ranges from 0 to 1. So soil particle movements on the soil surface is evaluated from large aggregates to lose single grained sands (Singh et al., 1997). Two major factors, field length and aggregate abrasion, have impact on dust generation and environmental air pollution, therefore, an integration of these two functions can be used in the model to calculate the rate of soil movement (Gregory et al., 2004; Singh et al., 1997). Consequently, the total soil loss is calculated via multiplying the highest rate of transport by the length factor (Gregory et al., 2004). The mathematical expressions for each component of the TEAM model are derived from mathematical models describing specific physical processes affecting wind erosion and can be found in Gregory et al. (2004).

For determining the soil detachment, transport rate, and dust generation, various input data are required. These input parameters are average hourly wind speed to determine friction velocity, relative soil moisture and clay content for determining threshold friction velocity, soil particle size distribution, surface vegetation cover and residue status, a soil erodibility factor, soil bulk density, soil porosity, the height of any windbreak and field length (Gregory et al., 2004; Singh et al., 1997). Total soil movement rate, concentration in saltation layer, dust concentration with height, particle size distribution with height, and length of visibility with height are also output by the TEAM model (Singh et al., 1997).

3.4.3. Limitations and applications of the TEAM model

TEAM is a model that includes different factors no other wind erosion model has such as relative humidity, a wind gust factor, and a dynamic length factor. Considering all these factors, TEAM is relatively easy to use and calculates soil movement quickly (Gregory et al., 2004). Like WEPS, this model provides a possibility for users to evaluate new soil types and cover conditions and select English or metric units for both input data and output, which makes this model flexible and user friendly (Gregory et al., 1999). On the other hand, TEAM lacks ability to adjust soil erodibility as a function of rainfall and wetting and drying cycles, which is a weakness. TEAM was used to analyse a dust storm that caused a multiple vehicle traffic accident in California (Singh et al., 1997). Pehrson and Chiou (1996) also demonstrated that the TEAM model could be used as an analysis tool for cleaning up a major contaminant site.

3.5. WEELS

3.5.1. History of the WEELS model

Wind Erosion on European Light Soils (WEELS) is a good example of an integrated model and is the first process-oriented assessment for European soils (Böhner et al., 2003). Four different countries (Germany, Netherlands, Sweden and the United Kingdom) were involved in the European Union (EU)-funded research project for WEELS in the North European Quaternary Plains at three field experimental sites which were located in Germany, Sweden, and the United Kingdom and wind tunnel experiments with selected soils. In the WEELS project, the main aim was to assess wind erosion spatial distribution risks through developing a spatially distributed wind erosion model, which can run with different temporal scales from hours to decades and also consider different management such as crop rotation period and climate scenarios (Böhner et al., 2003).

3.5.2. Structure of the WEELS model

The structure of the WEELS model contains a combination of different algorithms and approaches with inputs from topographic and climatological data. This model consists of two different groups of modules. The first group contains Wind, Wind Erosivity, and Soil Moisture modules, which consider temporal variations of climatic erosivity. The second group contains Soil Erodibility, Surface Roughness, and Land Use models for temporal soil and crop variables to account for erodibility (Böhner et al., 2003). Böhner et al. (2003) provided an overview of the WEELS model and described different modules and the input and output data for each module is present in Fig. 3.

3.5.3. Limitations and applications of the WEELS model

The WEELS model is limited to horizontal sediment transport rates in the saltation process. Furthermore, quantifying the rate of sediment transport as suspension is not evaluated by this model, therefore net soil losses are not calculated (Böhner et al., 2003). Without a suspension component, the model is incapable of evaluating air quality impacts of wind erosion.

In the EU-funded project, WEELS was applied to predict the long-term spatial distribution of wind erosion risks in terms of erosion hours and wind-induced soil loss and calculate aeolian sediment dynamics under different climate conditions and land use scenarios. it was also used to determine economic benefits and problems of wind erosion processes (Böhner et al., 2003). The WEELS model gives insight into the general changes of erosion risk by month, whereby damages due to wind erosion can be estimated and some policies for conservation

