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Modeling landscape wind erosion processes on rangelands using the APEX model

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ABSTRACT

Rangelands provide vital ecosystem services and comprise 36% of U.S. and 25% of world lands. Approximately 20 to 73% of these rangelands are already degraded. Soil erosion driven by winds is a significant cause of this degradation. Minimal work has been done to evaluate the influence of wind erosion on rangeland dominated landscapes or to assess the effect of landscape-scale soil and water conservation and management practices on reducing wind erosion due to its inherent complexity and nonpoint source nature. Our approach is to use an integrated and holistic eco-hydrologic model. The main objective of this study is to integrate process-based landscape wind erosion modeling schemes into the Agricultural Policy/Environmental eXtender (APEX) model (version 1905; APEX1905) for simulating horizontal aeolian sediment transport and vertical particles transport on rangelands. We demonstrate the performance and capability of the model using field data collected at the USDA ARS Jornada Experimental Range in New Mexico, U.S. A benchmark APEX1905 model that runs on high-resolution sub-daily wind speed data and daily average vegetation gap distribution derived from monthly field measurements. The benchmark APEX1905 model captured the variability in observed aeolian sediment transport during 2015–2017 reasonably well with an $R^2 = 0.58$ and a RMSE = 2.60. When the highly variable sub-daily measured wind speed and vegetation gap distribution data were substituted with the daily average wind speed and APEX1905 estimated daily vegetation gap, the APEX1905 reproduced well the benchmark model estimates with the performance statistic of $R^2 = 0.77$ and RMSE=0.54 for the horizontal aeolian sediment transport; and $R^2 = 0.82$ and RMSE = 0.85 for vertical particle transport. Overall, provided limited aeolian watershed data sets, the APEX1905 is demonstrated to be reliable in estimating wind erosion in arid, desert rangeland landscapes using daily average wind speed and simulated vegetation characteristics. Benefiting from the long-established algorithms of simulating plant growth dynamics and topsoil moisture content in APEX, APEX1905 offers a robust and process-based estimation of wind erosion in areas where wind and vegetation data are scarce.

1. Introduction

Rangelands claim 36% of the United States (Jones et al., 2018) and provide vital ecosystem services, including water, mineral and wood resources, livestock grazing, wildlife habitat, recreation and archeological artifacts. Deleterious impairments of the rangeland environment such as soil degradation, overgrazing, desertification, and reduced ecosystem services are a significant risk to the sustainability of rangelands in the United States. An assessment by the U.S. Department of Agriculture Natural Resource Conservation Service (USDA NRCS) suggests that approximately 21% of 160 million hectares of rangelands in the western U.S. has been degraded to some degree (Herrick et al., 2010). Based on a worldwide literature review, Weltz et al. (2014) determined that wind erosion is a major contributing factor to rangeland erosion, sediment loss, and soil degradation. Duniway et al. al.(2019) stated that disturbances including fire, domestic livestock grazing, and off-highway vehicles substantially increased horizontal aeolian flux and exacerbated dryland degradation on public rangelands. Wind-driven soil loss and sediment redistribution processes influence ecosystem dynamics and alter the provision of ecosystem services. Natural resource managers face enormous challenges in managing wind erosion effects because their impacts are widespread across spatial scales, and data are

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sparse. Pressures on land uses and development make it difficult to anticipate wind erosion potentials and manage risks (Webb et al., 2017). In this regard, reliable wind erosion models can provide means to monitor and predict how contributing factors affect wind erosion and assist with the implementation of conservation policies (Jarrah et al., 2020).

Key physical processes that drive aeolian soil particle transport on rangelands are: -Wind erosion occurs when the shear velocity of wind exceeds a threshold value at which particles start to get detached from the soil surface; -modeling approaches have been developed separately for rangelands due to the extent the factors affect erosion rates including 1. soil physical and chemical properties, 2. roughness elements (e.g., vegetation types and their spatial distribution patterns), and 3. management practices that can differ greatly between rangelands and croplands (Li et al., 2014).

Recently Jarrah et al. (2020) reviewed 12 widely used wind erosion models for cropland systems based on their data requirements, process representations and applicability. Their review highlighted, despite the improvements of wind erosion models from being empirical to process-based, their application is limited to agricultural fields. For example, the Wind Erosion Prediction System (WEPS) (Fryrear et al., 1991; Wagner, 2013) is a process-based, daily time-step model that simulates weather, field conditions, and wind erosion on croplands. In its current model structure, WEPS model has limitations for applications in rolling terrain such as rangelands and requires a complex large topographic database preparation (Hagen, 2004; Jarrah et al., 2020; Tatarko et al., 2016).

On the other hand, as presented in (Li et al., 2014, 2013) there are several rangeland wind erosion models that represent the horizontal sediment transport as a threshold-controlled process, where transport increases nonlinearly above the threshold shear velocity. Vegetation structural complexity and spatial scale are some of the factors that makes rangeland wind erosion modeling not trivial. Okin (2008) developed a new model that utilizes vegetation gap size to characterize the surface and thus explicitly accounts for spatial variability in the shear stress experienced by the soil. Li et al. (2013) parameterized and validated the Okin's wind erosion model on a variety of sites ranging from shrubby grassland to grassland and shrubland, including both degraded and undegraded plant communities. They reported that Okin's wind erosion model was able to explain 45% of the observed horizontal sediment transport ($n = 65$), indicating the reliability of the model for rangeland wind erosion assessment.

