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Consistency of wind erosion assessments across land use and land cover types: A critical analysis

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ABSTRACT

In recent decades, large areas of rangeland have been converted to cropland or vice versa in the western United States and elsewhere in the world, driven largely by increased crop prices, loss of access to irrigation water, and agricultural expansion/contraction. Wind erosion and dust emissions are key processes that have not been well studied during land use and associated land cover changes. This assessment is challenging because currently no model is available that can provide field- to landscape-scale estimates of wind erosion on both rangeland and cropland, and account for soil, vegetation and management changes. In this paper, we compare aeolian sediment transport estimates from available cropland models and a number of mass flux equations developed for rangelands, for a bare soil surface with different levels of crust and surface roughness under different wind speeds. Our results show that the simulated horizontal sediment mass fluxes are similar for cropland and rangeland models at large surface crust coverage and aerodynamic roughness. In situations of small to moderate crust cover and soil roughness, horizontal mass fluxes varied by over three orders of magnitude among the tested models. A correlation analysis shows that horizontal mass fluxes simulated by cropland and rangeland models are correlated, with correlation R^2 of 0.37–0.99 across different models. Finally, we propose an approach to estimate changes in aeolian transport with changes in land use. Although this approach may be limited to situations of unvegetated surfaces, it provides a preliminary method for land managers and policymakers to estimate potential wind erosion changes in response to land use change.

1. Introduction

Atmospheric dust emitted from arid and semiarid regions plays an important role in climate, nutrient and element cycling, snow hydrology, and public health (e.g., Sokolik and Toon, 1996; Griffin et al., 2001; Li et al., 2008; Painter et al., 2010; Webb et al., 2012). Dust production may be affected by both climate (at the global scale) and land use (at the regional scale) (Tegen et al., 2004; Ravi et al., 2011; Ginoux et al., 2012). In the western United States, large areas of rangeland have been converted to cropland or other land uses because of increases in human settlement and associated recreation development in the past several decades (Field et al., 2010). In addition, the desert grasslands of southwestern United States have undergone dramatic vegetation changes, with the expansion of shrublands in the last 150 years (Schlesinger et al., 1990). These anthropogenic and natural changes in land use and land cover, working in concert with projected climate changes, could lead to more frequent and greater wind erosion and dust emissions from these regions (Seager et al., 2007; Munson et al., 2011).

Although the fundamental mechanism of wind erosion is the same on both rangelands and croplands (e.g., shear velocity exceeds threshold shear velocity to initiate soil transport), factors affecting erosion rates including soil physical and chemical properties, roughness elements (e.g., vegetation types and their spatial distribution patterns), and management can differ greatly between these two systems (Webb and Strong, 2011). As a consequence of this complexity, models have been developed separately to evaluate rates of wind erosion and dust production from cropland (e.g., Hagen et al., 1995; Fryrear et al., 1998a) and rangeland systems (e.g., Marticorena and Bergametti, 1995; Shao and Leslie, 1997; Okin, 2008). The independent development of models for cropland and rangeland applications has created a situation in which the model inputs, representation of processes, and outputs have become specialized for the two environments. Robust models are

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now required that can be applied to evaluate wind erosion across land use systems and assess the impacts on erosion of ongoing land use and land cover change.

In cropland systems, representative models include the Revised Wind Erosion Equation (RWEQ) (Fryrear et al., 1998a) and the Wind Erosion Prediction System (WEPS), the stand-alone erosion sub-model of which is called the Single-event Wind Erosion Evaluation Program (SWEEP) (Hagen et al., 1995). Neither RWEQ nor SWEEP was developed for use in rangelands, and application of the models in this environment is not trivial. Modeling aeolian transport in rangeland is different than in cropland, partially due to the structural complexity of vegetation in rangeland as well as questions of scale: an agricultural field has a well-defined spatial scale, whereas rangeland does not. Aeolian transport in rangeland may be estimated by a number of empirical or experimental equations, and a majority of the equations show that horizontal mass flux is proportional to the 3rd power of shear velocity (Table 1).

Aeolian sediment flux has two principal components: horizontal mass flux and vertical dust flux (Okin et al., 2006; Field et al., 2010). Horizontal mass flux (expressed in units of mass per unit distance perpendicular to the wind per unit time) is comprised mostly of saltating particles with diameters from 20 to 500 μm. Vertical dust flux (also called dust emission, with units of mass per unit area per unit time) is the flux of particles with diameters <20 μm that are transported by suspension. Vertical flux dust particles are emitted when saltating particles sandblast the soil surface, overcoming the strong inter-particle forces between fine particles (Gillette, 1977). Saltation-sized particles travel close to the soil surface, which results in the re-distribution of surface soil within a system, whereas suspension-sized particles can be transported over long-distances and normally constitute the net loss of soil resources from an area.

For an aeolian transport in undisturbed, vegetated rangelands, the saltation flux out of an area may be replaced by saltation into the area or trapped locally by vegetation, resulting in no net change in the mass of saltation-sized particles. The change in suspension-sized particles, emitted during a saltation event can be negative (i.e., net mass loss) if emissions exceed deposition. In contrast, for agricultural fields with a definite spatial extent and relatively non-erodible up-wind boundary, the net horizontal flux into the field may be zero, and the net change in the mass of saltation-sized particles may be negative. Thus, the net sediment mass removal rate by wind erosion is the sum of the net loss of saltation- and suspension-sized particles.

