

Received:
13 September 2016
Revised:
3 November 2016
Accepted:
8 December 2016

Heliyon 2 (2016) e00215



Application of the WEPS and SWEEP models to non-agricultural disturbed lands

J. Tatarko^{a,*}, S.J. van Donk^b, J.C. Ascough II^{c,1}, D.G. Walker^d

^a USDA-ARS-PA, Agricultural Systems Research Unit, Fort Collins, CO 80526, USA

^b Iteris Incorporated, Grand Forks, ND 58203, USA

^c USDA-ARS-PA, Water Management and Systems Research Unit, Fort Collins, CO 80528, USA

^d David Walker and Associates Ltd (retired), Calgary, AB, Canada

* Corresponding author.

E-mail address: john.tatarko@ars.usda.gov (J. Tatarko).

¹ Deceased.

Abstract

Wind erosion not only affects agricultural productivity but also soil, air, and water quality. Dust and specifically particulate matter $\leq 10 \mu\text{m}$ (PM-10) has adverse effects on respiratory health and also reduces visibility along roadways, resulting in auto accidents. The Wind Erosion Prediction System (WEPS) was developed by the USDA-Agricultural Research Service to simulate wind erosion and provide for conservation planning on cultivated agricultural lands. A companion product, known as the Single-Event Wind Erosion Evaluation Program (SWEEP), has also been developed which consists of the stand-alone WEPS erosion submodel combined with a graphical interface to simulate soil loss from single (i.e., daily) wind storm events. In addition to agricultural lands, wind driven dust emissions also occur from other anthropogenic sources such as construction sites, mined and reclaimed areas, landfills, and other disturbed lands. Although developed for agricultural fields, WEPS and SWEEP are useful tools for simulating erosion by wind for non-agricultural lands where typical agricultural practices are not employed. On disturbed lands, WEPS can be applied for simulating long-term (i.e., multi-year) erosion control strategies. SWEEP on the other hand was developed specifically for disturbed lands and can simulate potential soil loss for site- and date-specific planned surface conditions and control practices. This paper

presents novel applications of WEPS and SWEEP for developing erosion control strategies on non-agricultural disturbed lands. Erosion control planning with WEPS and SWEEP using water and other dust suppressants, wind barriers, straw mulch, re-vegetation, and other management practices is demonstrated herein through the use of comparative simulation scenarios. The scenarios confirm the efficacy of the WEPS and SWEEP models as valuable tools for supporting the design of erosion control plans for disturbed lands that are not only cost-effective but also incorporate a science-based approach to risk assessment.

Keywords: Environmental Science

1. Introduction

Research has shown that wind erosion lowers soil productivity by removing the most fertile parts of the soil, most notably the clays and organic matter (Lyles and Tatarko, 1986). It also damages soil structure and water holding capacity and saltating grains can damage plants in the field (Lyles and Woodruff, 1960; Armbrust, 1984). Wind erosion can also degrade soil, air, and water resources. Dust from soil erosion by wind is well known as a serious threat to health and the environment throughout the United States and the world as it can decrease visibility, sometimes resulting in automobile accidents (Hagen and Skidmore, 1977), and often fills road ditches and irrigation canals where eroded particles can impact water quality (Wagner and Hagen, 2001). More recently, dust has been related to rapid spring-time melt of mountain snowpack which translates into early melt runoff and potential flooding downstream (Painter et al., 2007). Soil-derived dust can travel great distances and can be a major source of atmospheric particulates (Prospero, 1999; Diaz et al., 2010). Dust from wind erosion imperils animal and human health and degrades air quality (Pope et al., 1991; Wilson and Spengler, 1996). Inhalable particulates have been found to cause adverse effects on respiratory health and contribute to excess mortality (Dockery et al., 1989; Penttinen et al., 2001; Kanatani et al., 2010). Dust has also been shown to have impacts on climate change (Prospero and Lamb, 2003). Dust and specifically particulate matter $\leq 10 \mu\text{m}$ (PM-10), is regulated by the United States Environmental Protection Agency (USEPA) National Ambient Air Quality Standards at $150 \mu\text{g m}^{-3}$ of 24-hour average concentration “to protect and enhance the quality of the Nation's air resources so as to promote the public health and welfare and the productive capacity of its population” (USEPA, 1993).

Wind erosion models are generally designed to simulate on-site and in some cases off-site consequences of soil loss for given land conditions. The Wind Erosion Prediction System (WEPS) model (Hagen, 1991; Wagner, 2013) was developed by the USDA-Agricultural Research Service, primarily for use by the USDA Natural Resources Conservation Service (NRCS) to: 1) assist land managers in controlling

wind erosion; 2) establish acceptable field level conservation plans; and 3) determine wind erosion susceptibility as part of the Conservation Reserve Program (CRP) and other national conservation program enrollments. WEPS is a process-based, daily-time step model that simulates multiple processes (e.g., hydrology, plant growth and decomposition, and soil surface erodibility) to predict wind erosion soil loss as affected by site-specific climate, soil type, and land management (Hagen, 2004). WEPS simulation of wind movement of soil has undergone extensive field and wind tunnel testing and validation. Good agreements (i.e., coefficients of determination ranging from 0.87 to 0.98) were found in a number of studies between measured and WEPS-simulated erosion (Buschiazzo and Zobeck, 2008; Funk et al., 2004; Liu et al., 2014). Soil loss measurements from 46 storm events in six states were compared to predictions from the WEPS erosion submodel by Hagen (2004) who found measured and simulated erosion values were in “reasonable agreement” ($R^2 = 0.71$). Because of WEPS improvements over previous models, the United States Congress stipulated that “. . . the WEPS model will be used (by NRCS) where wind erosion is the primary causal factor for comparing the annual level of erosion before conservation system application to the expected annual level of erosion after conservation system application.” (Federal Register, 2010). WEPS has commonly been applied for long-term (i.e., multi-year) simulations; however, under many construction and other disturbed land situations, a site is only exposed or vulnerable to wind erosion during a short time period of days, weeks, or months. To assist in the management of disturbed lands, the WEPS erosion submodel was disaggregated into a stand-alone companion product known as the Single-Event Wind Erosion Evaluation Program (SWEEP) for simulating single-day wind storm events under a specified surface condition. SWEEP consists of the erosion submodel of WEPS with a graphical user interface (GUI) for ease of inputs and outputs.

Methods for using WEPS and SWEEP to simulate erosion by wind on disturbed lands have been developed where typical agricultural practices and control methods are not employed. WEPS is suitable for simulating long-term management strategies such as mulching, re-vegetation, wind barriers, and land roughening (van Donk and Skidmore, 2003; Wagner 2013). SWEEP on the other hand was developed to simulate potential soil loss for a given date while also providing probabilities of dust emission events by month (the smallest temporal resolution of historic wind probabilities in the SWEEP weather database), given site-specific planned surface conditions and control practices. Open emission sources of wind generated dust from disturbed lands include: 1) construction sites (both residential and non-residential), and linear areas such as roadways and pipelines; 2) mined and reclaimed land as well as stockpiled materials; 3) landfills; and 4) other disturbed lands such as grazing and recreational lands.