Our study proposes to dynamically link a processed-based aeolian transport model to the Agricultural Policy/Environmental eXtender (APEX) model (Williams et al., 2008) for estimating daily landscape wind erosion in rangelands. The APEX model is a continuous process-based agro-hydrological model for simulating the impact of land management on environmental quality at various spatial scales (plot-, watershed-, and regional-scale). The APEX model has been developed and updated since its inception with advances in technological development, process knowledge and many case studies with physical data as best possible (Gassman et al., 2010). The APEX model is publicly available and gets used and tested extensively in the U.S. and worldwide. The APEX model simulates surface/subsurface hydrology and water quality, production, sustainable growth, and competition of a wide range of crops, grasses, trees, shrubs among several environmental variables (Choi et al., 2017; Gassman et al., 2010; Kamruzzaman et al., 2020; Mudgal et al., 2010; Saleh et al., 2004; Wang et al., 2006, 2008, 2014). Recent advances in APEX code in rangeland simulation make APEX a suitable model for evaluating land management effects on soil degradation, water quality, and plant communities in rangeland watersheds (Wang et al., 2014; Zilverberg et al., 2017, 2018; Cheng et al., 2021).

The current version of APEX (version 1501) simulates wind erosion using the Wind Erosion Continuous Simulation (WECS Williams et al., 2008) model on smooth bare soils using daily wind speed distribution

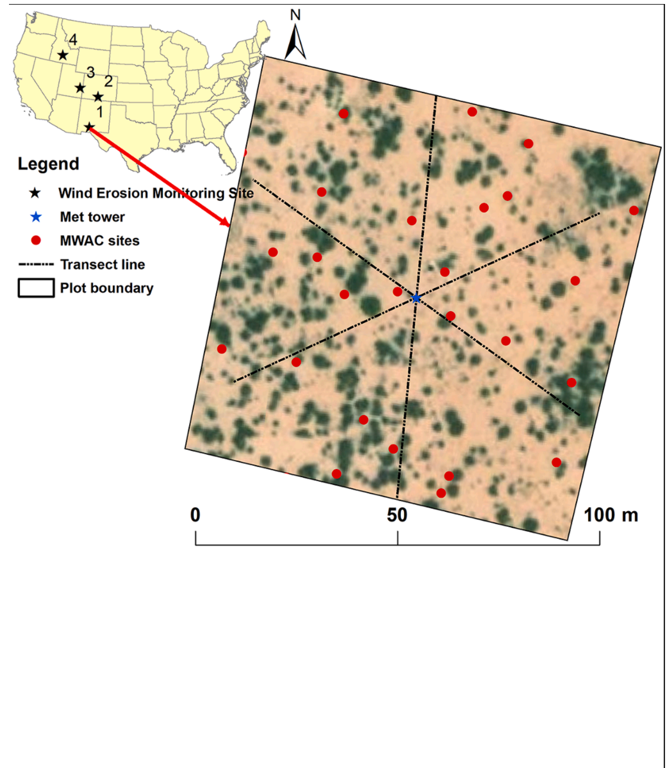

Fig. 1. Location of Jornada Experimental Range Site for wind erosion modeling along with monitoring spots for weather, wind-driven erosion using the Modified Wilson and Cooke (MWAC) sampler and vegetation variables. The black star in the U.S. map (1: Jornada Experimental Range, NM; 2: San Luis Valley, CO; Moab, UT and 4: Heart Rock Ranch, ID) indicates the wind erosion monitoring network site (top left).

utilizing the Skidmore (1986) erosion equation. The WECS method estimates actual soil erosion by adjusting the amount of potential erosion that includes four factors related to soil properties, surface roughness, plant cover, and unsheltered distance across the field in the dominant wind direction. Without new updates, the existing APEX model has limitations for application in rangelands. First, the model is empirical and developed for agricultural system (Potter et al., 1998). Second, it is data intensive and requires field properties such as ridge height and random surface height that are often difficult to measure on natural landscapes. We argue that enhancing APEX model capability for simulating wind erosion across different landcover types will be significantly beneficial because the model is being widely applied in cropland (Choi et al., 2017; Wang et al., 2008, 2006) and natural landscape (Cheng et al., 2021; Kim et al., 2020; Wang et al., 2014; Zilverberg et al., 2018). Additionally, APEX simulates landscape processes that strongly influence soil erosion, including soil moisture dynamics, plant growth, and land management practices. This is crucial to estimate wind erosion since collection of samples for soil and vegetation characteristics are often expensive and labor intensive. Coupling the landscape wind erosion model developed for rangeland ecosystems with APEX can improve the estimation of soil loss, including the effects of land management practices on rangelands. The main objective of this research is the integration of landscape wind erosion processes into the APEX (hereafter referred to as APEX1905) model for estimating the rate of horizontal and vertical sediment transport in rangelands.

2. Description of the study site and input data

The study site is part of both the Long Term Agro-ecosystem Research (LTAR) network (https://ltar.ars.usda.gov/sites/) and the

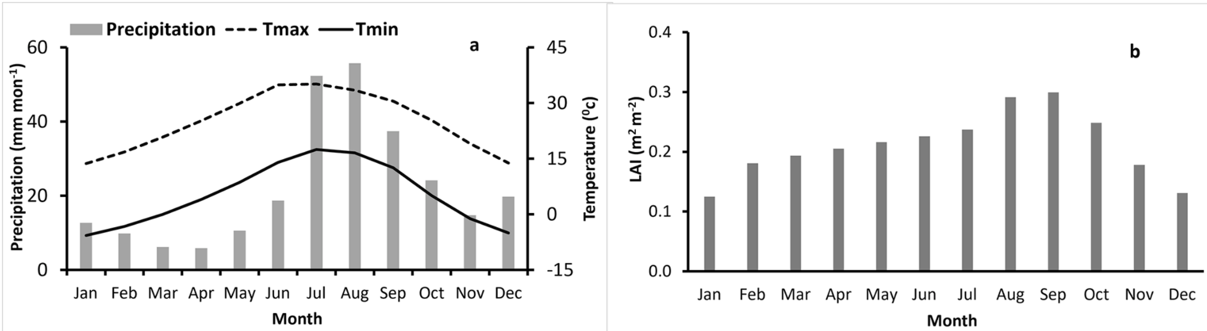

Fig. 2. a: Long-term average monthly rainfall and temperature at Jornada Exprimental Range site (1960–2017); b: MODIS Leaf Area Index (LAI) (2002–2017).