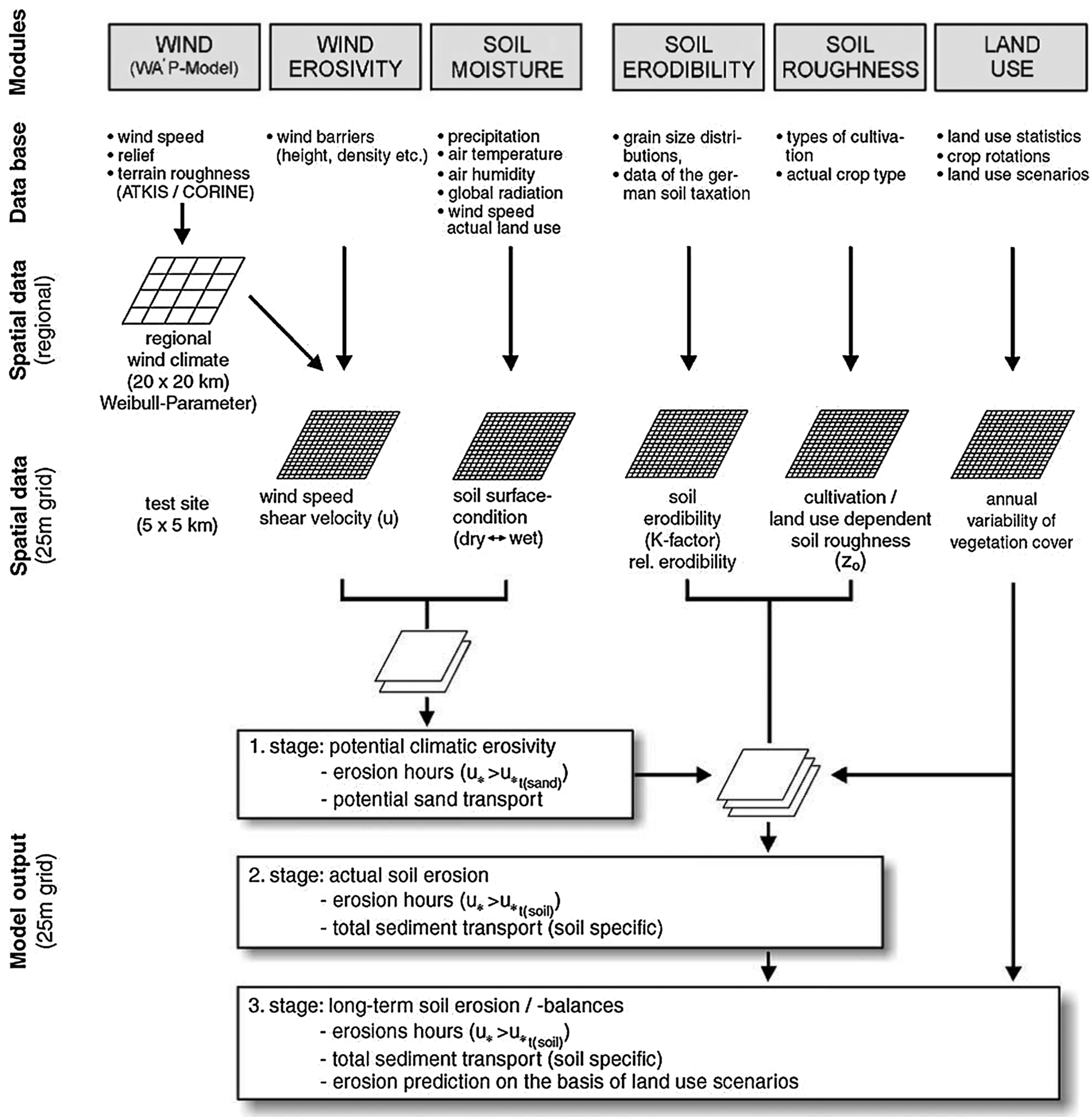

Fig. 3. Structure, input, and output data of the WEELS model (Böhner et al., 2003).

activities for each region might be formulated (Goossens and Riksen, 2004). WEELS has this ability to incorporate the output data into a GIS and simplifies the economical evaluations for current and the future scenarios (Böhner et al., 2003).

4. Other models

Over the past decades, several other models have been developed to describe and estimate wind erosion potential. However, these models are not suitable for all regions due to their inputs, which may not be available. In this section other models that are applicable under specific conditions are considered.

In 1995, an experimental, empirical model was developed by the Iranian Research Institute of Forests and Rangelands, named IRIFR, which can be applied for estimating the potential soil loss in desert areas of Iran with consideration of the specific ecological conditions of these areas (Ahmadi, 1998). This model is suitable for evaluating different scenarios of land management systems and land use change and has been applied to a number of studies for the region, such as a cost/benefit analysis of applied practices as well as the effects of human and animal environment interactions in desert conditions (Azarkar et al., 2006; Rezaei et al., 2016).

The Dust Production Model (DPM) was developed specifically for agricultural soils in Spain and Niger (Alfaro and Gomes, 2001). It estimates not only the vertical mass fluxes of particulate matter of aerodynamic size of 20 µm or less (PM20) released during wind erosion events, but also their size distribution. Aerodynamic parameters and soil characteristics are two important input data of this model, which has been used in various projects and validated for different regions such as the French funded PROgramme Soil and Erosion (PROSE) project in Niger and the Spanish Wind Erosion and Loss of SOil Nutrients in semi-arid Spain (WELSONS) project. Due to the lack of available data, more research is needed to validate other aspects of the model (Alfaro et al., 2004).

The Integrated Wind-Erosion Modelling System (IWEMS), is a combination of a regional weather-prediction model and a dust-

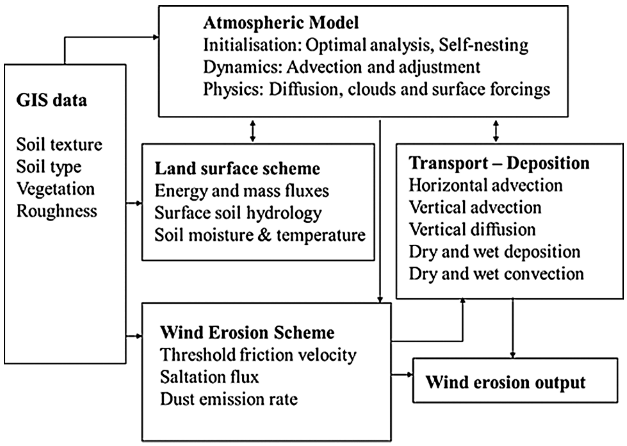

Fig. 4. Scheme of the IWEMS model (Lu and Shao, 2001).

emission and transport model, which are linked with a geographic information database providing the necessary input parameters for the system (Lu and Shao, 2001). IWEMS was a modelling effort for the quantitative assessment and prediction of dust-storm events at a regional scale and the intensity of dust emission and the transport of dust in the atmosphere. The structure of this model is shown in Fig. 4 (Lu and Shao, 2001).

Australian Land Erodibility Model (AUSLEM) (Webb et al., 2006) is a daily time-step model that was established through a systems analysis of the factors controlling wind erosion and developed as a geographic information system tool to assess land susceptibility to wind erosion across western Queensland, Australia. Inputs of this model are plant cover, soil moisture, soil texture and soil surface roughness. The model performs well in the arid southern and western regions of Queensland (Webb, 2008).

The Aeolian EROsion (AERO) model, is currently being developed to simulate wind erosion and dust emission through an interface to provide non-expert land managers a wind erosion decision-support tool (Edwards et al., 2018). AERO incorporates land surface processes and sediment transport equations from existing wind erosion models and was designed for application with available USA long-term monitoring datasets. The model simulates horizontal and vertical mass flux by particle size class on a plot scale from user inputs of meteorological, soil, and vegetation data. AERO addresses a need for a generalizable wind erosion model that can be applied across different land cover settings.

5. Discussion

A review of wind erosion models indicates that a need exists for long-term measurements to evaluate the rate of wind-induced soil erosion from changes to the environment. By accessing reliable measured data, computer-based models can be evaluated for predicting wind erosion under different conditions in different time intervals when models are calibrated and validated. Such data would need to account for the varied inputs and outputs of all models. In terms of wind erosion modelling, few studies provide complete information about different aspects of model performance in response to the main user questions regarding which model, in which region, and under which conditions each is appropriate for determining wind erosion rates. During recent decades, numerous erosion simulation models have been developed with varying degrees of sophistication from simple to complex. Each model has its own necessity and constraints that should be considered for specific application. However, some limitations in models are being overcome with the advent of high-speed computers. In the current review, some information about the background, structure, input and output data of each model were provided. For further insight of soil wind erosion models, a comparison was conducted three main viewpoints emphasizing validation, databases, and erosion processes.

5.1. Validation

In this section, we review the validations of the selected models by examining studies where model predictions were compared with field observations. A summary of the region where validated, the study site and type, parameters measured, and validation studies for some major wind erosion models is given in Table 3.