While the primary output of cropland aeolian transport models is total soil loss (units of mass per unit area per time) that incorporates both horizontal and vertical flux from a bounded area, rangeland aeolian transport models do not currently predict soil loss in a way that accounts for both horizontal and vertical flux. This makes direct comparison of the cropland and rangeland aeolian transport models problematic. However, because both cropland and rangeland models estimate horizontal sediment flux, this measure provides a basis for comparing the two model types. It is worth noting that because of the scale difference involved in both models, horizontal mass flux simulated by cropland and rangeland models may differ. Finally, it is important to note that neither set of models accounts for material that is transported by saltation (horizontal fluxes) and deposited on the area of interest. Consequently, none of the current models effectively predict net soil loss.

Government policies and market forces can influence land use and land cover change, and vice and versa, so providing consistent flux estimates to policymakers and landowners is critical. Models of aeolian transport suitable for rangeland and field agriculture need to provide consistent and comparable results if the effects of land use change are to be predicted. This is currently impossible, however, because no model is designed to provide field- to landscape-scale estimates of wind erosion on both rangelands and croplands. At the very least, both types of models should be able to model horizontal transport on unvegetated ground, the intersection of the two model domains, to provide a reasonable comparison.

The objectives of this study were to: (1) investigate horizontal mass flux calculations from SWEEP, RWEQ, and a number of mass flux equations for the case of unvegetated ground, with different soil characteristics and wind speeds, and (2) provide a simple method of estimating horizontal mass flux to apply both types of models in a consistent way when they would not otherwise be, therefore providing critical information for land managers or policymakers to evaluate scenarios of land cover or land use change on aeolian sediment transport. The paper does not evaluate the performance of the cropland and rangeland wind erosion models as detailed investigations of the models' performance have been provided elsewhere (e.g. Van Pelt et al., 2004; Feng and Sharratt, 2007, 2009; Buschiazzo and Zobeck, 2008; Li et al., 2013).

Our comparison of the cropland wind erosion models (SWEEP and RWEQ) and rangeland mass flux equations is based on a "bare" surface without vegetation or standing biomass. This condition enables the direct comparison and represents the simplest case in which both cropland models and mass flux equations are typically used; both croplands and rangelands can exist in vegetation-free conditions. An understanding of how the models behave for a bare soil condition is critical because (*a*) the highest rates of wind erosion occur from bare, or nearly-bare soil, and (*b*) with the exception of some minimum-till systems (e.g., northern Great Plains in the US), land use and land cover changes usually include removal of existing vegetation and disturbance of the soil surface.

2. Materials and methods

2.1. Description of the models

2.1.1. Cropland models

2.1.1.1. Single-event Wind Erosion Evaluation Program (SWEEP). SWEEP is the standalone version of the WEPS erosion sub-model.

Table 1
Wind erosion models and mass flux equations used in the model comparison of this study.

Wind erosion models/equations	Citation	Modeling studies
Cropland		
SWEEP	Hagen et al. (1995)	Hagen (2004) and Feng and Sharratt (2007, 2009)
RWEQ	Fryrear et al. (1998a)	Fryrear et al. (1998b), Van Pelt et al. (2004) and Buschiazzo and Zobeck (2008)
Rangeland		
$\frac{\rho}{g}u_*^3(1-\frac{u_{*t}^2}{u_*^2})$	Shao et al. (1993)	Shao and Leslie (1997), Lu and Shao (2001) and Okin (2008)
$\frac{\rho}{g}u_*^3(1-\frac{u_{*t}^2}{u_*^2})(1+\frac{u_{*t}}{u_*})$	Kawamura (1951)	Marticorena et al. (1997)
$\frac{\rho}{g}u_*^3(1-\frac{u_{*t}}{u_*})(1+17.75\frac{u_{*t}}{u_*})$	Sorensen (1991)	Li et al. (2013)
$\frac{\rho}{g}u_*^3(1-\frac{u_{*t}}{u_*})$	Lettau and Lettau (1978)	n/a
$\frac{\rho}{g}u_*^4\left(1-\frac{u_{*t}}{u_*}\right)$	Gillette and Passi (1988)	Gillette and Passi (1988)

SWEEP is able to simulate the components of wind erosion in response to wind speed, wind direction, and field and surface conditions on a sub-hourly basis. The SWEEP model simulates wind erosion over a rectangular region of interest, divided into smaller grid cells. Primary input parameters required by SWEEP are classified into: field, crop, soil, and weather. The primary model outputs are soil losses from a field (kg/m^2) by saltation/creep, suspension, and PM10 (particulate matter $\leqslant$10 μm in diameter), although estimates of horizontal sediment mass flux also can be obtained. The model uses a series of empirical equations to compute changes in soil temporal properties (e.g., aggregate size and distribution, random roughness, crust thickness etc.) over time that result from the erosion and deposition processes, which is designated as “surface updating” (Hagen et al., 1995, 1999; Hagen, 2008). A detailed description of the model and measurement techniques of the input parameters may be found in Hagen et al. (1995).