Emissions from disturbed non-agricultural lands are often regulated by government agencies, for example, the USEPA sets limits on particulate emission levels and establishes permits for pollution release (USEPA, 1993). In addition, state agencies often develop State Implementation Plans (SIP's) and operate permit programs for release of dust.

Published applications of WEPS and SWEEP to non-agricultural lands are limited. van Donk et al. (2003) parameterized WEPS for conditions resulting from military training activities although it was not used to design controls. Similarly, surface measurements and aerial imagery were used in Germany to determine SWEEP inputs to simulate the potential range in wind erosion losses for a 6 ha hydrologic catchment (Maurer and Gerke, 2011). Jia et al. (2014) also used SWEEP to simulate erosion loss from mine tailings in northern Sweden. The only published use of WEPS to design erosion controls on non-agricultural lands was by Hagen et al. (2009) where the model was used to estimate potential suspended particulate emissions from a confined sediment disposal facility in Indiana, USA. Snow fences, short barriers, and stabilized strips were simulated as potential erosion controls. The results showed that any of these could provide adequate reductions in emissions to meet target levels.

This paper demonstrates new uses of WEPS and SWEEP for developing erosion sediment and dust control management strategies on non-agricultural disturbed lands. Comparative simulation scenarios are presented where typical WEPS and SWEEP inputs and management operations have been modified to simulate control practices (including water and other dust suppressants, wind barriers such as silt and snow fencing or hay bales, straw mulch, re-vegetation, and other practices) for non-agricultural conditions. The paper is not intended to provide a detailed description of the operation of WEPS and SWEEP but rather to illustrate (through easily understandable simulation scenarios) how these models can be adapted and applied to non-agricultural disturbed lands. Note that although several control practices are used as examples herein, our intent is not to endorse any practice or product. As with the selection of any erosion control method, the effectiveness of the method in controlling wind erosion, labor and costs, length of effectiveness, as well as other factors should be considered.

2. Methods

2.1. WEPS model description

WEPS is a physically-based daily simulation model that simulates weather, field surface conditions, and wind erosion (Wagner, 2013). As shown in Fig. 1, WEPS has a modular structure that consists of a user interface (programmed in Java), a science model (programmed in FORTRAN) with a main controlling routine and six science submodels (hydrology, management, soil, crop growth, crop residue

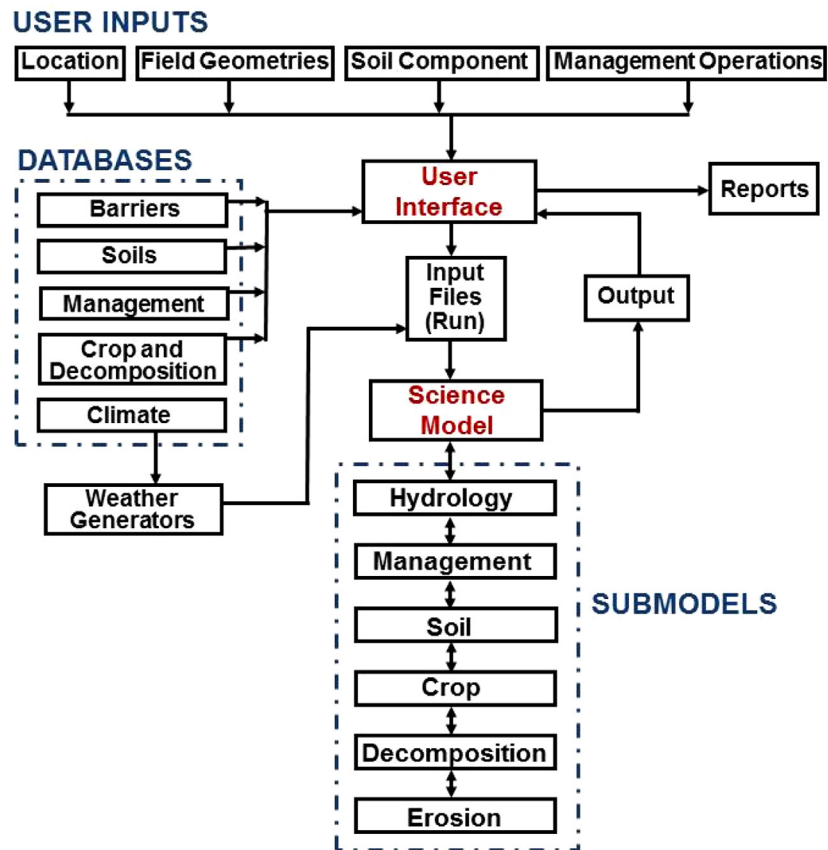


Fig. 1. WEPS model components, submodels, and databases (from Wagner, 2013).

decomposition, and erosion), and five databases (soil, crop, growth and residue decomposition, operations, wind barriers, and climate). This modular structure facilitates model maintenance, upgrades, and new applications (Gao et al., 2013). Climate is the primary driver for natural surface physical processes. The hydrology submodel simulates soil energy dynamic changes, including soil temperature and water content in soil layers. User-prescribed practices, including tillage, planting, harvesting, and irrigation, are simulated in the management submodel. The soil submodel simulates soil physical and chemical changes in soil layers and the surface due to weathering processes between management events. Crop growth is simulated in the plant growth submodel, and plant residue decomposition is accounted for in the decomposition submodel. The erosion submodel can be used to simulate or predict estimated losses in terms of total (< 2.0 mm), creep + saltation (2.0 to 0.1 mm), suspension (< 0.1 mm), and PM-10 emission into the atmosphere, and is the primary submodel of the six that comprise WEPS (Hagen, 1995). It simulates erosion processes if the surface threshold friction velocity is less than the actual friction velocity (computed from the hourly wind speed and current surface aerodynamic roughness).

WEPS is currently limited to simulating a region (field) represented by a single soil type, with a crop management sequence applied to the entire field, driven by weather from a single location. However, modifications are currently being made to the model to allow it to simulate multiple subregions, e.g., to handle a simulation site with non-homogeneous conditions, such as different soil types and management practices on different regions of the field as well as handling strip cropping practices directly within the model. WEPS has been extensively evaluated throughout the United States including eastern Colorado, USA (van Donk and Skidmore, 2003); Colorado, Kansas, Missouri, Nebraska, Texas, and Washington, USA (Hagen, 2004); Columbia Plateau, USA (Feng and Sharratt, 2007; Chung et al., 2013; and Gao et al., 2013) and also internationally including Canada (Coen et al., 2004); Germany (Funk et al., 2004); Argentina (Buschiazzo and Zobeck, 2008); and China (Chen et al., 2014).