National Wind Erosion Network (NWEN; https://winderosionnetwork.org/network-sites). The Jornada Experimental Range (JER) is located within the Jornada Basin in New Mexico at an elevation of 1323 m above sea level (Fig. 1). This region is characterized by an arid to semi-arid climate with a mean annual precipitation of 261 mm (1960–2017). Fig. 2a presents historical average monthly rainfall and maximum and minimum temperature at the study site based on 57 years of data. Seventy percent of the annual rainfall occurs from June through October (Fig. 2a).

The vegetation comprises diverse community native species warm season (C_4) grasses, perennial forbs, and shrubs. The grasses include dropseeds, tobosa grass, black grama, and burrograss and are interspersed throughout the site, along with moderately sized honey mesquite shrubs and scattered soaptree yucca. The remote sensing-based LAI data from NASA (2002–2017) provides that the vegetation growth follows the region's seasonal rainfall distribution pattern. The maximum LAI values are observed in August and September (Fig. 2b). Soil textures are primarily sandy loam to fine sandy loam.

The weather station provides wind speed data at 1 min intervals for heights ranging from 0.5 to 10 m and precipitation, temperature, and solar radiation data (Fig. 1). Vegetation gap, height, and cover fraction data were measured in 3 transect lines that are 100 m long (Fig. 1) per month from August 2015 to December 2017 as it occurs. Wind erosion data are measured using the Modified Wilson and Cooke (MWAC) sampler (Goossens, 2000). Webb et al. al.(2015) provide the details about protocols on wind-driven sediment flux measurements within the NWEN. A total of 27 MWAC stems are distributed spatially across the site to monitor wind-driven soil erosion (Fig. 1). We acquired all the measured data related to wind erosion modeling from USDA-ARS, Las Cruces, New Mexico (Nicholas Webb, personal communication on November 30, 2018). Remote sensing-based LAI data were obtained from MODIS for 2002–2017 to calibrate the plant growth simulation in the APEX1905 model.

3. Methods

3.1. APEX model description

APEX is a process-based agricultural and hydrologic model for simulating the impacts of land management on a variety of spatial and temporal scales (Williams et al., 2008). Williams et al. (2008) described 12 principal components of the model, including climate, hydrology, crop growth, wind and water erosion, nutrient cycling, grazing and land management practices. The model operates daily but can run a sub-daily time step for rainfall-runoff calculation and can simulate hundreds of years.

A watershed is divided into subareas in APEX to achieve homogeneity concerning soil properties, land use, and management. The APEX model allows the user to configure a channel network and water bodies between subareas. The channel routing module provides hydrologic routing and dynamic interactions between subareas involving surface runoff, return flow, sediment deposition and degradation, chemical transport, and groundwater return flow. These hydrologic components encompass all critical processes that occur in the hydrologic cycle of the watershed (Williams et al., 2008; Wang et al., 2012). Recently, the groundwater simulation in APEX is enhanced by integrating with MODFLOW – a three-dimensional, physically-based, distributed finite-difference groundwater model for variably saturated subsurface systems (Bailey et al., 2021). Plant canopies can intercept incoming precipitation. The sum of the precipitation, snowmelt water, and/or irrigation input is partitioned between surface runoff and soil infiltration, thereby increasing the soil moisture content of the top layer of the root zone. Soil water is routed vertically and laterally based on soil hydraulic properties, soil evaporation, and plant root uptake. Drainage pipes, often implemented in soils with a shallow groundwater table, accelerate lateral drainage of excess soil water. APEX offers multiple options for simulating water transport processes. For example, five potential evapotranspiration equations, six water erosion methods, two peak runoff rate equations, among others, are available.

The APEX plant growth module enables the growth and competition of multiple species within a plant community. Root zone competition includes water and nutrients, while surface competition depends on solar radiation (daily weather), water, and nutrients. The user can prescribe plant population (number of plants/m^2 for all perennial and annual plants; the number of plants /ha for trees).

3.2. Existing wind erosion model in APEX for croplands

The current wind erosion model in APEX – Wind Erosion Continuous Simulation (WECS) – is an empirical approach and developed to simulate soil loss in agricultural management systems (Williams et al., 2008). This model estimates potential wind erosion for a smooth bare soil surface by integrating the erosion equation through a day using the wind speed distribution. Eventually, the potential erosion rate (Eq. 1) is adjusted using four main controlling factors that reflects the field conditions including a soil erodibility factor, soil surface roughness, vegetation cover, and unsheltered distance across the field in the wind direction.

$$YWR = c\left(\frac{\rho_a}{g}\right)\left(u_{*w}^2 - u_{*t}^2 - 0.5 \times \left(\frac{sw}{wp}\right)^2\right)^{1.5} \quad (1)$$

where *YWR* is the potential wind erosion rate (kg m^{-1} s^{-1}), *c* is an empirical parameter (~2.5), ρ_a is the air density (kg m $^{-3}$), *g* is gravitational constant (9.8 m s $^{-2}$), u_{*w} is the shear velocity (m s^{-1}), and u_{*t} is the threshold shear velocity (m s^{-1}), *sw* and *wp* are the actual and 1500 kPa water content of the surface soil layer, respectively. The *sw/wp* ratio is referred to as the surface water parameter.

The actual wind erosion estimate (kg m^{-1}) for a day, *YW* is computed as:

$$YW = FI \times FRF \times FV \times FD \times YWR \quad (2)$$

where *FI* is the soil erodibility factor, *FRF* is the surface roughness factor, *FV* is the vegetative cover factor, and *FD* is the mean unsheltered travel distance of the wind across a field factor. Note that *YWR* is the integral of the wind erosion rate over the duration of the wind speed greater than a threshold velocity. More details about the computation of each factor is provided in Williams et al. (2008) and Potter et al. (1998).