In SWEEP, the wind shear velocity u_* is related to the mean wind speed U_z at height z by the Law of the Wall (Marticorena et al., 1997):

$$u_* = \frac{0.4U_z}{\ln\frac{z}{z_0}}. \tag{1}$$

SWEEP initiates the simulation of soil movement only when u_* exceeds the threshold shear velocity for particle entrainment, u_{*t}. In SWEEP, u_{*t} is a function of aerodynamic roughness height, z_0, which is, in turn, a function of surface soil properties including fraction covered by clods, crust, and rocks (>2 mm in diameter), soil aggregate characteristics, and surface water content. For non-vegetated soil surface, u_{*t} is estimated as:

$$u_{*t} = 1.7 - 1.35\exp(-cf) \tag{2}$$

where

$$c = \frac{1}{-0.076 + \frac{1.111}{\sqrt{z_0}}} \tag{3}$$

and f is soil fraction covered by clods, crust, and rock that do not emit, with the interval of [0,1]. In general, u_{*t} increases as the fraction of the non-erodible surface increases.

In SWEEP, z_0 is a function of oriented roughness, random roughness, and leaf and stem area index. For bare ground without standing biomass, z_0 (mm) is calculated as:

$$z_0 = 0.3a, \quad a > 1.5 \tag{4}$$

where a is the Allmaras random roughness in millimeters (Allmaras et al., 1966) represented by the standard deviation of the surface heights. In this study, we did not consider the case of oriented roughness (i.e., furrowed ground). Finally, saltation and creep are modeled as the time-dependent conservation of mass by using a set of partial differential equations that represent the evolution of the sediment transport across the field. Details of these equations may be found in Hagen et al. (1995).

2.1.1.2. *Revised Wind Erosion Equation (RWEQ).*

The RWEQ model calculates horizontal aeolian transport as it increases across an agricultural field to a maximum horizontal flux. The model calculates maximum horizontal flux, $Q_{t,\max}^{\mathrm{RWEQ}}$ following the equation (Fryrear et al., 1998a):

$$Q_{\max}^{\mathrm{RWEQ}} = 109.8 \cdot WF \cdot EF \cdot SCF \cdot K', \tag{5}$$

where WF is the weather factor, EF is the erodible fraction, SCF is the soil crust factor, K' is the soil roughness factor. WF is given by:

$$WF = \frac{\rho}{g}\sum_{i=1}^{N}\frac{(U_i - U_t)^2 U_i}{N}, \tag{6}$$

where U_i is the time-averaged wind speed measured at the height of 2 m at N time intervals, U_t is wind speed at 2 m at which erosion is initiated, ρ is air density, and g is the acceleration due to gravity.

Wind speed at 2 m can be calculated using measured wind speed at height z, U_z:

$$U_2 = U_z\frac{\ln(2/z_0)}{\ln(z/z_0)}, \tag{7}$$

where z_o was calculated using Eq. (4). For our purposes, threshold wind speed at 2 m, U_t, was calculated as:

$$U_t = \frac{u_{*t}}{0.4}\ln\left(\frac{2}{z_0}\right), \tag{8}$$

where u_{*t} is the threshold shear velocity on the soil surface. In this study, to maintain as much consistency as possible across models, we used the u_{*t} calculated in SWEEP for RWEQ rather than the (constant) entrainment threshold in the original version of RWEQ.

For a bare surface with sandy soil, EF is set to be the soil fraction that is free of soil crust and rocks. K' is a function of oriented and random roughness, measured with the chain method and denoted as the ratio of the length of chain required to span a rough surface to a set horizontal distance (Saleh, 1993). The chain roughness was further related to the Allmaras et al. (1966) random roughness

Table 2
Values of surface soil characteristics and other related input parameters used by SWEEP and RWEQ for initial model runs.

Upper layer characteristics[a]		Surface crust		Surface roughness		Other	
Sand fraction (Mg/Mg)	0.9	Surface crust fraction (m^2/m^2)	0.1	Allmaras random roughness (mm)	5	Number of soil layers	1
Very fine sand fraction (Mg/Mg)	0.2	Surface crust thickness (mm)	2	Ridge height (mm)	0	Layer thickness (mm)	1000
Silt fraction (Mg/Mg)	0.05	Loose material on crust (m^2/m^2)	0	Ridge spacing (mm)	10	Soil wilting point water content (Mg/Mg)	0.08
Clay fraction (Mg/Mg)	0.05	Loose mass on crust (kg/m^2)	0	Ridge width (mm)	0	Snow depth (mm)	0
Bulk density (Mg/m^3)	1.8	Crust density (mg/m^3)	0.6	Ridge orientation (deg)	0	Hourly surface water content (Mg/Mg)	0
Average aggregate density (Mg/m^3)	1.8	Crust stability (ln(J/kg))	1	Dike spacing (mm)	0	X-length (m)	Varies
Average dry aggregate stability (ln(J/kg))	2.5					Y-length (m)	25
GMD of aggregate size (mm)[b]	0.47					Field angle (deg)	0
GSD of aggregate size (mm/mm)[c]	12					Wind direction (deg)	270
Minimum aggregate size (mm)	0.01					Anemometer height (m)	10
Maximum aggregate size (mm)	10					Wind record interval (min)	5
Rock volume fraction (m^3/m^3)	0					Air density (kg/m^3)	1.20
						z_0 at anemometer site (mm)	10

[a] Soil particle fractions using USDA sizes.
[b] GMD-geometric mean diameter.
[c] GSD-geometric standard deviation.

(used in the SWEEP) by an empirical equation developed by Fryrear et al. (1998b).