WEPS contains a graphical user interface (GUI), coded in JAVA, for input of initial field conditions, calculating soil loss, and displaying either simple or detailed long-term simulation outputs for designing erosion control systems. Only four types of information are entered on the WEPS GUI main screen (Fig. 2): 1) a description of the simulation region geometry by defining the field dimensions and field orientation; 2) selection of the field location for which to generate simulated

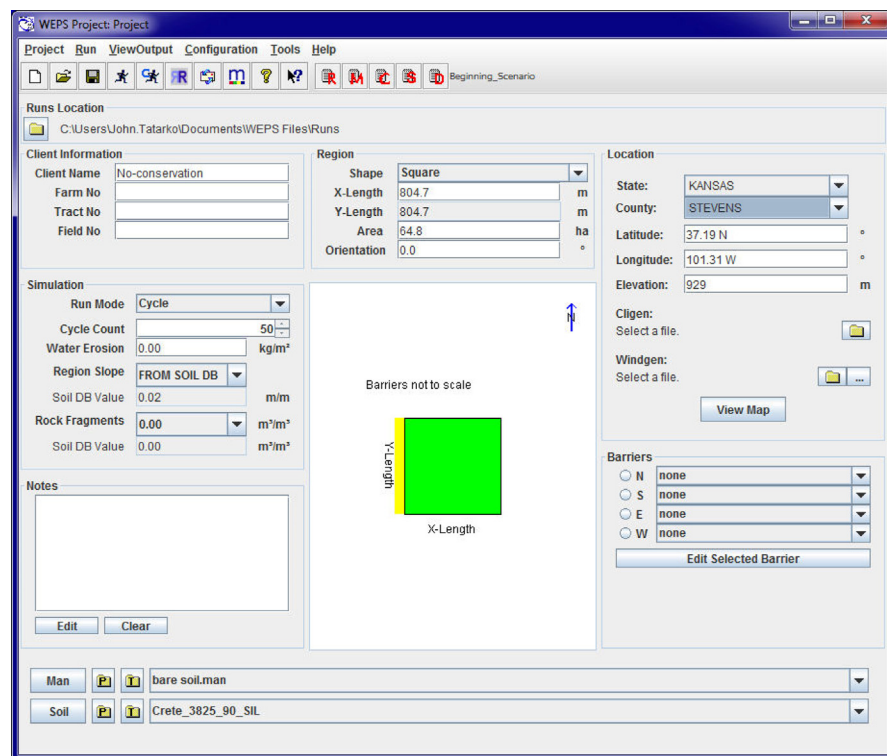


Fig. 2. WEPS graphical user interface (GUI) main screen.

weather; 3) soil type selection; and 4) management scenario selection. For United States simulations, the last three types of information may be selected from default lists provided with the WEPS model. New input files can easily be created, typically using existing input files as templates modified within the interface. By varying inputs, in particular the field management, the user can compare various alternatives to control soil loss by wind.

Field management is the most common means through which a land manager can control erosion. Management scenarios in WEPS are entered via the Management Crop Rotation Editor (MCREW) which is simply a date ordered list of management operations applied to the land. Management operations to be applied on specific dates are selected from a drop down list in MCREW. Parameters for the operation such as ridge directions, amount of mulch, or water applied are entered from the MCREW window as well. By observing bare soil loss and the direction of that loss, a manager can evaluate possible controls needed that are effective for the situation at hand. For example, if soil loss is mostly in one direction then directional controls such as ridges perpendicular to the wind direction causing the loss can be simulated. Similarly, if the soil loss is slight then a simple control such as applying water (i.e., via irrigation) may sufficiently control the erosion. If soil losses are large, more aggressive controls such as applied mulch may be added to the simulation to observe the effect on reducing loss. A full description of the use of MCREW, as well as examples of management file development is available in the WEPS User Manual which is included with the WEPS/SWEEP download (www.ars.usda.gov/services/software/software.htm).

Interpreting WEPS output is an integral part of using the model as a tool for developing conservation plans to control wind erosion. WEPS provides options for viewing detailed soil loss by periods (the default is two weeks); period output is also available for weather parameters such as wind energy as well as surface conditions such as soil erodibility and biomass amounts. Such information is useful in determining which period resulted in severe erosion and the specific conditions contributing to the loss. WEPS outputs also include the amount of soil loss for each wind direction which can aid the user in the placement of directional erosion controls such as oriented roughness, barriers, vegetative strips, or other directional control methods.

2.2. SWEEP model description

SWEEP model calculations are identical to the WEPS erosion submodel but are independent of the five other submodels that comprise WEPS. SWEEP requires input of 38 parameters (as described in [Feng and Sharratt, 2009](#)) that define crop and residue characteristics (e.g., growing and dead crop leaf area index and residue flat cover), soil properties (e.g., geometric mean diameter of aggregate size and

surface water content), and weather characteristics (e.g., wind direction and wind speed). The SWEEP model simulates soil loss (in terms of total, creep + saltation, suspension, and PM-10 emission) for site-specific, planned surface conditions and control practices for a given day of the year. For example, a construction schedule may call for the soil to be bare and open to the effects of wind for a short period of a few days to months. A simulation of these surface conditions will give the user an indication of the wind erosion potential for the specific soil type, surface conditions, and control methods at the location of interest. Fig. 3 shows the SWEEP GUI main screen. Land surface and weather conditions in SWEEP are described through a series of five tabs arranged along the top of the screen. The Field tab describes the area dimensions and orientation as well as the placement and properties of barriers, if present. Unlike WEPS, barriers in SWEEP may be placed in any location on the field to simulate erosion control features such as wind fencing or straw bales. The Biomass tab describes the crop and biomass conditions on the soil surface. The Soil Layers tab describes the soil properties in each layer of the soil. The Soil Surface tab describes the physical properties of the soil surface such as roughness or the presence of a crust. The Weather tab describes the weather parameters (i.e., wind speed and direction) for the simulation arrangement and location.

The user has three options for populating the input parameters on the tabs: 1) open a previously saved run, which may be run as is, or parameters may be modified and

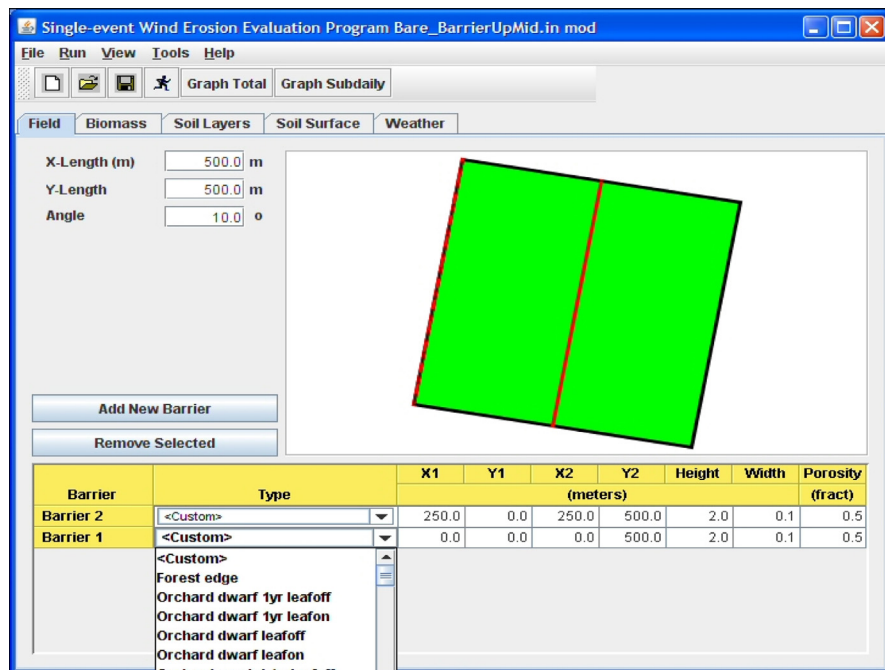


Fig. 3. The SWEEP GUI main screen showing the Field tab for a 500 × 500 m field with two wind barriers (red lines) in place.

then run; 2) download an NRCS soil file which populates soil dependent parameters allowing the user to populate remaining parameters; or 3) populate all parameters from scratch. Management in SWEEP is described by entering specific surface conditions. For example, vegetative mulch is input as the amount and placement of dead vegetative material on the land surface.