3.3. Description of selected rangeland wind erosion equations for integration in APEX

This section provides a brief description of the main wind erosion processes that are considered to estimate wind-driven soil erosion in rangelands for integration with APEX1905. In general mass flux equations developed for rangelands represent the horizontal sediment transport as a threshold-controlled process, where transport increases nonlinearly above the threshold shear velocity (Li et al., 2014). We considered reported evaluation results in Okin (2008) and Li et al. (2014, 2013) while selecting methods to integrate with APEX1905. Additionally, we considered the model type (i.e., being processed-based) and data requirement (i.e., being less data-intensive) as criteria. Consequently, we selected models such as Okin (2008) model for surface shear stress partitioning, Iverson and white (1982) model for threshold shear velocity, Gillette and Passi (1988) model for horizontal sediment transport and Shao et al. (2011) for vertical particle transport. In this study the combination of these models to estimate wind-driven soil erosion in rangelands referred as Landscape Wind Erosion (LWE) model. Below, a brief description of each component in the LWE model and their process representation are provided.

3.3.1. Shear stress partitioning on vegetated surfaces

Vegetation and nonerodable surface elements modulate the spatial distribution of shear stress near the surface (Okin, 2008), thereby considerably influencing aeolian transport. Therefore, it reasons that varying vegetation would impact the surface roughness, causing increased uncertainty in wind erosion modeling due to the inherent variability in the surface roughness estimation. Horizontal sediment transport (Q) is a function of the wind shear velocity (u_*) on the land surface that is in excess of a threshold friction velocity (u_{*t}) (Gillette and Passi, 1988). Aeolian transport models estimate $u_{*\mathrm{w}}$ by relating to the wind speed (u) at height z (m) and the aerodynamic roughness height z_o (m) through the logarithmic wind profile, which does not consider the effect of surface roughness due to vegetation growth.

Okin (2008) proposed a model that explicitly treats variability in surface shear stress by utilizing vegetation gap distances to characterize erodible soil surfaces. This model defines a landscape as a collection of vegetation gaps, each scaled by the height of the upwind sheltering plant, with a gamma probability distribution. The model uses the probability distribution of vegetation gaps between plants to determine the probability that any point in the landscape is distant from the nearest plant in the upwind direction (Okin, 2008). In addition, this model assumes that each plant is associated with a reduced shear stress wake zone using an exponential curve relationship per Eq. 3 (Okin, 2008):

$$u_* = u_{*w}\left(\left(\frac{u_*}{u_{*w}}\right)_{x=0} + \left(1-\left(\frac{u_*}{u_{*w}}\right)_{x=0}\right)\left(1-e^{-C/(x/h)}\right)\right) \tag{3}$$

where u_* is the shear velocity in the leeward of a plant (m s^{-1}), $\left(\frac{u_*}{u_{*w}}\right)_{x=0}$ is the ratio of u_* and $u_{*\mathrm{w}}$ in the immediate leeward of a plant–shear velocity ratio, C is the e-folding distance for the recovery of the shear velocity (u_*) in the lee of plants to the value it would have in the absence of vegetation ($u_{*\mathrm{w}}$) x is the distance to the nearest upwind plant (m), and h is the mean canopy height (m). The wind shear velocity without windbreak ($u_{*\mathrm{w}}$) is formulated as a function of the mean wind speed (u) at the height z (Eq. 4):

$$u_w = \frac{0.4u}{ln\left(\frac{z}{z_0}\right)} \tag{4}$$

wherez_o is the aerodynamic roughness length (m).

The threshold shear velocity (u_{*t}) is the minimum shear velocity required to initiate the motion of soil particles. This variable depends on soil texture, soil moisture, salt concentration, surface crusting, and surface roughness elements. Iversen and White (1982) noted the importance of interparticle forces (cohesive forces) in determining threshold friction velocity. The threshold friction velocity for a dry condition (u_{*t_dry}) is determined first and subsequently modified for soil moisture and roughness factors. In this study, Iversen and White's approach is used as formulated in Eq. 5.

$$u_{*t\_dry} = \sqrt{A_N\left(\frac{\rho_p g D}{\rho_a} + \frac{\Gamma}{\rho_a D}\right)} \tag{5}$$

where ρ_a and ρ_p are the air and particle density respectively, D is particle diameter, A_N and Γ are empirical coefficients. To account for soil moisture, we use Fecan et al. (1999) approach. The modifier for soil moisture (f_w) is computed by considering clay content and soil-water content to account for the interstitial water space as follows:

$$f_w = \begin{cases} 1 & for\, w < w' \\ \left[1 + 1.21(w - w')^{0.68}\right]^{0.5} & for\, w > w' \end{cases} \tag{6}$$

$$where\, w'(\%) = 0.0014(\%clay)^2 + 0.17(\%clay) \tag{6-1}$$

where w is the mass fraction of soil moisture content.

3.3.2. Horizontal sediment transport

Generally, wind-driven sediment flux has two main pathways: horizontal sedimen transport (Q) and vertical particles transport (F). The horizontal sediment transport comprises mainly saltating particles with diameters from 20 to 500 μm. Saltation-sized particles travel close to the soil surface, redistributing surface soils across the landscape. The transport of particles is initiated when the wind shear velocity exceeds the threshold friction velocity. Li et al. (2013) compared the performance of several aeolian transport models in estimating the horizontal sediment flux. They suggested that the method Gillette and Passi (1988) proposed provides a more accurate estimation of horizontal sediment transport than other methods. Therefore, this method is being used in APEX1905 (Eq. 7):

$$Q(d) = \begin{cases} (1 - FGC)A\frac{\rho_a}{g}{u_*}^4\left(1 - \frac{u_{*t}}{u_*}\right) & u_* > u_{*t} \\ 0 & u_* < u_{*t} \end{cases} \tag{7}$$

where A is a dimensionless constant that may vary between 0 and 1, and FGC is the fraction of ground cover by vegetation.