Given that WEQ is one of the oldest wind erosion models, surprisingly few validation studies have been made for the model. Fryrear et al. (1999) compared measured wind erosion events with WEQ predictions for 15 sites with varying soils and managements and reported a very low R^2 (0.01), although it should be noted that WEQ was not developed as an event-based model. Long-term predictions of wind erosion in a semi-arid region of Argentina with WEQ was found to be reliable ($R^2 = 0.96$), even with limited climatic data (Buschiazzo and Zobeck, 2008). Van pelt and Zobeck (2004) compared sums of field measurements with predictions of wind erosion from seven locations across six US states for a total of 14 periods with multiple years of observations. WEQ under-predicted the observed estimates for 11 of the 14 periods by as much as a factor of nine and overall predictions on average were only about 53% of the observed erosion.

Many studies have attempted to validate measured or observed wind erosion with RWEQ. Several studies found mixed results with R^2 values ranging from 0.01 to 0.81 (Youssef et al., 2012; Pi et al., 2017; Van Pelt et al; 2004). These studies were conducted on variable soil types with assumed varying suspension components. RWEQ may not perform well on soils with high suspension content compared to sandy soils since it does not simulate a suspension component. An improved validation was obtained by Buschiazzo and Zobeck (2008) for fine sandy loam soils in the Argentinean Pampas ($R^2 = 0.90$). The best validations ($R^2 = 0.91$ to 0.93) were obtained for a wide variety of events and locations in two studies (Fryrear et al., 1999, 2008). Since the lead author of these studies, D.W. Fryrear was the developer of RWEQ, perhaps the good results suggest an intimate understanding of models is essential for proper parameterization and use.

WEPS and SWEEP have also been extensively evaluated and validated throughout the United States, as well as in Europe, Africa, China, and South America, often in comparison with other models. van Donk and Skidmore (2003) compared measured field parameter values with WEPS simulated parameters of surface roughness and residue and found no significant differences. A wind tunnel study by Liu et al., 2014) showed very good agreement for controlled conditions ($R^2 = 0.94$–0.999). Buschiazzo and Zobeck, (2008) found SWEEP to accurately predict measured wind erosion for single storms lasting approximately 24 h on a bare and smooth soil ($R^2 = 0.89$). Validations with a large number of observations generally gave improved comparisons (Hagen, 2004, 46 events, $R^2 = 0.71$; Funk et al., 2004, 49 events, $R^2 = 0.93$–0.98). WEPS and SWEEP however, were found in several studies to under-predict or not predict some relatively small erosion events on soils covered with plants, residues, or had a high surface roughness (Funk et al., 2004; Feng and Sharratt, 2007; Feng and Sharratt, 2009; Pi et al., 2014). Feng and Sharratt (2009) concluded that the model underestimated soil loss by overestimating the threshold friction velocity. Hagen (2004) also noted this limitation of WEPS for simulations of small storms, which he attributed to spatial variability of study sites containing small inclusions of surfaces with higher erodibility than the average surface. Field spatial variability and its effect on wind erosion prediction were also cited by both van Donk and Skidmore (2003) and Visser et al. (2005) for WEPS validations. Agricultural fields often have areas that vary in one or more characteristics, including natural variability in vegetation or a field with more than one soil type. These differences across a field can affect wind erosion (Okin, 2005) and are not accounted for in WEPS validations.

Table 3
Validation studies of selected wind erosion models.

Model	Validation region	Land / site / study type	Parameters measured	Measure of fit *	References
WEQ	USA	Fifteen sites; six states; varying soil and management	Period erosion	$R^2 = 0.01$	Fryrear et al., 1999
	USA	Seven sites; six states; varying soil and management	Period erosion	Predicted was 53.3% of observed	Van Pelt and Zobeck, 2004
	Argentina	Fine sandy loam; bare, conventional, and no-till management	Period erosion	$R^2 = 0.96$	Buschiazzo and Zobeck, 2008
REWQ	USA	Fifteen sites, six states	Saltation	$R^2 = 0.927$	Fryrear et al., 1999
	USA	Six cropland fields	Saltation, 41 events	$R^2 = 0.62$	Zobeck et al., 2001
	USA	Six sites, five states; varying soil and management	Saltation for 24 events	$R^2 = 0.38$	Van Pelt et al., 2004
	Africa, Burkina Faso	RWEQ in PCRaster; degraded, valley floor, and dune sites	Maximum transport (Q_{max}); critical field length (S); 11 events	Average Q_{max} underpredicted by 66.9 to 79.9%; Average S underestimated by 7.4 to 13.9%	Visser et al., 2005
	Argentina	Fine sandy loam; bare, conventional, and no-till management	Saltation	$R^2 = 0.90$	Buschiazzo and Zobeck, 2008
	Egypt, Northwest	Coastal sites	Saltation, 52 events	$R^2 = 0.91$ to 0.93	Fryrear et al., 2008
	Syria, Khanasser Valley	RWEQ in PCRaster; patchy landscape	Saltation	$R^2 = 0.01$ to 0.083	Youssef et al., 2012
	China and USA, Columbia Plateau	Cotton and date orchard, China; Winter wheat-fallow, Washington, USA	Saltation, 6 events China and 12 events USA	$R^2 = 0.02$ to 0.81	Pi et al., 2017
	Europe	RWEQ in GIS; arable lands	Erosion sensitive locations	Identified 94·4% of erosion sensitive locations	Borrelli et al., 2017
WEPS	USA, Eastern Colorado	Winter wheat field	Roughness and residue conditions	No significant differences ($p > 0.05$)	Van Donk and Skidmore, 2003
	USA	Seven cropland fields, six states	Erosion, 46 events	$R^2 = 0.71$	Hagen, 2004
SWEEP	Germany, Northeast	49 events; sandy soil	Erosion	$R^2 = 0.93$ to 0.98	Funk et al., 2004
	Africa, Burkina Faso	WEPS erosion submodel (i.e., SWEEP) in PCRaster; degraded, valley floor, dune sites	Spatial erosion	"suitable for application in the Sahel"	Visser et al., 2005b
	USA, Columbia Plateau	Two sites, silt loam, cultivated fallow with winter wheat late in the study, six events	Erosion, total and PM10	Total, $R^2 = 0.55$, d = 0.85 PM10, $R^2 = 0.46$, d = 0.68	Feng and Sharratt, 2007
	Argentina, Pamas	Fine sandy loam; bare, conventional and no-till management	Erosion for 54 events	$R^2 = 0.89$	Buschiazzo and Zobeck, 2008
	USA, Columbia Plateau	Two sites, silt loam, contrasting tillage under summer fallow, six events	Erosion, total and PM10	SWEEP simulated no erosion while erosion losses were measured	Feng and Sharratt, 2009
	China, Tarim Basin	Cotton and red date orchard	Friction velocity	$R^2 = 0.21$ to 0.98	Pi et al., 2014
	China	Sandy soils; wind tunnel	Erosion	$R^2 = 0.944$ to 0.999	Liu et al., 2014
EPIC & WESS	USA, Texas	Agricultural field	Number of events	"Accurately predicted" 8 of 24 events	Van Pelt et al., 2004
	Canada, Alberta	Dark Brown Chernozem, fallow; agricultural field, 7 events	Erosion	"Approximated the magnitude for six of seven events"	Potter et al., 1998
APEX	China, Tarim Basin; USA, Washington	China, cotton, date orchard and desert ecotone; USA, Winter wheat-fallow, 9 events	Erosion	Cotton $R^2 = 0.50$ Date $R^2 = 0.64$ Ecotone $R^2 = 0.91$ Wheat $R^2 = 0.25$	Pi et al., 2017
TEAM	USA	Tested model components against various datasets	Vegetative cover, maximum transport, field length, dust fraction, soil cover	Vegetative cover, $R^2 = 0.99$; Max. transport, $R^2 = 0.95$; Length, $R^2 = 0.93$; Dust fraction, $R^2 = 0.997$; Soil cover, $R^2 = 0.99$	Singh et al., 1997
	USA	Various historic datasets	Horizontal flux	$R^2 = 0.71$ to 0.82	Gregory et al., 2004
WEELS	Germany and United Kingdom, Quaternary Plains	Erosion risk for two areas of agricultural land, sensitivity analysis only	Observed and modelled patterns	"appears to give satisfactory estimates of the spatial distribution of the wind-induced erosion"	Böhner et al., 2003