A useful tool in SWEEP is the Threshold Run utility (listed under the Run menu button). This allows the user to select a wind station for which to calculate the probability that erosion will occur as well as other wind parameters by direction and month for the surface conditions entered. Therefore, given the known land conditions, one can determine the likelihood of an erosion event occurring. Output information for SWEEP is presented in both graphical and tabular form (Fig. 4) and has many options for a detailed analysis of the conditions as well as location and type of erosion within the area. Information for many erosion parameters including soil loss and deposition is available by grid cell as well as for total, creep + saltation, suspension, and PM-10 size loss. Total amounts crossing each cell boundary are also provided. Similar to WEPS, the SWEEP model has been extensively validated in both the United States and internationally (e.g., Feng and Sharratt, 2009; Liu et al., 2014; Pi et al., 2014a; Pi et al., 2014b; Pi et al., 2016) and has been shown to perform well across a wide range of soils and cropping systems.

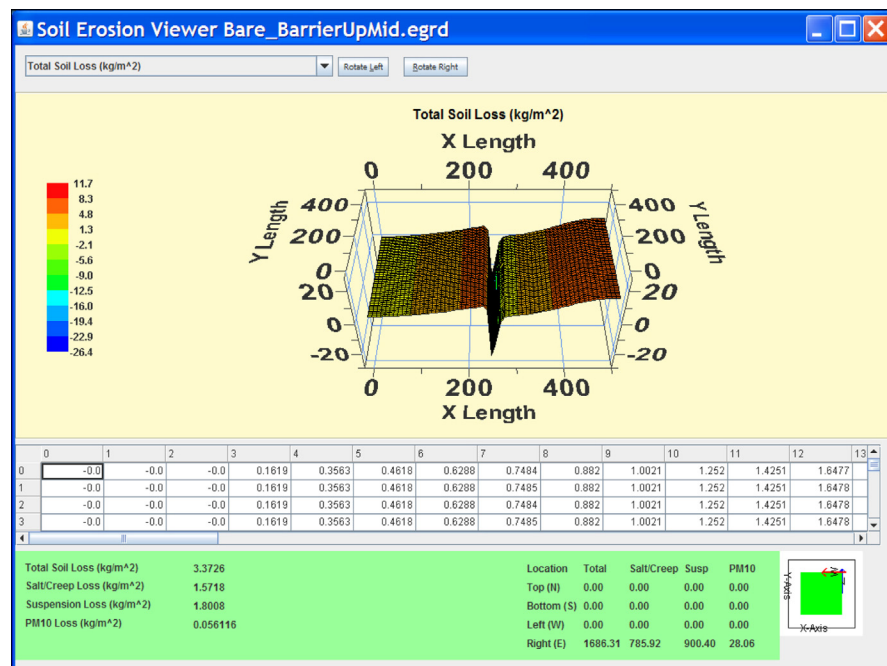


Fig. 4. Example SWEEP output screen for the field configuration shown in Fig. 2.

3. Results and discussion

3.1. Comparative simulation scenarios: WEPS model

WEPS simulates soil loss on a long term basis and accounts for differences in soil properties, climate, site geometry (parcel size, shape, and wind barriers, if present), management, and control practices. Typically, the soil type, climate, and site geometries for a given site cannot be changed or adjusted by the land manager. [Table 1](#) presents comparisons of soil loss at various locations in the United States as simulated by WEPS. To illustrate a typical, non-vegetated, non-agricultural disturbed site, a bare 64.7 ha (160 ac) square field with no ridge roughness and no vegetation or barriers was simulated. To minimize the primary effect of precipitation on vegetation growth at each location, no vegetation was simulated. The results clearly illustrate the impact of differing soil textures and location on total soil loss when all other factors are kept the same (i.e., the same minimal management is applied to all locations and soils). The general increase in soil loss as soils become sandier is a result of poorer aggregation and higher percentage of erodible size aggregates ([Tatarko, 2001](#)). Smaller aggregates also result in less surface roughness ([Mirzamostafa et al., 1998](#)). Varying location illustrates the effects of climate on soil erosion. Therefore, the main difference in the simulations between locations was due to a combination of wind energy, the effect of precipitation and temperature on soil surface properties at each location. [Table 1](#)

Table 1. Effect of location (i.e., weather) and soil texture on soil loss for a bare, smooth, 64.7 ha field as simulated by WEPS.

Soil texture	Great Falls, MT	Albuquerque, NM	Manhattan, KS	Sacramento, CA	Minneapolis, MN	Atlanta, GA
<i>Average annual erosive wind energy (kJ m⁻² day⁻¹)^a</i>						
	4122	1438	1494	481	868	204
<i>Average annual precipitation (mm)^b</i>						
	372	219	823	417	675	1241
<i>Average annual number of freezing days^c</i>						
	161	106	120	16	153	47
<i>Soil loss (kg m⁻² yr⁻¹)</i>						
Fine sand	735	353	310	111	124	34
Fine sandy loam	193	108	56	16	14	11
Loam	132	66	38	8.2	6.3	8.3
Silt loam	85	46	25	5.1	2.4	6.0
Clay	92	47	21	5.0	2.9	5.2

^a Average annual wind energy as stochastically simulated by Windgen, the WEPS wind generator ([van Donk et al., 2005](#)).

^b Average annual precipitation as stochastically simulated by Cligen, the WEPS weather generator ([Meyer et al., 2008](#)).

^c Source: [NCDC \(2013\)](#).

also illustrates the potential interaction of climate and soils. Clay soils at Great Falls, Albuquerque, and Minneapolis exhibit more erodibility than the silt loam soils. This is likely due to a combination of precipitation and freezing effects at these colder locations, making higher clay soils less aggregated and more erodible. Similarly, differences between locations within the same soil result from effects of wind energy on soil erosion.

An important inference from [Table 1](#) is that for many locations and soils in the United States, wind erosion would be considered a problem where fields are large, smooth, and have no vegetative cover (i.e., bare soil) – a virtual definition of an erodible surface. Note that erosion values for all locations and soils in [Table 1](#) are above 1.12 kg m^{-2} (which is greater than a tolerable loss limit T of 5 tons acre⁻¹). This leaves management practices as often the only and best way to control soil loss and dust emissions. In WEPS, land management is entered as a date-ordered list of “operations” that are applied to the land. This can include a variety of actions such as roughening the land surface, planting vegetation, adding straw mulch, burning, and wetting the surface (irrigation). Several scenarios follow demonstrating the use of WEPS for non-agricultural erosion control planning.