The soil crust factor (*SCF*) is estimated as a function of percent clay (*CL*) and organic matter (*OM*) content following (Fryrear et al., 1998b):

$$SCF = 1/((1 + 0.0066(CL) + 0.021(OM)^2). \tag{9}$$

All RWEQ runs used a clay content of 5%, which is consistent with the SWEEP runs (Table 2). Soil organic matter content is not a required parameter in SWEEP; for RWEQ, it was set as 0.5%.

2.1.2. Rangeland mass flux equations

Representative mass flux equations appropriate for rangeland are listed in Table 1. All these models represent the horizontal aeolian sediment flux as a threshold-controlled process, where transport increases nonlinearly above the threshold shear velocity. Nearly all of these equations have been previously tested by wind erosion modeling studies (see Table 1). As with RWEQ, evaluation of these mass flux equations was done with values of u_{*t} derived from SWEEP. We do not imply through this process that SWEEP correctly estimates u_{*t}, rather, SWEEP is the only model/equation tested in this study that predicts u_{*t}, so this approach allows for a direct comparison of sediment flux estimates among the different models. Because sediment transport is threshold-controlled in all models, using inconsistent u_{*t} values in the model comparison would have guaranteed disagreement among the approaches.

2.2. Model setup and simulation runs

The initial soil and wind parameters for SWEEP and RWEQ are listed in Table 2. Most of these model parameters are in the range of a typical wind susceptible agricultural environment. These parameters were used for all simulations unless otherwise stated. All models were run with three wind speeds (10, 15, and 20 m s^{-1} to represent low, medium, and high wind speeds, respectively) at the height of 10 m, with different levels of soil surface

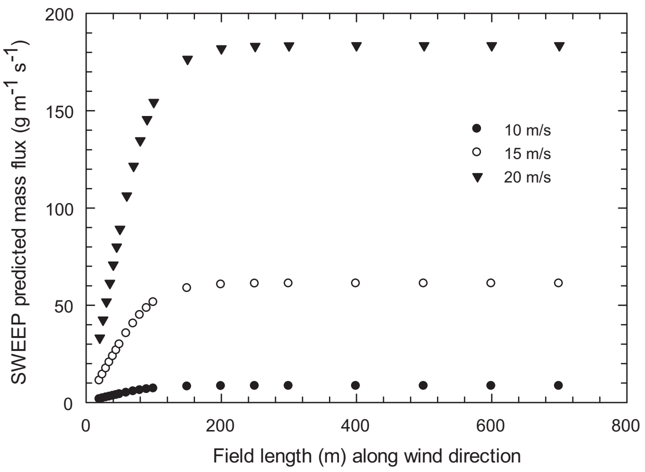

Fig. 1. Change of SWEEP predicted horizontal mass flux as a function of field length along wind direction.

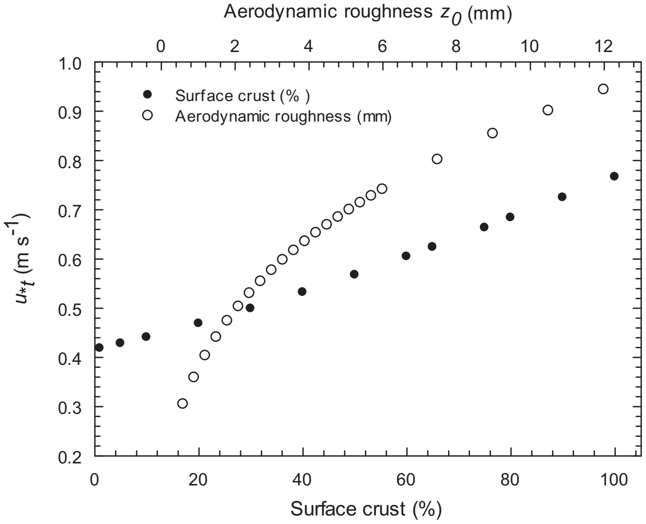

Fig. 2. SWEEP calculated threshold shear velocity (u_{*t}) as a function of soil surface crust and aerodynamic roughness z_0. See the other model inputs in Table 2.