* R^2 is the Correlation Coefficient and d is the Index of Agreement. Qualitative statements from the cited literature are in quotes.

Potter et al. (1998) evaluated EPIC erosion sub-model WESS on a tilled field near Alberta, Canada. They state that the model significantly overestimated erosion for one event while it simulated erosion for three days with no measured erosion, although they provided no measure of significance. Field length had more effect on simulation during large erosion events than for smaller events. The surface soil water content effect on wind erosion appeared to be captured by the model, but only limited data were available to evaluate surface water. WESS predictions were also compared to measured erosion from 24 of individual wind events at Big Spring, TX by Van Pelt et al. (2004). They found that WESS under-predicted 9 events, accurately predicted 8 events, and over-predicted 7 events. In general, the events that WESS under-predicted were large magnitude storms with an overall $R^2 = 0.38$.

Validation of the APEX model is limited to only one study we could find in the literature. Pi et al, (2017) evaluated the model on a wide variety of land uses including cotton, date orchard, and a desert ecotone in China's Tamrin Basin and winter wheat in Washington, USA. The R^2 values varied greatly ($R^2 = 0.25$–0.91) and they found that simulations could be improved with site specific calibration of the model parameters using the method of Youssef et al., (2012).

The TEAM model has had various component routines validated as well as the entire model against several datasets from other studies, mostly the Fryrear, Big Spring dataset (Fryrear et al., 1991; Gregory et al., 2004; Singh et al., 1997). The components tested included the simulation of field length factor ($R^2 = 0.93$), soil cover (i.e., clods and ridges, $R^2 = 0.99$), vegetative cover (i.e., live and dead, $R^2 = 0.99$), dust fraction ($R^2 = 0.997$), and the maximum transport ($R^2 = 0.95$). The focus of the erosion loss validation only included the non-suspension components in TEAM, however Gregory et al. (2004) report R^2 values of "0.8 or better" for measured vs. simulated soil transport rate.

Much of the WEELS development was based on wind tunnel experiments on sandy soils. Validation with independent measured data has had only limited study by Böhner et al. (2003) at two sites in the UK and Germany, each with long-term measured datasets of 29 and 13 years respectively. Good agreement between observed and modelled patterns as well as the spatial variability of erosion risks were said by the authors to be reasonably estimated for the two sites. They did not provide any quantitative or statistical comparisons because model results were compared to local knowledge of erosion events such as visual observations.

5.2. Databases

The databases for WEQ, RWEQ and WEPS models are based on long-term climatic data, but each model uses such data in different ways to drive the erosion process. For example, the WEQ model requires average annual wind speed and prevailing wind direction for each month. Whereas, the climatic database of RWEQ has monthly probabilities for wind speed and direction as well as solar radiation, temperature and precipitation for locations in the USA (Buschiazzo and Zobeck, 2008). Needed soil information for RWEQ includes texture, organic matter and calcium carbonate. The WEPS wind database contains wind speed and direction distribution by month from which hourly wind speeds and daily direction are stochastically generated. Monthly mean maximum/minimum air temperatures, dew point temperature, solar radiation, and precipitation amount are obtained from a separate climate database known as CLIGEN (Nicks et al., 1995). The WEPS soil database for the USA are extracted interactively from the USDA-NRCS national soil database. Crop growth, residue decomposition, and management operations in WEPS are configured by a set of parameters that define and drive the processes represented in the model code. Databases with these parameters for the United States was developed by ARS and NRCS, which allows users to construct site-specific crop management practices to simulate cropland conditions for WEPS. SWEEP uses the same soil, wind, and wind barrier databases as WEPS. The EPIC and APEX models simulate soil loss for wind erosion under different management strategies, but these models need more input data in comparison with other models for reflecting the effect of soil management practices. Therefore, these models are only useful with an adequate database (Gassman et al., 2009; Pandey et al., 2016; Wang et al., 2006). The TEAM model has a climate database that is accessed when the user specifies a location to obtain wind, relative humidity, and rain day data. Other data are simply calculated based on user input such as soil type to determine soil particle size distribution as well as cover selection (bare soil, grass, and crop rotations). WEELS accesses available topographic and climatic information from databases (Böhner et al., 2003). Wind data are obtained by accessing the Wind Atlas Analysis and Application Program (Mortensen et al., 1993). With climatic data sets from an existing network of meteorological stations. Terrain is obtained from digital terrain models with a spatial resolution of 50 × 50 m that were processed and converted into contour lines (vector data) with a 2-m contour interval.

5.3. Representation of processes

Many models are unable to distinguish between fields where erosion events are source limited and those that are wind energy limited, because they fail to update the surface conditions during the erosion event. Some examples of surfaces where this capability is needed include desert pavements, narrow fields, highly aggregated surfaces, or ridged fields where the ridges can become armored with immobile aggregates. The WEPS and SWEEP models are the only models that update surface conditions during storm events (Hagen, 2008).