3.1.1. Straw mulch

The effect of vegetative cover on soil loss by wind is well known (e.g., [Chepil et al., 1963](#); [Skidmore and Nelson, 1992](#)). Adding straw mulch is a common practice to control erosion as well as to conserve moisture until vegetation can be established. This practice is used on a variety of disturbed lands including road construction. Using straw mulch requires anchoring by matting, crimping, or other methods to prevent blowing or the washing away of the mulch and seed. A crimper is a tractor attachment that has serrated disk blades about 10–20 cm apart which forces straw mulch into the soil and leaves much of the straw in a vertical position. Since standing vegetation is much more effective than flat residue in reducing the force of the wind on soils ([Hagen, 1996](#)) and because anchoring prevents blowing, crimping is a preferred method of control as opposed to blowing straw into a flat, loose position on the surface ([Chepil et al., 1960](#)). [Table 2](#) shows the simulated effect of increasing the amount of straw mulch on wind erosion for a silt loam soil at Manhattan, KS, USA. As expected, the WEPS-simulated amount of wind erosion soil loss decreases as the amount of mulch increases. This shows how WEPS can be used to estimate levels of mulch to apply to control wind erosion for a given soil and location, thereby minimizing the cost of mulch and labor to apply it.

3.1.2. Wind barriers

Wind barriers are typically, linear, vertical structures of live or artificial material put in place to reduce the force of the wind on the surface and thus reduce wind

Table 2. Effect of varying straw mulch stem population, standing, and flat mass on soil loss as simulated by WEPS for a silt loam soil in Manhattan, KS.

Standing population (# stems m ⁻²)	Standing mass at 0.1 m height (kg ha ⁻¹)	Flat mass (kg ha ⁻¹)	Soil loss (kg m ⁻² yr ⁻¹)	Suspension loss (kg m ⁻² yr ⁻¹)
0	0	0	25	17
20	200	0	18	12
50	500	0	3.2	2.1
50	500	300	0.6	0.3
100	1000	0	0.2	0.1
200	2000	0	0.03	0.02

erosion (Lyles et al., 1984). Barriers might include somewhat permanent structures like trees, shrubs, or board fencing as well as temporary structures like silt or snow fencing or hay bales. Barriers influence the size and location of the leeward protected area and thus reduce the effective field length available for wind erosion soil loss (Chepil and Woodruff, 1963). Within WEPS, barriers can be placed on the border of the area being simulated and the height, width, and porosity of the barrier specified. Barriers can affect both gross and net soil loss. In WEPS, gross loss is considered the total amount removed from the soil surface and moving across a field. Net loss is considered the gross loss minus any soil that is re-deposited (within the simulation area) downwind of a barrier as a result of the barrier effect on reducing the wind.

An example of the use of WEPS to design the placement of wind barriers is illustrated for a field where straw bales were placed on the surface in a grid pattern to control wind erosion on a pipeline re-vegetation project in a highly erosive environment (Fig. 5). In this case, WEPS simulates each individual grid cell as a small “field” or simulation region surrounded on all sides by barriers consisting of straw bales. Although, the larger the grid cell, the larger the number of bales are needed to surround it, a fewer number of total bales are required to cover the entire re-vegetation area. By varying the size of the grid cell or field in WEPS, comparisons of soil loss for each field grid size can be made. Table 3 shows the simulated effect of increasing grid side length on gross and net soil loss with barriers (i.e., bales with height = 50 cm, width = 30 cm, length = 100 cm, and porosity = 0%) on all four sides for a silt loam soil at Manhattan, KS. As can be seen, soil loss increases as the grid size increases. An optimum grid size can be designed with WEPS to control wind erosion with the least amount of hay bales and labor to place them over the area. Similarly, WEPS can also be used to design the optimum amount and placement of silt or snow fencing for wind erosion control on disturbed lands.



Fig. 5. Straw bale grid placed on the surface to act as a wind barrier (top) until vegetation is established (bottom).

Table 3. WEPS-simulated effects of varying field grid size with straw bale barriers on gross and net total and suspension soil loss.

Grid side length (m)	Length of bales needed to grid a 25 ha field (m)	Gross soil loss (kg m ⁻² yr ⁻¹)	Net soil loss (kg m ⁻² yr ⁻¹)	Net suspension loss (kg m ⁻² yr ⁻¹)
5	10000	0	0	0
10	2500	0.02	0.02	0.001
50	1000	0.33	0.18	0.05
100	500	0.8	0.6	0.2
200	250	4.2	3.2	1.8
300	167	9.6	9.6	4.8

3.2. Comparative simulation scenarios: SWEEP model

Table 4 presents example comparisons of several control methods as simulated by SWEEP for a 500×500 m field, again for a silt loam soil in Manhattan, KS. Barriers were simulated as a snow type fence (2 m high) with 50% porosity, placed perpendicular to the simulated wind direction. To simulate a dust suppressant, we considered a generic chemical product sprayed onto the soil surface to bind particles together to prevent them from becoming airborne. Water sprayed onto the surface has the same effect although it has a shorter period of effectiveness. For this study, a dust suppressant was simulated by adding a surface crust that assumed full coverage (100%) of the surface with a small fraction (0.1) of loose material remaining on the crust surface after treatment with the suppressant. Fig. 6 illustrates how a typical dust suppressant might be simulated in SWEEP by adjusting surface crust parameters. Actual effectiveness of any suppressant for wind erosion control may depend on the particular suppressant and amount applied. Crimped straw was simulated by adding standing wheat straw (10 cm high and $3200 \text{ stems m}^{-2}$) and 20% flat cover (Fig. 7). The stem area index was estimated using a 3.0 mm diameter stem.

As presented in Table 4, adding barriers can reduce wind erosion on an area of this size (i.e., 500×500 m) but as numbers of barriers increase, the reduction in soil loss diminishes. With increasing numbers and decreasing spacing between barriers, one can determine the minimal numbers of barriers and their relative placement to reduce soil loss to acceptable levels. Installing such barriers can be labor intensive and may not give complete control depending on the size of the area and number of barriers used. Some erosion control practices such as barriers or oriented roughness are most effective when arranged perpendicular to the expected wind direction. Actual wind direction variation is difficult to predict. The best practice is to orient directional controls perpendicular to the prevailing wind direction with the understanding that their effectiveness will decrease as winds change to more parallel to the directional control. Note that SWEEP provides prevailing wind

Table 4. SWEEP-simulated soil loss for a field with different erosion control practices.