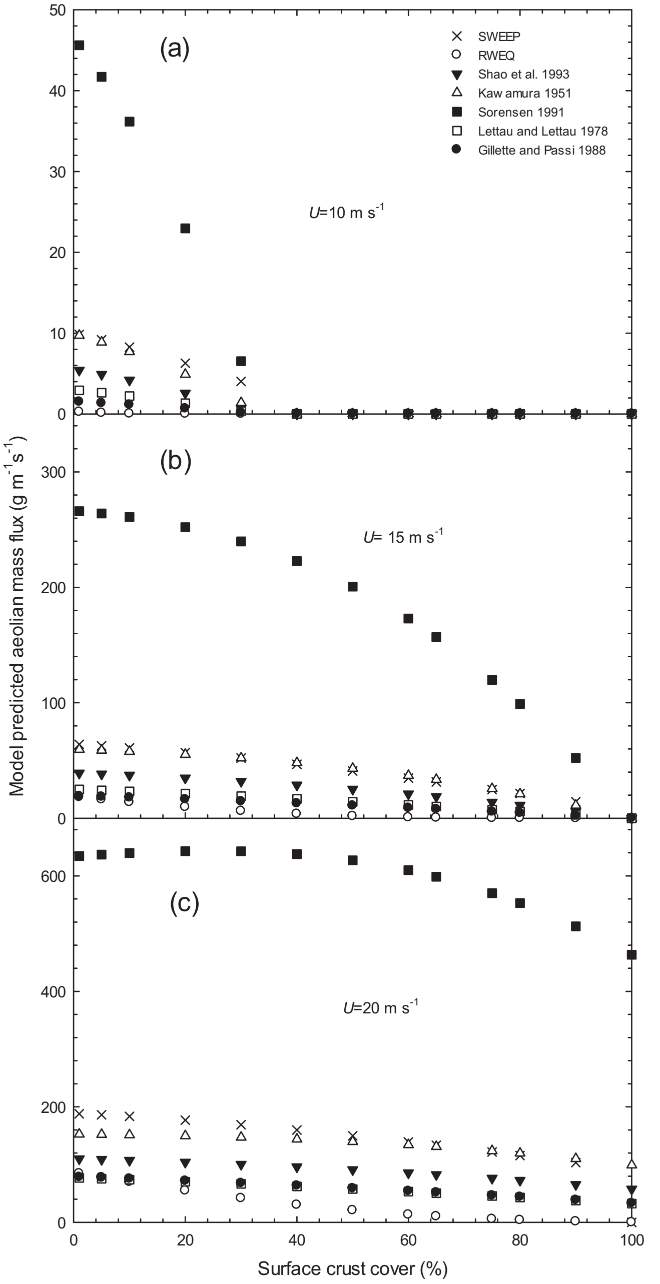

Fig. 3. Model predicted horizontal mass flux as a function of soil surface crust with different wind speeds of 10, 15, and 20 m s^{-1}. SWEEP model runs were conducted with Allmaras random roughness of 5 mm and aerodynamic roughness z_o = 1.5 mm, with the other parameters listed in Table 2.

crust cover and roughness separately. SWEEP model runs were conducted with a storm duration of 24 h, a time period that potentially yields the maximum total amount of material transported in the models, which are the basis of comparison here. Surface updating is a feedback mechanism in WEPS and SWEEP that adjusts the surface properties of loose particulates, clods, crusts, and soil roughness as a result of erosion processes during single-day erosion events (Hagen, 2008). Since the other models in this study do not account for within event surface changes, updating within SWEEP was turned off to allow similar comparisons.

A number of preliminary model runs were conducted for SWEEP to determine the downwind distance at which transport capacity was reached. That is, the maximum horizontal flux in g m^{-1} s^{-1}, comparable to $Q_{\max}^{\mathrm{RWEQ}}$ and calculated directly by the other transport equations. All subsequent SWEEP model runs were conducted at a simulated downwind distance much larger (e.g., 1500 m) than the distance of transport capacity to ensure maximum mass flux was achieved for the tested model conditions.

2.3. Model comparison approach

Differences in how the examined models handle the threshold at which aeolian transport occurs (i.e., u_{*t}) complicate the model comparison. In SWEEP, u_{*t} is calculated internally based on prescribed soil conditions. In the other approaches, including RWEQ and the mass flux equations, u_{*t} can be prescribed directly. In SWEEP, u_{*t} is also affected by the soil aerodynamic roughness z_o, which is related to a prescribed random roughness through Eq. (4). For the model comparison we manipulated the percent crust cover and random roughness in SWEEP, as a proxy for varying u_{*t}, without affecting other model predictions. SWEEP runs were conducted first, and u_{*t} as determined by SWEEP was prescribed for the other models, including RWEQ, to allow a direct comparison of cropland models and rangeland horizontal flux equations.

In this study, we used horizontal transport units of g m^{-1} s^{-1} as the basis of comparison between SWEEP, RWEQ, and the set of mass flux equations (Table 1). In the case of SWEEP, wind erosion and soil loss are simulated for a definite spatial extent with a non-eroding surface on the upwind edge. For general configuration of the model, the mass flux of saltation/creep may or may not reach transport capacity by the downwind edge of the field. In our simulations with field lengths greater than the distance required to attain transport capacity, SWEEP always provided an estimate of the sediment flux at transport capacity. In RWEQ, the simulation area is also a field bounded by a non-eroding surface, but $Q_{\max}^{\mathrm{RWEQ}}$ can be calculated alone as a measure of horizontal mass flux. The rangeland mass flux equations presented in Table 1 have no relevant or specific spatial scale (i.e., the size of the area over which flux is estimated does not matter) and are directly comparable with $Q_{\max}^{\mathrm{RWEQ}}$.

A linear regression analysis was conducted between the mass fluxes predicted by SWEEP, RWEQ, and rangeland mass flux equations for different soil and wind characteristics in order to derive correction factors that allow production of comparable estimates from the cropland and rangeland models. The regression was developed in the form:

$$\begin{pmatrix} Y_1 \\ Y_2 \\ \cdot \\ \cdot \\ \cdot \\ Y_n \end{pmatrix} = m \begin{pmatrix} X_1 \\ X_2 \\ \cdot \\ \cdot \\ \cdot \\ X_n \end{pmatrix} + b, \tag{10}$$

in which Y_1 to Y_n are the mass fluxes calculated from SWEEP or RWEQ, and X_1 to X_n are the mass fluxes computed from rangeland mass flux equations for a number of n model runs. m is the slope of the regression line and is interpreted as a multiplicative conversion factor between cropland models and rangeland mass flux equations, and b is the intercept of the regression line and is interpreted as an additive conversion factor. A value of $m < 1$ indicates that rangeland mass flux equations predicted mass flux was generally larger than that of SWEEP or RWEQ, whereas $m > 1$ suggests the opposite.