3.3.3. Vertical particle transport

Vertical particle transport refers to the suspension of particles less than 20 μm that is emitted when saltating particles sandblast the soil surface, overcoming the strong inter-particle forces between fine particles (Li et al., 2013; Shao, 2004; Shao et al., 2011). Unlike particles in the horizontal sediment transport, vertical flux particles are transported long distances outside their source area (Li et al., 2014). Shao et al. (2011) proposed a scheme to estimate vertical particle transport that considers saltation bombardment and the disintegration of aggregates. In this approach, vertical particle transport is proportional to the horizontal sediment flux, in which the proportionality depends on soil texture and soil plastic pressure. This strategy was evaluated using observation data from several locations globally (Shao, 2004; Shao

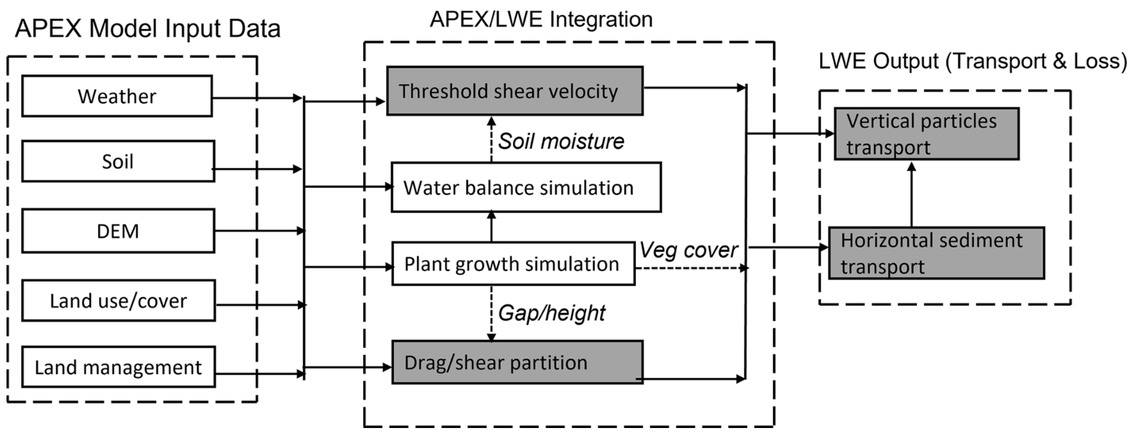

Fig. 3. Schematic of APEX1905 and Landscape Wind Erosion (LWE) processes and module integration. The LWE processes are designated in gray boxes, and the outgoing state variables from APEX1905 to LWE (broken arrows) are depicted in italic.

et al., 2011). We utilized the same equation in APEX1905 to simulate the vertical particle transport as follows:

$$F(d_i, d) = c_y \eta_{fi} \left[(1 - \Upsilon) + \Upsilon \sigma_p\right](1 + \sigma_m)\frac{gQ(d)}{u_*^2} \tag{8}$$

where $F(d_i; d)$ is the vertical particle transport rate of the particle size d_i (from the ith size bin) generated by saltation of particles, c_y is a dimensionless vertical particle transport coefficient and η_{fi} is the amount of vertical particles emitted from the ith vertical particle bin in relation to the parent soil characteristics represented in the fully disturbed particle size distribution. Soil particle size distribution varies depending on the destructive forces applied to the soil sample during analysis. To circumvent this problem, Shao et al. (2011) defined two limiting particle size distributions: (1) minimally disturbed particle size distribution, $p_m(d)$, the limiting case in which the parent soil sample is analyzed with no disturbance, and (2) fully disturbed particle size distribution, $p_f(d)$, the limiting case in which aggregates are broken up as much as possible by mechanical forces. σ_p is the ratio between the amount of free vertical particles ($p_m(d)$) and that of aggregated vertical particles ($p_f(d)$).

The bombardment efficiency (σ_m) is the ratio between the mass of particles ejected by bombardment and the mass of impacting particles and is computed by:

$$\sigma_m = 12u_*^2 \frac{\rho_b}{P}\left(1 + 14u_*\sqrt{\frac{\rho_b}{P}}\right) \tag{9}$$

where ρ_b is the soil bulk density (kg m^{-3}), and P is the soil plastic pressure (Pa). Υ is a function that describes how easily aggregated vertical particles can be released and estimated as:

$$\Upsilon = exp - k(u_* - u_{*t})\left(1 + 14\sqrt{\frac{\rho_b}{P}}\right) \tag{10}$$

3.4. Coupling the landscape wind erosion modules with APEX1905

The selected core wind erosion processes that are developed for rangelands (see Section 3.3) were written in Fortran and added to the APEX model's source code. Fig. 3 illustrates APEX's main inputs and LWE core processes and outputs for rangelands. The new component enables APEX1905 to simulate wind-driven horizontal sediment and vertical particle transport on a continuous daily time-step using high-resolution wind speed and vegetation gap distribution data at multiple spatial scales. The APEX1905 model can use daily average wind speed inputs, simulated soil moisture and vegetation characteristics (i.e., mean plant height, vegetation fraction of cover, mean vegetation gap) in areas where observed data are limited. This makes APEX1905 uniquely valuable in data-scarce regions to evaluate the effects of land management practices on wind-degraded lands.