Erosion control practice	Total soil loss (kg m^{-2})	Creep + saltation soil loss (kg m^{-2})	Suspension soil loss (kg m^{-2})	PM-10 soil loss (kg m^{-2})
Bare field (no control)	6.2	2.9	3.3	0.13
Barrier (upwind)	5.7	2.7	3.0	0.12
Barriers (upwind and mid-field)	3.4	1.6	1.8	0.06
Barriers (upwind, mid-field, and downwind)	2.6	0.9	1.7	0.05
Dust suppressant	0.3	0.17	0.14	0.01
Crimped straw	0.0	0.0	0.0	0.0

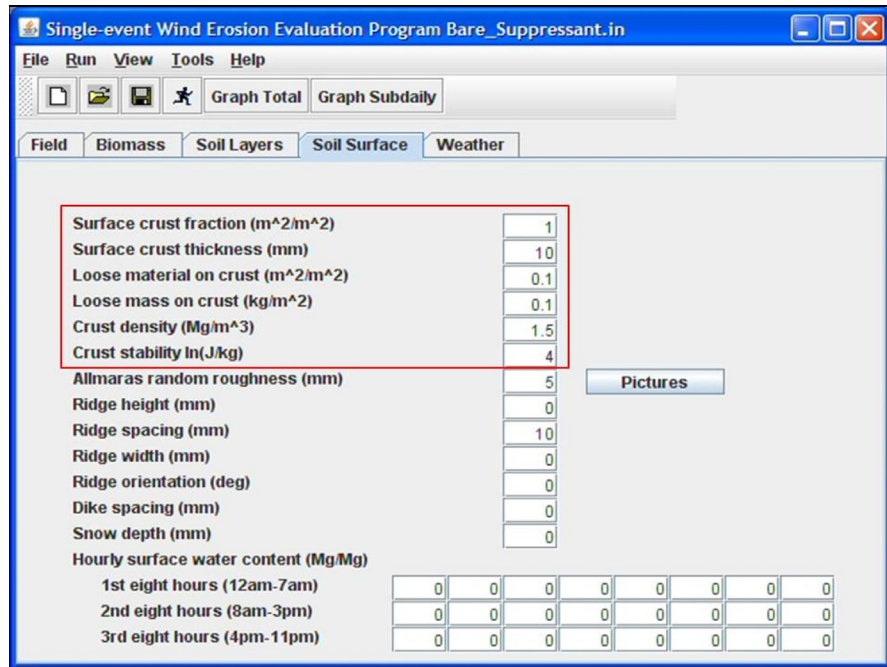


Fig. 6. SWEEP GUI Soil Surface tab screen with soil properties entered for simulating a dust suppressant.

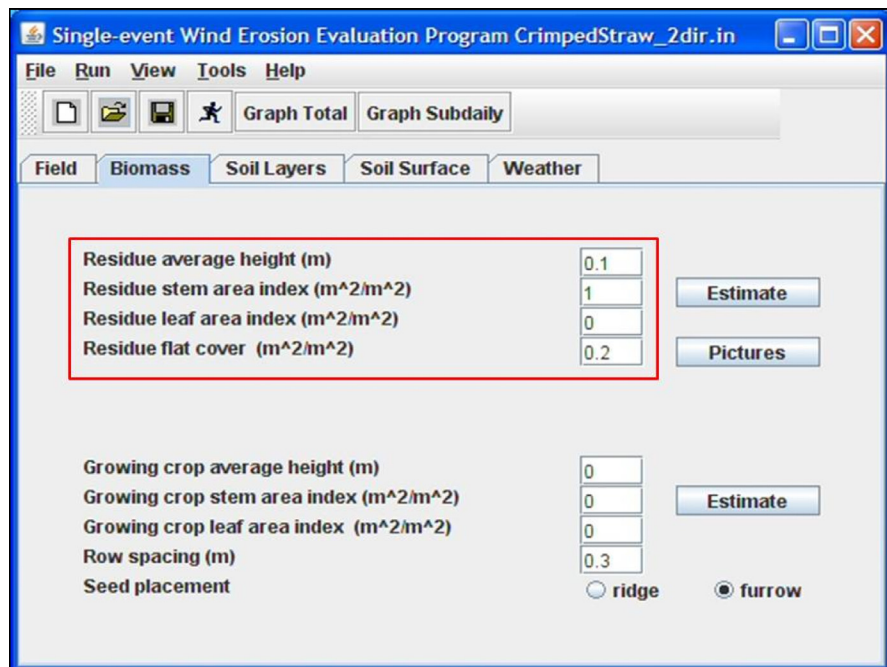


Fig. 7. SWEEP GUI Biomass tab screen with soil properties entered for simulating crimped straw with an average residue height of 0.1 m, stem area index of 1 (i.e., estimated for 10 cm high and 3.0 mm diameter straw and 3200 standing stems), and flat cover of 20%.

direction by month as well as the probability of that wind direction occurring for many locations in the United States (see Threshold Run utility below). The use of a dust suppressant showed much better control. Since suppressants vary in effectiveness and longevity, the cost compared to the benefit of this control should be considered. Crimped straw mulch, although applied at a high rate, provided the best control of the methods considered with zero soil loss.

3.2.1. SWEEP Threshold Run utility

The wind speed at which particle movement is initiated is called the threshold speed and is dependent on the state of the soil surface. A soil surface that is rough or protected with non-erodible material (e.g., anchored vegetation) will require a stronger wind to initiate particle movement than a bare, smooth surface. This means that for a given field, there is no single threshold speed but rather a range of speeds depending on the soil surface type in terms of aggregation, roughness, vegetation status, and moisture. Also, the effectiveness of directional controls such as barriers, ridges, or berms depends on their orientation relative to the wind. Therefore an understanding of the threshold speed for various surfaces as well as the probabilities of wind direction can aid in the development of the best controls. The SWEEP Threshold Run utility provides a simple way observe the wind characteristics for a given location and surface condition, based on monthly historical wind data. The Run Threshold option under the Run menu item, allows the user to select a wind station for which to calculate the wind speed threshold for the simulated soil and surface conditions at which erosion will occur as well as other wind parameters. The Run Threshold utility provides the following data by month and direction (Fig. 8 and Fig. 9):

- Threshold (m/s)—Wind speed from the specified direction at which erosion begins based on the given surface conditions (e.g., soil aggregation, roughness, and ridges and biomass characteristics).
- Winds > Threshold (%)—Percent of winds coming from the specified direction for the month that exceeds the threshold wind speed for that direction.

	N-0	NNE-22	NE-45	ENE-67	E-90	ESE-112	SE-135	SSE-157	S-180	SSW-202	SW-225	WSW-247	W-270	WNW-292	NW-315	NNW-337	Total
Threshold (m/s)	18.0	18.0	17.0	14.0	10.0	14.0	17.0	18.0	18.0	18.0	17.0	14.0	10.0	14.0	17.0	18.0	
Winds > Thresh (%)	0.00	0.00	0.00	0.40	25.95	1.70	0.00	0.05	0.10	0.15	0.50	1.60	14.05	1.85	0.10	0.00	
Dir Prob (%)	9.80	3.00	2.30	1.90	7.20	5.60	6.90	4.40	9.90	5.20	6.70	6.00	9.30	6.40	6.50	6.00	97.10
Thresh Prob (%)	0.00	0.00	0.00	0.01	1.87	0.10	0.00	0.00	0.01	0.01	0.03	0.10	1.31	0.12	0.01	0.00	3.55

Fig. 8. April threshold and wind data by direction for a loamy sand soil located in Albuquerque, NM with ridges (200 mm height, 100 mm spacing, and 200 mm width) oriented east-west (90 degrees from north).

	N-0	NNE-22	NE-45	ENE-67	E-90	ESE-112	SE-135	SSE-157	S-180	SSW-202	SW-225	WSW-247	W-270	WNW-292	NW-315	NNW-337	Total
Threshold (m/s)	10.0	14.0	17.0	18.0	18.0	18.0	17.0	14.0	10.0	14.0	17.0	18.0	18.0	18.0	17.0	14.0	
Winds > Thresh (%)	1.40	0.00	0.00	0.05	0.50	0.30	0.00	0.30	7.70	2.05	0.50	0.10	0.15	0.15	0.10	0.25	
Dir Prob (%)	9.80	3.00	2.30	1.90	7.20	5.60	6.90	4.40	9.90	5.20	6.70	6.00	9.30	6.40	6.50	6.00	97.10
Thresh Prob (%)	0.14	0.00	0.00	0.00	0.04	0.02	0.00	0.01	0.76	0.11	0.03	0.01	0.01	0.01	0.01	0.01	1.16

Fig. 9. April threshold and wind data by direction for a loamy sand soil located in Albuquerque, NM with ridges (200 mm height, 100 mm spacing, and 200 mm width) oriented north-south (0 degrees from north).