WEQ and RWEQ estimate the average total rate of soil loss at different field scales for annual and sub-monthly time periods respectively. In WEQ suspension is included as part of total loss and continues to increase downwind, so soil loss continues as field length increases. RWEQ sets an erosion transport capacity, which is only true for saltation and thus, ignores the large emission and transport of suspension downwind, because suspension has nearly unlimited transport capacity. RWEQ considers the suspension component negligible and thus underestimates this portion of loss. Hence, simply increasing the scale of fields in RWEQ beyond the length set for transport capacity decreases soil loss per unit area – not a result likely to lead to helpful erosion control designs on large fields. The WEPS and SWEEP models simulate soil loss at field scales from the wind erosion processes of creep plus saltation and suspension as well as the amount of soil loss as PM10 as a subset of the suspension component, which is important in air quality estimates (Sharratt et al., 2015; Tatarko et al., 2019). These models also simulate loss by direction for each simulation day, which provides useful information on off-site effects, as well as direction controls such as the placement of barriers. The TEAM model can simulate the amount of suspension sized dust emission and visibility calculated based on dust concentration with height (Singh et al., 1997). TEAM also varies transport and loss as the erosion process transitions across changing cover (Gregory et al., 2004). WEELS estimates the rate of sediment transport through the saltation process as affected by soil moisture, soil erodibility and roughness, and land use (Böhner et al., 2003). The WEELS model also simulates spatial variability in terms of loss and deposition in different parts of a simulated field, based on topography.

5.4. Selecting a suitable model

According to the literature, researchers select certain model types over others depending on three main needs: the represented processes, available databases or the final output. Each model serves a purpose that relies heavily on the function that the model provides, so a specific model type may not be considered more applicable in all situations (Merritt et al., 2003). The adoption of a particular model should consider its accuracy, robustness, ease of use with minimum input data, capability to consider changes in land use, climate and conservation practices, validity of results for each specific application, and time scale of simulation (Pandey et al., 2016; Routschek et al., 2014). We also note that some models may no longer be maintained or extended. To determine the level of support, maintenance, and development for individual models is a task that is beyond the scope of this review. However, we do believe that the literature for each model provides some measure of the current development state of each model.

Here we highlight several steps that lead to selecting an appropriate model to minimize the risk of selecting the wrong model. First, correctly recognize the issue of interest to identify the desired outputs. The second step is to access comprehensive information about the modelled system for estimating different parameters in the model equations, which affect the accuracy and reliability of outputs. Validating and calibrating the model may be a necessary third step. The model's validity should be evaluated for erosion simulation results compared with field measurements over the applied area or region. Models may also require calibration with field data before validation. Govers (2010) expressed the notion that models only can be applied for conditions where they were calibrated and validated. However, the more physical-based process models should require little or no calibration.

Wind erosion models are categorized in three different groups: empirical, conceptual, and physical based models and range from the simple to complex. The practical application of each wind erosion model depends on the model natural complexity and accuracy. However, the accuracy of each model should not be considered to be related to the level of model complexity. Steefel and Van Cappellen (1998) believed that a model's value along with its simplicity is related to its power in explaining results. For instance, Letcher et al. (1999) argued that simple conceptual models or empirical models, when used within the developed framework, may be more accurate than complicated models. In some cases, complicated models have a high degree of uncertainty due to untested equations, interactions among factors, many input requirements, and unavailability of accurate datasets, which decrease the benefits of such models. By improving physically based erosion models, we can reduce the need to develop empirical calibration factors and thereby reduce much of the work needed in applying models to wind erosion problems. Where resources are limited for developing databases, conceptual and empirical models are often more adaptable to scenarios with limited data due to less requirement for input parameters compared to process-based models (Blanco-Canqui and Lal, 2008a).

6. Future research needs

When reviewing various wind erosion models, some ideas are evident to serve as guides to future research. A few suggestions include:

- Improve measurement and modeling of surface and subsurface soil wind erosion parameters in response to tillage and weather forces.
- Better utilize remote sensing technologies to measure indicators of wind erosion potential.
- Further develop, calibrate, and validate models that are adaptable for plot to regional scales.
- Use models to develop new and innovative wind erosion control and management practices.
- Integrate wind erosion models with other models including those of driving forces (e.g., weather) and controls (e.g., plant growth).
- Test models under different climates, land use, and soils at varying temporal and spatial scales to aid in assessing wind erosion potential.
- Develop databases for models to extend them to new areas of the world with wind erosion problems.
- Develop improved models and databases for improved application to non-uniform and hilly terrain.
- Develop ability of models to direct land management decisions regarding wind erosion impacts on ecosystem services.
- Use models to inform policy makers for improved soil, air, water, and health quality.

Many models such as WEPS, given accurate inputs, are now quite useful to assess the impact of typical control practices on erosion. But when conventional controls are not effective, or more likely, are too expensive, new solutions are needed. For example, cloddy tillage ridges are widely employed to control erosion when the crop type or drought do not provide sufficient residue. But freeze/thawing and/or wetting/drying may turn the immobile clods to mobile aggregates. Some form of cost effective protection for the armor of cloddy surfaces would provide a much needed solution to the problem.

7. Conclusion

The most accepted soil erosion models range from empirical to physics-based or some combination of both. We summarized several models in terms of their history, structure, processes, limitations, and applications. In addition, we evaluated the databases required, as well as the inputs and outputs to provide information about each model to aid in model selection based on the desired applications and conditions. To minimize soil loss and optimize land productivity in regions that are subjected to wind erosion, predicting soil loss is an important step in land use planning, market-controlled management strategies, and farming practices. Wind erosion models can provide useful tools to researchers of surface and erosion processes, as well as land managers and policy makers to address key issues of natural resource management and sustainability.

Acknowledgements

Appreciation is extended to Julius Kuehn Institute (JKI), Federal Research Centre for Cultivated Plants (Germany), Institute for Crop and Soil Science and Technische Universität Braunschweig (Germany), Institute of Geoecology. The authors acknowledge the helpful comments from Dr. Lawrence J. Hagen.