3. Results and discussion

3.1. Transport capacity of SWEEP

With the surface updating off and using all initial model inputs listed in Table 2, SWEEP shows that horizontal mass flux increases with the downwind distance but reaches the transport capacity at a distance of about 200 m, irrespective of wind speed (Fig. 1). This distance is substantially smaller than the field length of 1500 m used to attain transport capacities in actual model runs.

3.2. Effects of soil surface crust (f)

As surface soil crust cover, f, increases from 1% to 100%, SWEEP predicts that u_{*t} increases from 0.42 to 0.77 m s^{-1} (Fig. 2, z_o = 1.5 mm). At a wind speed of 10 m s^{-1}, none of the models predict mass flux when the surface is covered by more than 40% crust (Fig. 3a).

Table 3

Summary of linear regression analysis between cropland wind erosion models (SWEEP and RWEQ) and rangeland mass flux equations with different wind speeds and surface crust cover (1–100%).

Wind erosion models	U = 10 m s^{-1}			U = 15 m s^{-1}			U = 20 m s^{-1}		
	m	b	R^2	m	b	R^2	m	b	R^2
SWEEP									
Shao et al. (1993)	1.87	0.33	0.96	1.56	2.57	0.99	2.69	−99.7	0.85
Kawamura (1951)	1.03	0.30	0.96	1.03	−0.76	0.99	2.77	−233.7	0.89
Sorensen (1991)	0.22	0.30	0.96	0.22	−1.48	0.98	0.84	−360.2	0.89
Lettau and Lettau (1978)	3.48	0.36	0.95	2.41	5.75	0.99	3.05	−34.2	0.80
Gillette and Passi (1988)	6.83	0.36	0.95	3.14	5.74	0.99	2.99	−34.2	0.80
RWEQ									
Shao et al. (1993)	0.03	−0.01	0.71	0.44	−5.0	0.71	1.62	−112.9	0.84
Kawamura (1951)	0.02	−0.01	0.69	0.28	−5.27	0.63	1.51	−172.1	0.72
Sorensen (1991)	0.003	−0.01	0.69	0.06	−5.20	0.60	0.38	−196.8	0.51
Lettau and Lettau (1978)	0.05	−0.01	0.72	0.71	−4.57	0.78	1.94	−79.66	0.89
Gillette and Passi (1988)	0.11	−0.01	0.72	0.94	−4.57	0.78	1.90	−79.7	0.89

All regression equations are significant at p = 0.01. Values of m > 1 indicate rangeland model predictions are less than cropland model predictions.

At wind speeds of 15 and 20 m s^{-1}, all models, except RWEQ, predict mass flux until the surface is completely covered by crust (Fig. 3b and c). For all the wind speeds investigated, mass fluxes calculated by the equation of Sorensen (1991) are substantially higher than all the other mass flux schemes, including both cropland models and rangeland equations.

At different levels of surface crust, horizontal fluxes predicted by cropland models and rangeland mass flux equations are highly correlated with a coefficient of determination (R^2) ranging from 0.80 to 0.96 for SWEEP, and 0.51 to 0.89 for RWEQ (Table 3). For both SWEEP and RWEQ, this correlation generally weakens at a high wind speed of 20 m s^{-1}. Overall, mass flux calculated with SWEEP is the closest to that of the Kawamura's (1951) prediction, and the RWEQ calculated mass flux is substantially smaller (with $m < 1$) than that of the rangeland models, particularly at wind speeds of 10 and 15 m s^{-1}.

3.3. Effects of aerodynamic roughness (z_0)

As aerodynamic roughness, z_o, increases from 0.6 to 12 mm, u_{*t} predicted by SWEEP increases from 0.28 to nearly 0.85 m s^{-1} (Fig. 2). At a wind speed of 10 m s^{-1}, none of the models predicted mass flux with $z_o > 2.5$ mm (Fig. 4a). Fig. 4 further shows that mass flux simulated by the cropland models and rangeland mass flux equations generally decreases with increasing z_o, except for the Sorensen (1991) and Kawamura (1951) models, which do not show a simple linear trend at wind speeds of 15 and 20 m s^{-1}. Similar to the mass flux at different surface crust cover (Fig. 3), mass fluxes calculated with Sorensen (1991) are always substantially larger than the other models, and SWEEP-calculated fluxes are the closest to that of Kawamura (1951) (Fig. 4).

At wind speeds of 10 and 15 m s^{-1}, horizontal mass fluxes modeled by SWEEP show a strong linear relationship with those of the other mass flux equations with regard to different z_o, with R^2 falling in the range of 0.88–0.99 (Table 4). The correlation is generally weaker between RWEQ and the rangeland mass flux equations. At a higher wind speed of 20 m s^{-1}, the linear relationship of mass flux calculated between cropland models and rangeland equations failed, particularly for Kawamura (1951) and Sorensen (1991).