- Dir Prob (%)—Probability of wind coming from the specified direction for the month.
- Thresh Prob (%)—Probability of wind exceeding the threshold wind speed from any direction for the month (combination of the above two: Winds > Threshold and Dir Prob).

Fig. 8 shows the April threshold and wind data by direction for a loamy sand soil located in Albuquerque, NM with ridges (200 mm height, 100 mm spacing, and 200 mm width) oriented east-west (90 degrees from north). For the row labeled Threshold, the minimum speed required to initiate wind erosion for the surface specified is shown. Since ridges are oriented east-west, the threshold is much lower when the winds are parallel to the ridges (i.e., E-90, and W-270) than when perpendicular to the ridges (i.e., N-0 and S-180). The Winds > Threshold row indicates that nearly 26% of the winds out of the east at this location are historically greater than the threshold speed, as are 14% of the westerly winds. The Dir Prob row shows the historic probability of winds coming from the specified direction. Note that 16.5% (7.2% + 9.3%) of the winds at this location are likely to come from the east or west direction. Finally the Thresh Prob row shows that historically speaking, 3.18% (1.87% + 1.31%) of the time a wind erosion event from the east or west is probable given the surface configuration. These are the most likely directions that a wind event will cause erosion. In addition, a wind erosion event has a 3.55% chance of occurring under these conditions. Although the north and south directions have a high probability of winds (9.8% and 9.9%, respectively), the probability of those winds being greater than the threshold are very low.

Fig. 9 shows the Threshold Run Table for the same conditions and location, except that the ridges are oriented to the north-south. By reorienting the ridge direction, the probability of having a wind erosion event is reduced to 0.05% in the east and west winds and to 1.16% for all directions. The Threshold Run utility can therefore be used to determine the historic probability of having a wind erosion event given the location and surface characteristics.

4. Conclusions

The WEPS and SWEEP models have undergone extensive testing and validation and are considered the wind erosion prediction tool of choice on cultivated agricultural lands. With adjustments to management inputs, WEPS and SWEEP provide useful tools for aiding the design of erosion control plans on non-agricultural disturbed lands that are a cost-effective and science-based approach to risk assessment. There are many control practices available to land managers and only a few examples are presented here. It should be noted that models such as WEPS and SWEEP alone cannot quantify the advantage of a particular erosion control method over another as various methods are a function of multiple physical, climatic, logistical, and economic factors. For example, water is sometimes used as a dust suppressant. While chemical dust suppressants may provide longer protection, there is an additional cost to be considered.

As part of a comprehensive approach to erosion control planning, WEPS and SWEEP can be used to compare various control scenarios and develop effective control strategies for non-agricultural lands. However, additional research and development of WEPS and SWEEP are essential to continually improve the models for use on both cultivated agricultural and non-agricultural disturbed lands. Improved interfaces are desirable for the models that are customized with input screens for non-agricultural applications. Additionally, there is also a need to evaluate and improve processes that define the surface state of erodibility through validation with independent datasets and field measurements. Validations of WEPS and SWEEP model response to non-agricultural surfaces such as mine tailings will provide further robustness to the simulation of such surfaces. Similarly, parameterization of specific control operations such as dust suppressants is needed. In summary, the WEPS and SWEEP models described herein are valuable tools for supporting the design of erosion control plans that are not only cost-effective but also incorporate a science-based approach to risk assessment.

Declarations

Author contribution statement

John Tatarko: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Simon J. van Donk: Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data.

James C. Ascough II: Analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

David G. Walker: Conceived and designed the experiments.

Competing interest statement

The authors declare no conflict of interest.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Additional Information

No additional information is available for this paper.

Acknowledgements

We acknowledge the contributions of our co-author, James C. Ascough II, and dedicate this paper to his memory as an outstanding researcher, trusted colleague, and good friend.

References

- Armbrust, D.V., 1984. Wind and sandblast injury to field crops: Effect of plant age. *Agron. J.* 76, 991–993.
- 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. Processes Landf.* 33, 1839–1850.
- Chen, L., Zhao, H., Han, B., Bai, Z., 2014. Combined use of WEPS and Models-3/CMAQ for simulating wind erosion source emission and its environmental impact. *Sci. Total Environ.* 466–467 (2014), 762–769.
- Chepil, W.S., Woodruff, N.P., 1963. The physics of wind erosion and its control. *Adv. Agron.* 15, 211–302.
- Chepil, W.S., Woodruff, N.P., Siddoway, F.H., Lyles, L., 1960. Anchoring vegetative mulches. *Agric. Eng.* 41 (11), 754–755 759.
- Chepil, W.S., Woodruff, N.P., Siddoway, F.H., Fryrear, D.W., Armbrust, D.V., 1963. Vegetative and nonvegetative materials to control wind and water erosion. *Soil Sci. Soc. Am. Proc.* 27 (1), 86–89.
- Chung, S.H., Herron-Thorpe, F.L., Lamb, B.K., VanReken, T.M., Vaughan, J.K., Gao, J., Wagner, L.E., Fox, F., 2013. Application of the wind erosion prediction

system in the AIRPACT regional air quality modeling framework. *Trans. ASABE* 56 (2), 625–641.

Coen, G.M., Tatarko, J., Martin, T.C., Cannon, K.R., Goddard, T.W., Sweetland, N.J., 2004. A method for using WEPS to map wind erosion risk of Alberta soils. *Environ. Modell. Softw.* 19 (2), 185–189.

Diaz, E.N., Tatarko, J., Jazcilevich, A.D., Garcia, A.R., Caetano, E., Ruiz-Suarez, L.G., 2010. A modeling study of Aeolian erosion enhanced by surface wind confluences over Mexico City. *Aeolian Res.* 2, 143–157.

Dockery, D.W., Speizer, F.E., Stram, D.O., Ware, J.H., Spengler, J.D., Ferris Jr., B. G., 1989. Effects of inhalable particles on respiratory health of children. *Am. Rev. Respir. Dis.* 139 (3), 587–594.

Federal Register, 2010. Notice of implementation of the Wind Erosion Prediction System for soil erodibility system calculations for the Natural Resources Conservation Service. *Federal Register* 75, No. 234 (7 December 2010), 75961–75962. Print.

Feng, G., Sharratt, B.S., 2007. Validation of WEPS for soil and PM10 loss from agricultural fields on the Columbia Plateau of the United States. *Earth Surf. Processes Land.* 32, 743–753.

Feng, G., Sharratt, B.S., 2009. Evaluation of the SWEEP model during high winds on the Columbia Plateau. *Earth Surf. Processes Landf.* 34, 1461–1468.