Being a daily time-step model, APEX model, in general requires model input data pertinent to weather and state variables to be daily values. The main input requirements to simulate LWE within APEX1905 are the daily wind speed distribution, fraction of vegetation cover, vegetation height and vegetation gaps distribution. Additionally, the LWE module requires simulated daily soil moisture fraction in the topsoil layer (i.e., 5 mm) and soil characteristics related to soil texture and particle size distribution. Wind probability functions are developed from daily wind speed data in APEX weather inputs as presented in Section 3.3.1. Changes in vegetation gaps are estimated based on two-state variables of APEX, including plant population and leaf area index

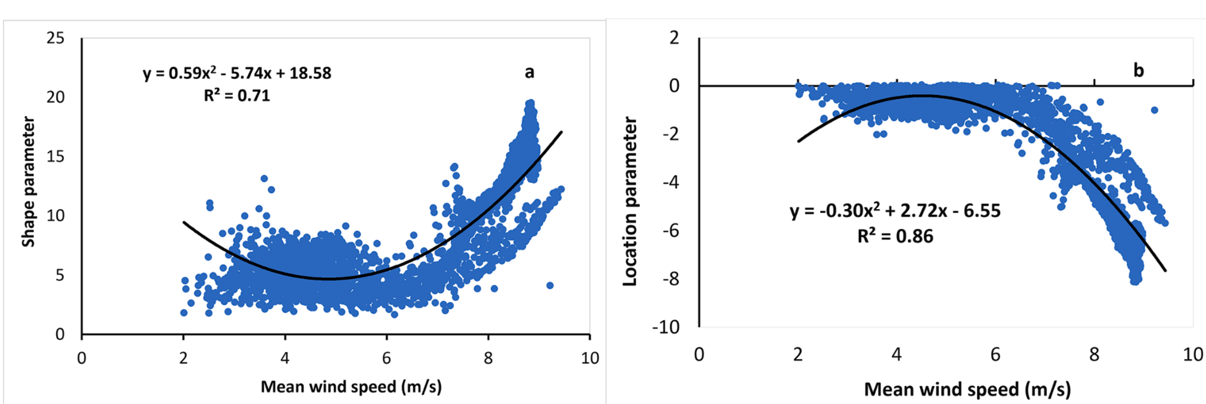

Fig. 4. The relationship between mean wind speed and shape (a) and location (b) parameters of gamma distributions using several locations across the U.S.

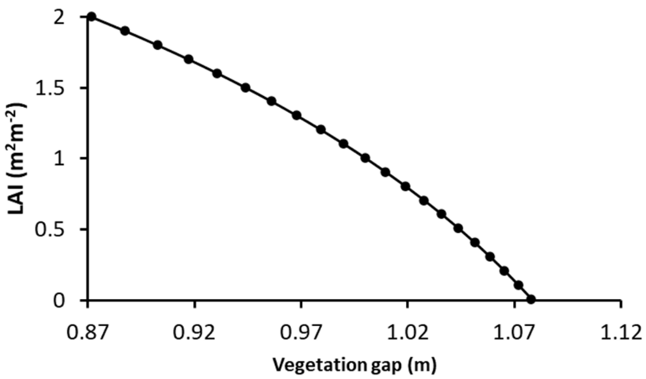

Fig. 5. APEX1905 model simulation of Jornada Experiment Range National Wind Erosion Network site for the extent of average vegetation gap declines as the LAI increase along the growing season.

(see Section 3.3.2). The probabilistic approach in the LWE takes advantage of the process-based wind erosion equations for simulating soil erosion in rangelands.

3.4.1. Mean-based daily wind speed distribution

Wind speed is often reported as the daily mean value. However, wind erosion models require wind speed distribution and use a stochastic wind generator. This study developed an empirical method to estimate the wind speed distribution using the gamma model (with specified shape, location, and scale parameters) for a given mean wind speed. A database of gamma distribution parameters covering the U.S., derived from long-term re-analysis climate data, was used to find empirical relationships between mean wind speed and the gamma parameters. We discovered a strong statistical correlation between gamma parameters and mean wind speed based on data randomly selected at 3000 locations. For example, Fig. 4 presents relationships between the shape (a) and location (b) parameters of the gamma function and their mean wind speed values.

3.4.2. Computing vegetation gap distribution

The distribution of vegetation gaps on the landscape is crucial to compute the partitioning of shear stresses in Okin's approach (Okin, 2008). As demonstrated in Eq. 9, the vegetation gap (G_{act}) is estimated as a function of plant population and LAI. This approach determines the maximum possible gap length (i.e., diameter by assuming a circular area) that corresponds to the length of a subarea. Given the dynamics in the plant growth during a growing season, we used an exponential decline curve to reduce the gap between plants within the annual growth cycle (Fig. 5). In Eq. 11, the maximum plant density (i.e., prescribed plant population) is associated with the minimum gap length and vice versa.

$$G_{act} = G_{den}\left(1 - \exp\left(-2.5 + LAI_{adj\_factor}\right)\right) \quad (11)$$

where G_{den} denotes the average gap between plants based on plant population (number of plants m^{-2}) prescribed in APEX. LAI_{adj_factor} is an adjustment factor that ranges between 0 (start of the growing season) and 1 (at maturity) and mainly depends on a plant development stage.

3.5. Plot scale APEX1905 model setup and calibration procedures

We configured the APEX1905 for the study site (Fig. 1) with a single subarea using unique elevation, soil, and land use data. A modified Soil Conservation Service (SCS) curve number method (USDA SCS, 1972) estimated surface runoff. The Hargreaves method (Hargreaves and Samani, 1985) was selected for estimating daily potential evapotranspiration rates. The site had mixed native species, including C4 grasses and perennial shrubs, and two dominant species (black grama grass and honey mesquite) were selected for simulation in APEX1905. The simulation was run for 27 years (1988–2014) for parameter establishment and is considered as a warm-up period to stabilize plant growth and state variables before running the evaluation period. Initially, the calibration was performed to capture overall water balances based on literature values in the area. Once the APEX model simulated local water balances, for example, confirming the dominant part of the precipitation translated to evapotranspiration, historical LAI values translated from MODIS datasets were used to calibrate the seasonal variability of plant growth details. We used measured vegetation gaps, vegetation cover fraction and canopy heights to constrain plant growth within APEX1905 further.