References

Ahmadi, H., 1998. Applied geomorphology: desert and wind erosion. Tehran University Publication, pp. 85–395.
Alfaro, S.C., Gomes, L., 2001. Modeling mineral aerosol production by wind erosion: emission intensities and aerosol size distributions in source areas. J. Geophys. Res. 106, 18075–18084.
Alfaro, S.C., Rajot, J.L., Nickling, W., 2004. Estimation of PM20 emissions by wind erosion: main sources of uncertainties. Geomorphology 59, 63–74.
Azarkar, S.M., Ahmadi, H., Khorasani, N., Karami, M., 2006. Investigating the relationship between wind erosion and value of animal habitats in desert areas. Intern. J. Environ. Sci. Tech. 2, 387–393.
Bagnold, R., 1943. The physics of blown sand and desert dunes. Methuen, London, pp. 265.
Bhuyan, S.J., Kalita, P.K., Janssen, K.A., Barnes, P.L., 2002. Soil loss predictions with three erosion simulation models. Environ. Modell. Software 17, 137–146.
Blanco-Canqui, H., Lal, R., 2008a. Soil and water conservation. In: Blanco, H., Lal, R. (Eds.), Principles of Soil Conservation and Management. Springer, Netherlands, Dordrecht, pp. 1–19.
Blanco-Canqui, H., Lal, R., 2008b. Wind Erosion. In: Blanco, H., Lal, R. (Eds.), Principles of Soil Conservation and Management. Springer, Netherlands, Dordrecht, pp. 55–80.
Boardman, J., Poesen, J., 2006. Soil erosion in Europe: major processes, causes and consequences, soil erosion in Europe. John Wiley & Sons Ltd, pp. 477–487.
Böhner, J., Schäfer, W., Conrad, O., Gross, J., Ringeler, A., 2003. The WEELS model: methods, results and limitations. Catena 52, 289–308.
Borrelli, P., Lugato, E., Montanarella, L., Panagos, P., 2017. A new assessment of soil loss due to wind erosion in European agricultural soils using a quantitative spatially distributed modelling approach. Land Degrad. Dev. 28, 335–344.
Buschiazzo, D.E., Zobeck, T.M., 2008. Validation of WEQ, RWEQ and WEPS wind erosion for different arable land management systems in the Argentinean Pampas. Earth Surf. Proc. Land. 33, 1839–1850.
Chen, L., Gao, J., Ji, Y., Bai, Z., Shi, S., Liu, H., 2014. Effects of particulate matter of various sizes derived from suburban farmland, woodland and grassland on air quality of the central district in Tianjin. China. Aerosol Air Quality Res. 14, 829–839.
Cheng, H., Liu, C., Li, J., Zou, X., Liu, B., Kang, L., Fang, Y., 2017. Wind erosion mass variability with sand bed in a wind tunnel. Soil Tillage Res. 165, 181–189.
Chepil, W., 1945a. Dynamics of wind erosion: I. Nature of movement of soil by wind. Soil Sci. 60, 305–320.