Funk, R., Skidmore, E.L., Hagen, L.J., 2004. Comparison of wind erosion measurements in Germany with simulated soil losses by WEPS. *Environ. Model. Softw.* 19 (2), 177–183.

Gao, J., Wagner, L.E., Fox, F., Chung, S.J., Vaughan, J.K., Lamb, B.K., 2013. Spatial application of WEPS for estimating wind erosion in the Pacific Northwest. *Trans. ASABE* 6 (2), 613–624.

Hagen, L.J., 1995. Erosion submodel. In: *Wind Erosion Prediction System Technical Description*. Proc. of WEPP/WEPS Symposium, August 9–11, 1995, Des Moines, IA. Soil and Water Conservation Society, Ankeny, IA.

Hagen, L.J., 1991. Wind erosion mechanics: abrasion of aggregated soil. *Trans. ASAE* 34 (4) 891-837.

Hagen, L.J., 1996. Crop residue effects on aerodynamic processes and wind erosion. *Theoretical Appl. Climatology* 54, 39–46.

Hagen, L.J., 2004. Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields. *Environ. Modell. Softw.* 19 (2), 171–176.

- Hagen, L.J., Skidmore, E.L., 1977. Wind erosion and visibility problems. *Trans. ASAE* 20 (5), 898–903.
- Hagen, L.J., Schroeder, P.R., Thai, L., 2009. Estimated particle emissions by wind erosion from the Indiana Harbor Combined Disposal Facility. *Pract. Period. Hazard. Toxic Radioact. Waste Manag.* 13 (1), 20–28.
- Jia, Q., Al-Ansari, N., Knutsson, S., 2014. Modeling of wind erosion of the Aitik tailings dam using SWEEP model. *Engineering* 6 (7) doi:<http://dx.doi.org/10.4236/eng.2014.67038>.
- Kanatani, K.T., Ito, I., Al-Delaimy, W.K., Adachi, Y., Mathews, W.C., Ramsdell, J.W., 2010. Desert dust exposure is associated with increased risk of asthma hospitalization in children. *Am. J. Respir. Crit. Care Med.* 182, 1475–1481.
- Liu, B., Qu, J., Niu, Q., Han, Q., 2014. Comparison of measured wind tunnel and SWEEP simulated soil losses. *Geomorphology* 207, 23–29.
- Lyles, L., Tatarko, J., 1986. Wind erosion effects on soil texture and organic matter. *J. Soil Water Conserv.* 41 (3), 191–193.
- Lyles, L., Tatarko, J., Dickerson, J.D., 1984. Windbreak effects on soil water and wheat yield. *Trans. ASAE* 27 (1), 69–72.
- Lyles, L., Woodruff, N.P., 1960. Abrasive action of windblown soil on plant seedlings. *Agron. J.* 52, 533–536.
- Maurer, T., Gerke, H.H., 2011. Modelling Aeolian sediment transport during initial soil development on an artificial catchment using WEPS and aerial images. *Soil Tillage Res.* 117, 148–162.
- Meyer, C.R., Renschler, C.S., Vining, R.C., 2008. Implementing quality control on a random number stream to improve a stochastic weather generator. *Hydrol. Processes* 22 (8), 1069–1079.
- Mirzamostafa, N., Hagen, L.J., Stone, L.L., Skidmore, E.L., 1998. Soil aggregate and texture effects on suspension components from wind erosion. *Soil Sci. Soc. Am. J.* 62, 1351–1361.
- NCDC, 2013. Comparative Climatic Data for the United States through 2012. National Oceanographic and Atmospheric Administration, Asheville, NC, CCD-2-012. Accessed October 2015. <http://www1.ncdc.noaa.gov/pub/data/ccd-data/CCD-2012.pdf>.
- Painter, T.H., Barrett, A.P., Landry, C.C., Neff, J.C., Cassidy, M.P., Lawrence, C. R., Thatcher, K.P., Farmer, L., 2007. Impact of disturbed desert soils on duration of mountain snow cover. *Geophys. Res. Lett.* 34 (12), L12502. doi:<http://dx.doi.org/10.1029/2007GL030208>.

- Penttinen, P., Timonen, K.L., Tiittanen, P., Mirme, A., Ruuskanen, J., Pekkanen, J., 2001. Ultrafine particles in urban air and respiratory health among adult asthmatics. *Eur. Respir. J.* 17, 428–435.
- Pi, H., Feng, G., Sharratt, B.S., 2014a. Performance of the SWEEP model affected by estimates of threshold friction velocity. *Trans. ASABE* 57, 1675–1685.
- Pi, H., Sharratt, B.S., Feng, G., Zhang, X., 2014b. Comparison of measured and simulated friction velocity and threshold friction velocity using SWEEP. *Soil Sci.* 179, 393–402.
- Pi, H., Sharratt, B., Feng, G., Lei, J., Li, X., Zheng, Z., 2016. Validation of SWEEP for creep, saltation, and suspension in a desert-oasis ecotone. *Aeolian Res.* 20, 157–168.
- Pope, C.A., Dockery, D.W., Spengler, J.D., Raizenne, M.E., 1991. Respiratory health and PM₁₀ pollution: a daily time series analysis. *Am. Rev. Respir. Dis.* 144, 668–674.
- Prospero, J.M., 1999. Long-range transport of mineral dust in the global atmosphere: Impact of African dust on the environment of the southeastern United States. *Proc. Natl. Acad. Sci. U. S. A.* 96, 3396–3403.
- Prospero, J.M., Lamb, P.J., 2003. African droughts and dust transport to the Caribbean: climate change implications. *Science* 302, 1024–1027.
- Skidmore, E.L., Nelson, R.G., 1992. Small-grain equivalent of mixed vegetation for wind erosion control and prediction. *Agron. J.* 84 (1), 98–101.
- Tatarko, J., 2001. Soil aggregation and wind erosion- processes and measurements. *Ann. Arid Zone* 40 (3), 251–263.
- US EPA, 1993. PM-10 Guideline Document. United States Environmental Protection Agency, Office of Air Quality Planning and Standards. EPA-452/R-93-008. Research Triangle Park, NC, USA
- van Donk, S.J., Skidmore, E.L., 2003. Measurement and simulation of wind erosion, roughness degradation and residue decomposition on an agricultural field. *Earth Surf. Processes Landf.* 28 (11), 1243–1258.
- van Donk, S.J., Huang, X., Skidmore, E.L., Anderson, A.B., Gebhart, D.L., Prehoda, V.E., Kellogg, E.M., 2003. Wind erosion from military training lands in the Mojave Desert, California, USA. *J. Arid Environ.* 54 (4), 687–703.
- van Donk, S.J., Wagner, L.E., Skidmore, E.L., Tatarko, J., 2005. Comparison of the Weibull model with measured wind speed distributions for stochastic wind generation. *Trans. ASAE* 48 (2), 503–510.

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., Hagen, L.J., 2001. Application of WEPS generated soil loss components to assess off-site impacts. in: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds.) *Sustaining the global farm. Proc. of 10th International Soil Conservation Organization Conference, May 24–29, 1999, Purdue Univ., West Lafayette, IN.* pp. 935–939.

Wilson, R., Spengler, J., 1996. *Particles in our Air: Concentrations and Health Effects.* Harvard University Press, Boston, USA.