Next, before calibrating wind erosion parameters, we conducted a parameter sensitivity analysis using a one-factor at a time approach to quantitatively evaluate the sensitivity of the horizontal sediment transport and vertical particles transport to LWE parameters. Table 1 presents the LWE parameters and their value ranges as well as selected parameter values used in the sensitivity analysis. The LWE parameters were manually adjusted to match the simulated horizontal sediment transport to observed values during calibration. The calibration of wind erosion was carried out using 29 data points of horizontal sediment transport measured in 2015–2017. In contrast, since no measured vertical particle data were available, representative literature values were used for vertical particle data. The goodness-of-fit of the simulated horizontal sediment transport was tested against observed values using the coefficient of determination (R^2), root mean squared error (RMSE) and percent of bias.

The sensitivity analysis and calibration were conducted using the APEX1905 model with the LWE module that runs on high-resolution sub-daily wind speed data and monthly vegetation gap distribution derived from monthly field measurements. This model is referred to as the benchmark model with which the additional simulations of APEX1905 will be compared. To evaluate the reliability of LWE module in APEX1905 while using daily mean wind speed and vegetation gap as

Table 1
List of LWE parameters and their ranges provided in Li et al. (2013) and Shao et al. (2011) and calibrated values (current study). Par1 to Par5 are the parameter values used during sensitivity analysis.

Parameters	Process	Value range	Parameter values					Calibrated value
			Par1	Par 2	Par 3	Par4	Par5	APEX1905
Surface roughness height (m), Z_0	Horizontal transport	10^{-7} – 10^{-1}	7.7×10^{-5}	7.7×10^{-4}	7.7×10^{-3}	7.7×10^{-2}	0.1	3.7×10^{-4}
Scaling factor (s m^{-1}), A	Horizontal transport	0 – 1	0.1	0.3	0.5	0.7	0.9	0.65
e-folding distance for the recovery of the shear velocity in a lee of a plant, C	Horizontal transport	4.8 – 10	4.8	6	7	8	9	7.1
Shear velocity ratio in the immediate lee of a plant, $\left(\frac{u_*}{u_{*w}}\right)_{x=0}$	Horizontal transport	0.0 – 32	0.05	0.1	0.15	0.2	0.25	0.38
Vertical particle transport coefficient, C_y	Vertical transport	10^{-5} – 10^{-4}	2.7×10^{-5}	3.7×10^{-5}	4.7×10^{-5}	6.7×10^{-5}	7.7×10^{-5}	5.7×10^{-5}
Soil plastic pressure (Pa), p	Vertical transport	10^3 – 10^6	10^3	10^4	4.0×10^4	8.0×10^4	10^6	20,250
Shape factor for particle size distribution, K	Vertical transport	0 – 1	0	0.25	0.6	0.8	1	0.5

Table 2
Summary statistics on the comparison of daily wind speed gamma distribution derived from 1 min interval observations and daily mean wind speed.

Site	Observation-based Mean (m s^{-1})	Variance	IQR	Skewness	Kurtosis	Mean-based Mean (m s^{-1})	Variance	IQR	Skewness	Kurtosis
San Luis Valley, CO	3.5	3.9	2.4	1.7	18.1	3.7	4.1	2.4	1.6	16.3
Jornada Exprimental Range, NM	3.4	3.8	2.3	1.6	17.1	3.5	3.7	2.3	1.5	14.8
Moab, UT	3.3	3.5	2.3	1.4	14.5	3.6	3.8	2.3	1.5	15.1
Heart Rock Ranch, ID	3.1	4.1	2.4	1.9	20.7	3.4	3.5	2.2	1.5	14.0

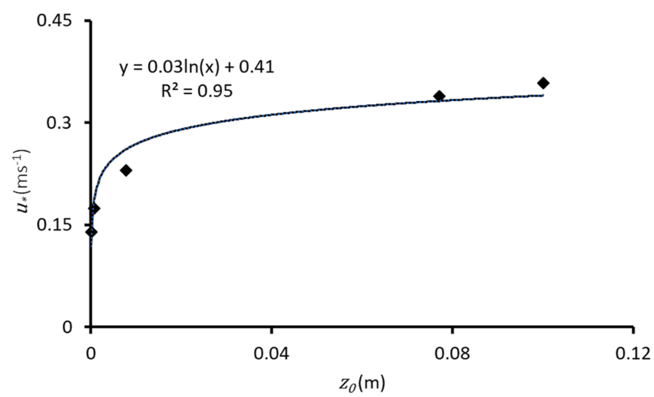

Fig. 6. Sensitivity of shear velocity (Y-axis) to changes in roughness height (X-axis).

an input, outputs from APEX1905 simulations were compared with benchmark APEX1905 simulations. It is worth underscoring that the only difference between the benchmark 1905 and APEX1905 models is their input data for the LWE module.

4. Results and discussion

4.1. Daily wind speed and vegetation gap distribution estimations for limited observed data availability

To evaluate the mean-based daily wind speed distribution computed by the empirical method described in Section 3.3.1, we compared multiple dispersion and skewness values at four National Wind Erosion Network sites (Fig. 1). Wind speed was monitored at 1 min intervals. Table 2 presents a statistical summary of wind speed distributions for wind speed measurements in 2016. It is notable that skewness coefficients of the wind speed distribution calculated for the mean-based approach range between 1.47 and 1.57. These values are comparable to observation-based skewness values (i.e., ranging from 1.37 to 1.86). It is worth noting that the statistical measures for variation and skewness from the observation- and mean-based methods are comparable, indicating that the mean-based approach can reasonably reproduce the probability distribution of daily wind speed.

Fig. 5 shows the simulated vegetation gap and LAI relationship in a single year. The measured mean vegetation gap ranges 0.6 m – 1.0 m between 2015 and 2017, while the simulated gap ranges from 0.8 to 1 m for the same period, indicating that the APEX1905 simulated the mean vegetation gap for the study site is acceptable.

4.2. Sensitivity analysis

4.2.1. Parameters related to sediment transport

Surface roughness height is a key parameter that strongly influences the distribution of surface shear stresses (Fig. 6); therefore, it is considerably influential in estimating horizontal sediment transport. This entails that in a heterogeneous landscape, the spatio-temporal non-linear response of shear stress to the surface roughness height makes it harder to determine a reliable representative quantity of horizontal sediment transport and can be a source of uncertainty.