Chepil, W., 1945b. Dynamics of wind erosion: II. Initiation of soil movement. Soil Sci. 60, 397.
Chepil, W., 1945c. Dynamics of wind erosion: III. The transport capacity of the wind. Soil Sci. 60, 475–480.
Chepil, W., 1959. Wind erodibility of farm fields. J. Soil. Water Conserv. 14, 214–219.
Chepil, W., Woodruff, N., 1963. The physics of wind erosion and its control. Adv. Agron. 15, 211–302.
Clow, D.W., Williams, M.W., Schuster, P.F., 2016. Increasing aeolian dust deposition to snowpacks in the Rocky Mountains inferred from snowpack, wet deposition, and aerosol chemistry. Atmos. Environ. 146, 183–194.
Cole, G., 1983. Wind erosion modeling. In: Proc. 1983 Natural Resources Modeling Symp. USDA-ARS, Pingree Park, Colorado, pp. 59–63.
Cole, G.W., Lyles, L., Hagen, L.J., 1983. A simulation model of daily wind erosion soil loss. Trans. Am. Soc. Agric. Engin. 26 (6), 1758–1765.
Cornelis, W.M., 2006. Hydroclimatology of wind erosion in arid and semiarid envirmonments. In: D'Odorico, P., Porporato, A. (Eds.), Dryland Ecohydrology. Springer, Netherlands, Dordrecht, pp. 141–159.
de Oro, L.A., Colazo, J.C., Buschiazzo, D.E., 2016. RWEQ–Wind erosion predictions for variable soil roughness conditions. Aeolian Res. 20, 139–146.
Doetterl, S., Berhe, A.A., Nadeu, E., Wang, Z., Sommer, M., Fiener, P., 2016. Erosion, deposition and soil carbon: a review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. J Earth-Science Reviews. 154, 102–122.
Durar, A., Skidmore, E., 1995. WEPS technical documentation: hydrology submodel. SWCS WEPP/WEPS Symposium, Ankeny, IA.
Edwards, B.L., Webb, N.P., McCord, S.E., 2018. AERO: A wind erosion modeling framework with applications to monitoring data. In: 73rd Soil and Water Conservation Society Annual Conference, Albuquerque, USA.
Feng, G., Sharratt, B., 2007. Validation of WEPS for soil and PM10 loss from agricultural fields within the Columbia Plateau of the United States. Earth Surf. Proc. Land. 32, 743–753.
Feng, G., Sharratt, B., 2009. Evaluation of the SWEEP model during high winds on the Columbia Plateau. Earth Surf. Proc. Land. 34, 1461–1468.
Fisher, P., Skidmore, E., 1970. WEROS: a Fortran IV program to solve the wind-erosion equation. USDA-ARS 41–174, 13 pp.
Fryrear, D., Bilbro, J.D., Saleh, A., Schomberg, H., Stout, J.E., Zobeck, T.M., 2000. RWEQ: Improved wind erosion technology. J. Soil Water Cons. 55, 183–189.
Fryrear, D., Saleh, A., Bilbro, J.D., Schomberg, H., Stout, J.E., Zobeck, T.M., 1998. Revised wind erosion equation (RWEQ). Wind Erosion and Water Conservation Research Unit, USDA-ARS, Southern Plains Area Cropping Systems Research Laboratory. Technical Bulletin 1.
Fryrear, D., Stout, J., Hagen, L., Vories, E.D., 1991. Wind erosion: field measurement and analysis. Trans. ASAE. 34, 155–0160.
Fryrear, D., Sutherland, P., Davis, G., Hardee, G., Dollar, M., 1999. Wind erosion estimates with RWEQ and WEQ, Proceedings of Conference Sustaining the Global Farm. In: 10th International Soil Conservation Organization Meeting. Purdue University, pp. 760–765.
Fryrear, D., Wassif, M., Tadrus, S., Ali, A., 2008. Dust measurements in the Egyptian northwest coastal zone. Trans. ASABE 51, 1255–1262.
Funk, R., Skidmore, E.L., Hagen, L.J., 2004. Comparison of wind erosion measurements in Germany with simulated soil losses by WEPS. Environ. Modell. Software 19, 177–183.
Gassman, P.W., Williams, J.R., Wang, X., Saleh, A., Iseiu, E., Hauck, L.M. Cesar, Izaurralde, R., Flowers, J.J., 2009. The Agricultural Policy Environmental Extender (APEX) model: An emerging tool for landscape and watershed environmental analyses, Technical Report 09-TR 49. Center for Agricultural and Rural Development Iowa State University Ames, Iowa.
Gillette, D., 1978. A wind tunnel simulation of the erosion of soil: Effect of soil texture, sandblasting, wind speed, and soil consolidation on dust production. Atmos. Environ. (1967) 1735–1743.
Gillette, D.A., Walker, T.R., 1977. Characteristics of airborne particles produced by wind erosion of sandy soil, High Plains of west Texas. Soil Sci. 97–110.
Goossens, D., Riksen, M.J.P.M., 2004. Wind erosion and dust dynamics at the commencement of the 21st century. Preface. In: Goossens, D., Riksen, M.J.P.M. (Eds.), Wind Erosion and Dust Dynamics: Observations, Simulations, Modelling. Wageningen University, Wageningen, pp. 7–14.
Govers, G., 2010. Misapplications and Misconceptions of Erosion Models, Handbook of Erosion Modelling. John Wiley & Sons Ltd 117–134.
Gregory, J.M., Vining, R., Peck, L., Wofford, K., 1999. TEAM: the Texas tech wind erosion analysis model. In: Stott, D.E., Mohtar, R.H., Steinhardt, G.C. (Eds.), Sustaining the global farm: selected papers from the 10th International Soil Conservation Organization Meeting. Purdue University and the USDA-ARS National Soil Erosion Research Laboratory, pp. 29.
Gregory, J.M., Wilson, G.R., Singh, U.B., Darwish, M.M., 2004. TEAM: integrated, process-based wind-erosion model. Environ. Modell. Software 19, 205–215.
Hagen, L., 1991. A wind erosion prediction system to meet user needs. J. Soil Water Conserv. 46, 106–111.
Hagen, L., 1995. Wind Erosion Prediction System (WEPS) technical description: erosion submodel. Proceedings of the WEPP/WEPS Symposium. Soil and Water Conservation Society, Ankeny, IA.
Hagen, L., Wagner, L., Skidmore, E., 1999. Analytical solutions and sensitivity analyses for sediment transport in WEPS. Trans ASAE 42, 1715–1721.
Hagen, L., Zobeck, T., Skidmore, E., Elminyawi, I., 1995. WEPS technical documentation: soil submodel. SWCS WEPP/WEPS Symposium, Ankeny, IA.
Hagen, L.J., 2004. Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields. Environ. Modell. Software 19, 171–176.
Hagen, L.J., 2008. Updating soil surface conditions during wind erosion events using the Wind Erosion Prediction System (WEPS). Trans. ASABE 51, 129–137.
He, X., Zhou, J., Zhang, X., Tang, K., 2006. Soil erosion response to climatic change and human activity during the Quaternary on the Loess Plateau, China. Reg. Environ. Change 6, 62–70.
Jiang, H., Dun, H., Tong, D., Huang, N., 2017. Sand transportation and reverse patterns over leeward face of sand dune. Geomorphology 283, 41–47.
Letcher, R.A., et al., 1999. Review of Techniques to Estimate Catchment Exports. Environment Protection Agency, Sydney, pp. 110.
Liu, B., Qu, J., Niu, Q., Han, Q., 2014. Comparison of measured wind tunnel and SWEEP simulated soil losses. Geomorphology 207, 23–29.
Lu, H., Shao, Y., 2001. Toward quantitative prediction of dust storms: an integrated wind erosion modelling system and its applications. Environ. Modell. Software 16, 233–249.
Lyles, L., 1983. Erosive wind energy distributions and climatic factors for the West. J. Soil and Water Conserv. 38, 106–109.
Lyles, L., 1988. 4. Basic wind erosion processes. Agric. Ecosyst. Environ. 22, 91–101.
Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environ. Modell. Software 18, 761–799.
Mortensen, N.G., Landberg, L., Troen, I., Petersen, E.L., 1993. Wind atlas analysis and application program (WAsP). Riso National Laboratory, Roskilde, Dänemark.
Nicks, A.D., Lane, L.J., Gander, G.A., 1995. Chapter 2. Weather Generator. In: Flanagan, D.C., Nearing, M.A. (Eds.), USDA-Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation. NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana, pp. 21–222.
Okin, G.S., 2005. Dependence of wind erosion and dust emission on surface heterogeneity: stochastic modeling. J. Geophys. Res. 110, D11208.
Pandey, A., Himanshu, S.K., Mishra, S.K., Singh, V.P., 2016. Physically based soil erosion and sediment yield models revisited. Catena 147, 595–620.
Pehrson, J.R., Chiou, J., 1996. Emissions of contaminated fugitive dust under extreme (non-tornado) wind conditions. In: Proceedings of the topical meeting on the best of D&D–creative, comprehensive and cost-effective: Chicago, Illinois, April 14-17, 1996. American Nuclear Society, pp. 147.
Pi, H., Feng, G., Sharratt, B.S., Li, X., Zheng, Z., 2014. Validation of SWEEP for contrasting agricultural land use types in the Tarim Basin. Soil Sci. 179, 433–445.
Pi, H., Sharratt, B., Feng, G., Lei, J., 2017. Evaluation of two empirical wind erosion models in arid and semi-arid regions of China and the USA. Environ. Modell. Software 91, 28–46.
Plotkin, S., et al., 2013. APEX calibration and validation of water and herbicide transport under US southern Atlantic coastal plain conditions. Trans. ASABE 56, 43–60.
Potter, K., Williams, J., Larney, F., Bullock, M., 1998. Evaluation of EPIC's wind erosion submodel using data from southern Alberta. Can. J. Soil Sci. 78, 485–492.
Puurveen, H., Izaurralde, R., Chanasyk, D., Williams, J., Grant, R., 1997. Evaluation of EPIC's snowmelt and water erosion submodels using data from the Peace River region of Alberta. Can. J Soil Sci. 77, 41–50.
Retta, A., Armbrust, D., 1995. WEPS technical documentation: Crop submodel. SWCS WEPP/WEPS Symposium, Ankeny, IA.
Rezaei, M., Sameni, A., Fallah Shamsi, S.R., Bartholomeus, H., 2016. Remote sensing of land use/cover changes and its effect on wind erosion potential in southern Iran. PeerJ 4, e1948.
Routschek, A., Schmidt, J., Kreienkamp, F., 2014. Impact of climate change on soil erosion – a high-resolution projection on catchment scale until 2100 in Saxony/Germany. Catena 121, 99–109.
Saleh, A., Fryrear, D., 1999. Soil roughness for the revised wind erosion equation (RWEQ). J. Soil Water Conserv. 54, 473–476.
Shao, Y., 2008. Physics and modelling of wind erosion. Springer Science & Business Media.
Sharratt, B.S., Tatarko, J., Abatzoglou, J.T., Fox, F.A., Huggins, D., 2015. Implications of climate change on wind erosion of agricultural lands in the Columbia plateau. Weather Clim. Extremes 10 (Part A), 20–31.
Singh, U.B., Gregory, J.M., Wilson, G.R., 1997. Texas erosion analysis model: theory and validation. In: Proceedings of Wind Erosion: An International Symposium/Workshop. 3–5 June 1997, Manhattan, Kansas, USA.
Skidmore, E., 1986. Wind erosion climatic erosivity. Clim. Change 9, 195–208.
Skidmore, E.L., Williams, J., 1991. Modified EPIC wind erosion model. Modeling plant and soil systems 457–469.
Stallings, J.H., 1951. Mechanics of wind erosion. U.S. Department of Agriculture, Soil Conservation Service. TP 98. U.S. Governent Printing Off., Washington, D.C.
Steefel, C.I., Van Cappellen, P., 1998. Reactive transport modeling of natural systems. J. Hydrol. 209, 1–7.
Steiner, J., Schomberg, H., Unger, P., 1995. WEPS technical documentation: Residue decomposition submodel. In: SWCS WEPP/WEPS Symposium. Ankeny, IA.
Stout, J.E., Warren, A., Gill, T.E., 2009. Publication trends in aeolian research: An analysis of the Bibliography of Aeolian Research. J Geomorphology 105, 6–17.
Suter-Burri, K., Gromke, C., Leonard, K.C., Graf, F., 2013. Spatial patterns of aeolian sediment deposition in vegetation canopies: Observations from wind tunnel experiments using colored sand. Aeolian Res. 8, 65–73.
Tatarko, J., 2001. Soil aggregation and wind erosion: processes and measurements. Ann. Arid Zone 40, 251–264.
Tatarko, J., Sporcic, M.A., Skidmore, E.L., 2013. A history of wind erosion prediction models in the United States Department of Agriculture prior to the Wind Erosion Prediction System. Aeolian Res. 10, 3–8.
Tatarko, J., van Donk, S., Ascough, J., Walker, D., 2016. Application of the WEPS and SWEEP models to non-agricultural disturbed lands. Heliyon 2 (12), e00215.
Tatarko, J., Wagner, L.E., Fox, F., 2019. The wind erosion prediction system and its use in conservation planning. In: Wendroth, O. (Ed.), Bridging Among Disciplines by