3.4. Values of conversion factor (m)

Regression analysis conducted between mass fluxes predicted by SWEEP and rangeland flux equations shows that the mean values of the conversion factor m are >1 for all models. This suggests that the sediment flux estimates from the cropland models (SWEEP and RWEQ) were generally larger than estimates from the other mass flux equations. An exception was found for the Sorensen (1991) model, which has a mean value of $m = 0.35$, indicating that the average mass flux calculated by this equation is nearly 5-times larger than that of SWEEP (Figs. 3 and 4 and Tables 3 and 4). The largest mean value $m = 4.24$ was found for the Gillette and Passi (1988) model, suggesting that this equation generally predicted the lowest mass fluxes compared with those of SWEEP. Mass fluxes calculated from Kawamura (1951), in general, are the closest to those of SWEEP, with an estimated mean m value of approximate 1.25 (Table 5). The conversion factors between RWEQ and rangeland flux equations, however, are smaller than those of SWEEP, ranging from 0.1 for Sorensen (1991) to 1.23 for Gillette and Passi (1988), with relatively high values of standard deviation associated with different wind and soil surface conditions (Table 5).

This study sought to compare the simulation outputs of established, widely-used wind erosion models for agricultural lands (SWEEP and RWEQ) with existing theoretical and experimental flux equations more commonly used for rangeland and other natural systems. The comparison was conducted to address the absence of a universal model that can be applied to assess wind erosion in both croplands and rangeland environments and evaluate the potential impacts of land use change, land management strategies, and land cover change. Our research indicated that cropland wind erosion models can provide horizontal mass flux data comparable to rangeland models if corrected by a conversion factor and a constant.

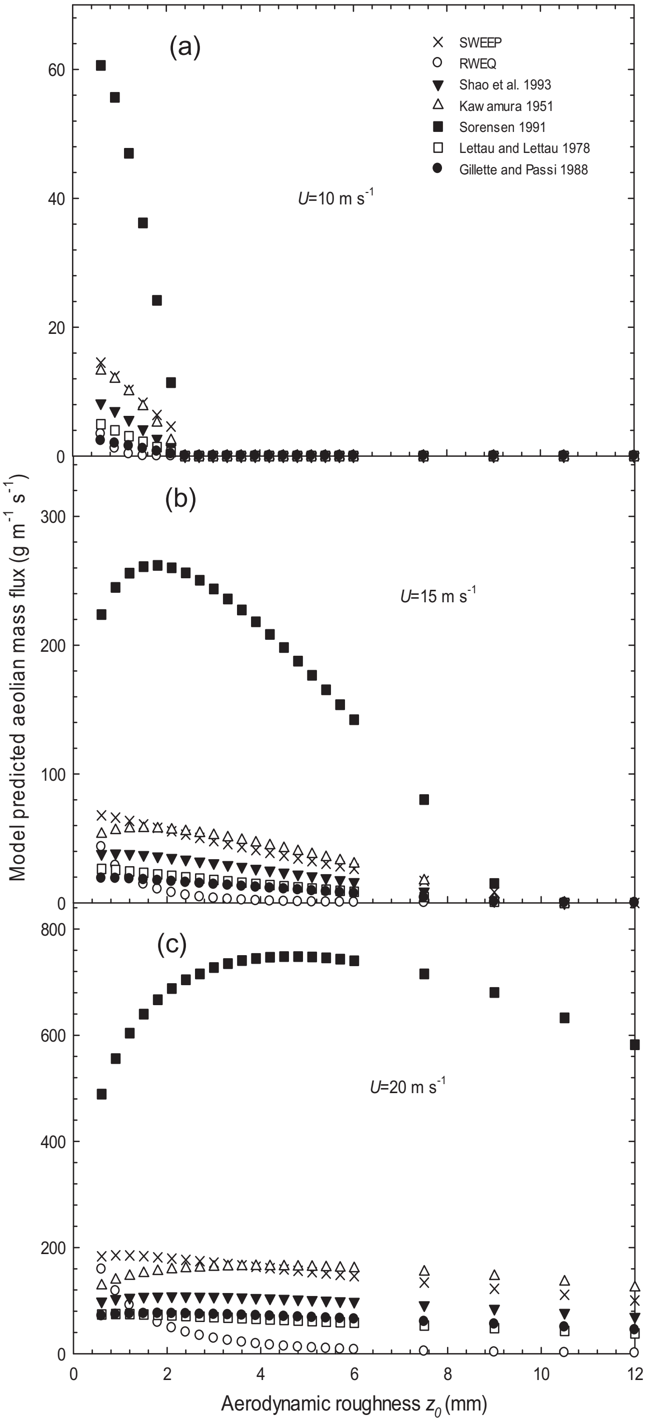

Fig. 4. Model predicted horizontal mass flux as a function of aerodynamic roughness with different wind speeds of 10, 15, and 20 m s^{-1}. All SWEEP model runs were conducted with surface crust of 10% with other parameters listed in Table 2.

Table 4
Summary of linear regression analysis between cropland wind erosion models (SWEEP and RWEQ) and rangeland mass flux equations with different wind speeds and aerodynamic roughness (0.6–12 mm).

Wind erosion model	$U = 10\ \mathrm{m\ s^{-1}}$			$U = 15\ \mathrm{m\ s^{-1}}$			$U = 20\ \mathrm{m\ s^{-1}}$		
	m	b	R^2	m	b	R^2	m	b	R^2
SWEEP									
Shao et al. (1993)	1.81	0.17	0.98	1.60	0.46	0.98	2.12	−53.6	0.83
Kawamura (1951)	1.07	0.11	0.99	1.01	−1.64	0.92	–	–	–
Sorensen (1991)	0.23	0.10	0.99	0.22	−1.33	0.88	–	–	–
Lettau and Lettau (1978)	3.13	0.24	0.97	2.47	4.02	0.99	2.35	9.9	0.99
Gillette and Passi (1988)	6.40	0.20	0.98	3.31	2.0	0.99	2.76	−29.2	0.94
RWEQ									
Shao et al. (1993)	0.23	−0.07	0.61	0.54	−6.67	0.37	–	–	–
Kawamura (1951)	0.13	−0.07	0.60	–	–	–	–	–	–
Sorensen (1991)	0.03	−0.07	0.55	–	–	–	−0.42	329.7	0.58
Lettau and Lettau (1978)	0.42	−0.08	0.67	0.98	−7.47	0.51	2.75	−139.6	0.47
Gillette and Passi (1988)	0.84	−0.08	0.64	1.21	−7.1	0.44	–	–	–

All regression equations are significant at $p = 0.01$ unless otherwise indicated. "–"indicates the regression is not significant at $p = 0.01$. Values of $m > 1$ indicate rangeland model predictions are less than cropland model predictions.

Table 5
Mean values of the conversion factor m for the horizontal mass flux calculated between cropland models (SWEEP and RWEQ) and rangeland equations (see Eq. (10)). Values in the brackets are one standard deviation, $n = 6$.

Models	Shao et al. (1993)	Kawamura (1951)	Sorensen (1991)	Lettau and Lettau (1978)	Gillette and Passi (1988)
SWEEP	1.96 (0.41)	1.25 (0.76)	0.35 (0.27)	2.82 (0.46)	4.24 (1.85)
RWEQ	0.70 (0.63)	0.44 (0.61)	0.10 (0.15)	1.14 (1.01)	1.23 (0.86)

Our results show that simulated horizontal sediment mass flux is similar for cropland and rangeland models at large surface crust coverage and aerodynamic roughness (Figs. 3 and 4), indicating strong impacts of high u_{*t} on the performance of these models. When extended to the entire range of surface crust cover and aerodynamic roughness tested in this study, the horizontal mass flux estimates varied by over three orders of magnitude among models. The wide range of fluxes predicted here suggests that the ratio of the horizontal flux to some power of wind speed (typically the cube of wind speed) is not universal and depends upon the specific environment. Global modelers face the same challenge relating wind strength to dust emission and typically adjust emission empirically to match some observed variables related to dust (Cakmur et al., 2006).

Although model results are simple, the application of models (especially multiple models) and their results must be done with great care. Our results suggest that a question that can be reasonably answered about changes in aeolian sediment transport with land use change is "By what factor will aeolian transport change if land use changes?" To answer this question, we suggest using the m and b parameters in the following way. Consider the case of conversion of rangeland to cropland. Let $Q^{t_0}_{\mathrm{Range}}$ be the horizontal flux predicted by a rangeland horizontal flux model that uses one of the transport equations studied here at time t_o before the conversion occurs. Although the area may be vegetated at t_o, multiplication of $Q^{t_0}_{\mathrm{Range}}$ by the appropriate m, plus the corrective parameter b, gives a value that can be compared numerically with $Q^{t_i}_{\mathrm{Crop}}$, the SWEEP/WEPS- or RWEQ-predicted cropland flux at time t_i sometime after the conversion (e.g., a few years). We propose that a reasonable way to answer the question of how much aeolian transport will change if land use changes is to calculate the ratio of transport after the change to transport before the change, modified by the conversion factors that bring the model estimates into alignment. In the case considered above (rangeland to cropland conversion), this factor is:

$$\Delta_{R\to C} = \frac{Q^{t_i}_{\mathrm{Crop}}}{mQ^{t_0}_{\mathrm{Range}} + b}. \tag{11}$$

In the case of cropland to rangeland conversion, this factor is:

$$\Delta_{C\to R} = \frac{mQ^{t_i}_{\mathrm{Range}} + b}{Q^{t_0}_{\mathrm{Crop}}}. \tag{12}$$

Although the Δ factors involve calculation of horizontal flux, these factors should be equally applicable for estimating changes in dust emissions. Under the common assumption, dust emission, F is linearly related to horizontal flux by a soil-specific coefficient: $F = kQ$ (Gillette, 1977; Marticorena and Bergametti, 1995). Thus, at a location under the assumption that the soil does not change (thereby changing the k), if one were to replace the Q's with F's in the Δ equations and then expand the F's to kQ, the k factors would cancel, and one would be left with the original Δ equations. Of course, in the long term, soils change as a result of wind erosion, either by the winnowing of fines from the soil or the exposure of subsurface horizons with different soil texture from the original surface horizon (Li et al., 2007, 2009). Nonetheless, the assumption of constant k is likely valid for a short time (months in the case of extremely high post-conversion erosion and years in the case of little post-conversion erosion), thus the Δ equations can be a useful guide to understanding the short-term consequences of land use on dust emission as well as total horizontal aeolian flux.

4. Summary

Assessing wind erosion in the context of land use and land cover change in croplands and rangelands is challenging due to differences in the physical characteristics of the two environments and differences in their management. This research represents a first step toward developing an approach that can provide field- to landscape-scale estimates of wind erosion in both rangeland and cropland. The approach we present here provides a preliminary method for land managers and policymakers to estimate the impacts of land use change on potential aeolian sediment mass flux, as might occur under the conversion of rangeland pasture to cropland. The tested approach is limited to the assessment of wind erosion for bare fields, in the absence of vegetation. Further investigation is required to account for changes in both soil and vegetation properties that are associated with land cover change, and more importantly, to develop a system that can be applied across all land use and land cover conditions.

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