Synthesizing Soil and Plant Processes, Adv. Agric. Syst. Model. 8. ASA, CSSA, and SSSA, Madison, WI.
Toure, A., Major, D., Lindwall, C., 1995. Comparison of five wheat simulation models in southern Alberta. Can. J Plant Sci. 75, 61–68.
Van Donk, S.J., Skidmore, E.L., 2003. Measurement and simulation of wind erosion, roughness degradation and residue decomposition on an agricultural field. Surf. Proc. Land. 28, 1243–1258.
Van Pelt, R.S., Zobeck, T.M., 2004. Validation of the Wind Erosion Equation (WEQ) for discrete periods. Environ. Modell. Software 19, 199–203.
Van Pelt, R.S., Zobeck, T.M., Potter, K.N., Stout, J.E., Popham, T.W., 2004. Validation of the wind erosion stochastic simulator (WESS) and the revised wind erosion equation (RWEQ) for single events. Environ. Modell. Software 19, 191–198.
Visser, S., Stroosnijder, L., Chardon, W., 2005a. Nutrient losses by wind and water, measurements and modelling. Catena 63, 1–22.
Visser, S.M., Sterk, G., Karssenberg, D., 2005b. Wind erosion modelling in a Sahelian environment. Environ. Modell. Software 20, 69–84.
Wagner, L.E., 2013. A history of Wind Erosion Prediction Models in the United States Department of Agriculture: The Wind Erosion Prediction System (WEPS). Aeolian Res. 10, 9–24.
Wagner, L.E., Fox, F.A., 2013. The management submodel of the wind erosion prediction system. Appl. Eng. Agric. 29 (3), 361–372.
Wang, X., Potter, S., Williams, J., Atwood, J.D., Pitts, T., 2006. Sensitivity analysis of APEX for national assessment. Trans. ASABE 49, 679–688.
Wang, X., Williams, J., Atwood, J., Norfleet, M., King, A., 2011. APEX model upgrades, data inputs, and parameter settings for use in CEAP cropland modeling.
Wang, X., Williams, J., Atwood, J.D., Norfleet, M.L., Kign, A.D., 2012. EPIC and APEX: Model use, calibration, and validation. Trans. ASABE 55, 1447–1462.
Webb, M.N., 2008. Modelling land susceptibility to wind erosion in western Queensland. Australia. Environ. Modell. Software 24, 214–227.
Webb, N.P., McGowan, H.A., Phinn, S.R., McTainsh, G.H., 2006. AUSLEM (Australian Land Erodibility Model): a tool for identifying wind erosion hazard in Australia. Geomorphology 78, 179–200.
Weinan, C., Fryrear, D.W., 1996. Grain-size distributions of wind-eroded material above a flat bare soil. Phys. Geography 17, 554–584.
Williams, J., Izaurralde, R., Steglich, E., 2008. Agricultural policy/environmental extender model. Theoretical Documentation, Version 604, 2008-17.
Williams, J., Jones, C., Dyke, P., 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27, 129–144.
Williams, J., Jones, C., Gassman, P., Hauck, L., 1995. Simulation of animal waste management with APEX. Innovat. New Horizons Livestock Poultry Manure Manage. 1, 22–26.
Williams, J., et al., 2010. APEX model validation for CEAP. USDA-Natural Resources Conservation Service, Temple, Texas, pp. 1–13.
Williams, J.R., Izaurralde, R., 2006. The APEX model. Watershed models 437–482.
Woodruff, N., Siddoway, F., 1965. A wind erosion equation. Soil Sci. Soc. Am. J. 29, 602–608.
Youssef, F., Visser, S., Karssenberg, D., Bruggeman, A., Erpul, G., 2012. Calibration of RWEQ in a patchy landscape; a first step towards a regional scale wind erosion model. Aeolian Res. 3, 467–476.
Zobeck, T.M., Van Pelt, R.S., Stout, J.E., Popham, T.W., 2001. Validation of the Revised Wind Erosion Equation (RWEQ) for Single Events and Discrete Periods. In: Ascough, J.C., Flanagan, D.C. (Eds.), Soil Erosion Research for the 21st Century, Proc. Int. Symp. St. Joseph. MIASAE, MI.