Fig. 7a depicts the effect of surface roughness height (z_o), scaling factor (A), e-folding distance for the recovery of the shear velocity (C) and Shear velocity ratio in the immediate lee of a plant $\left(\frac{u_*}{u_{*w}}\right)_{x=0}$ selected parameter values ranging from lower (Par1) to higher (Par5) with respect to simulated horizontal sediment transport. For instance, roughness height values range from 10^{-7} to 10^{-1} m, and the horizontal sediment transport estimates corresponding to these values range between 10^2 and 10^4 gd^{-1}m^{-1}. This demonstrates a strong sensitivity of the horizontal sediment transport to the surface roughness height parameter, which is further highlighted by large ranges of RMSE values in Fig. 7 b (i.e., 0.53 to 1.24 gd^{-1}m^{-1}). The scaling factor, A, showed a linear pattern on the simulated horizontal sediment, as shown in Fig. 7 a. The changes in the exponential recovery rate for the shear velocity in the lee of a plant, C, from low to high values had an inverse relationship with simulated horizontal sediment transport, as shown in Fig. 7 a. The shear velocity ratio in the lee of a plant was less sensitive than other parameters. Yet, an increase in shear ratio value increased horizontal sediment transport, as shown in Fig. 7 a.

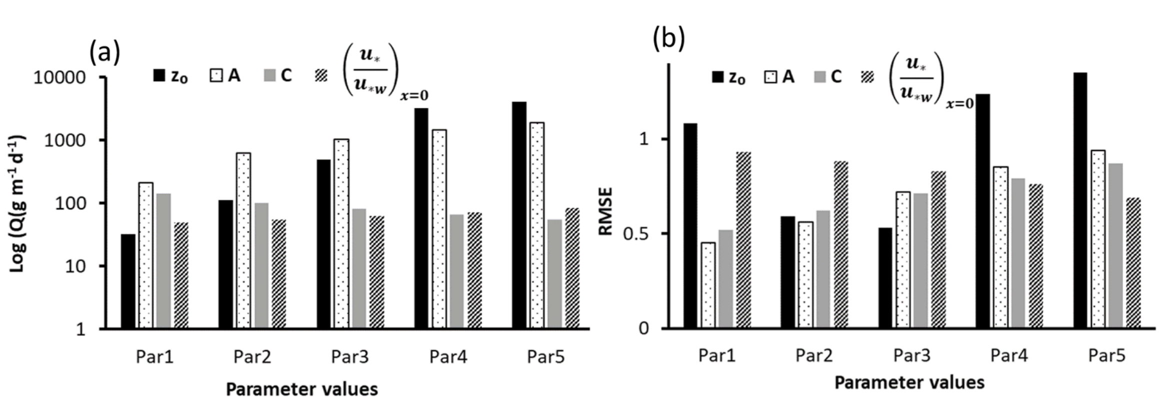

Fig. 7. Effects of LWE parameters on sediment transport magnitude (Y-axis) (a) and changes in goodness-of-fit (Y-axis) (b). The definition of each LWE parameter and the values of the parameters used (Par1 to Par5) are provided in Table 1.

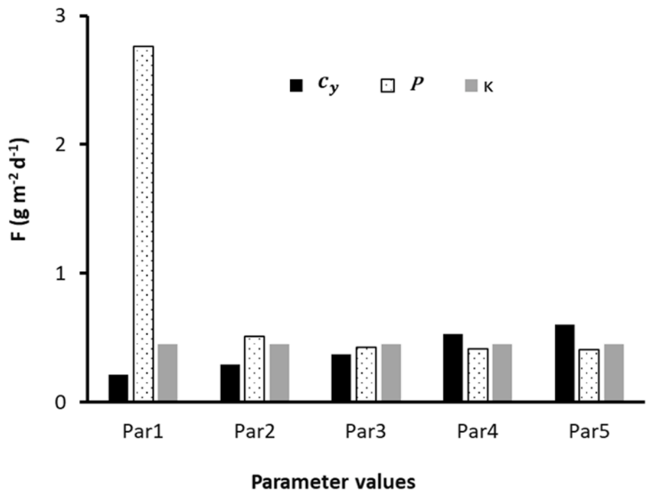

Fig. 8. Effects of LWE parameters on vertical particle transport simulation (Y-axis). The definition of each LWE parameter and the values of the parameters used (Par1 to Par5) are provided in Table 1.

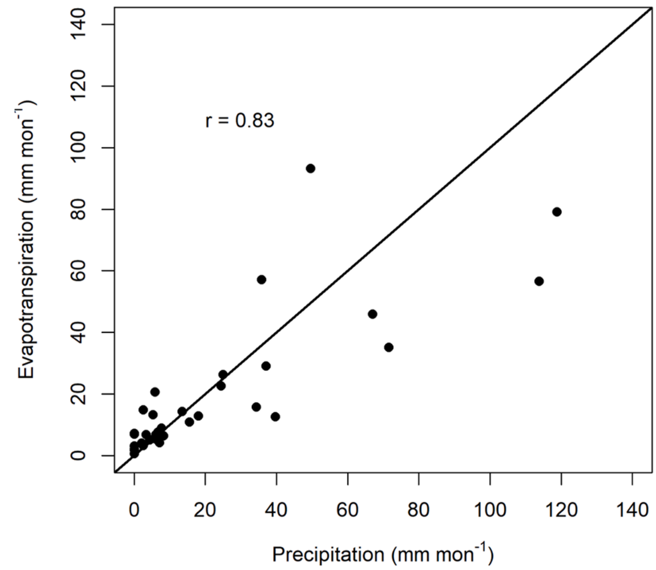

Fig. 9. A strong linear relationship between precipitation and APEX1905 simulated evapotranspiration is shown with r = 0.82.

Table 3
APEX calibrated parameters for simulation water balance and plant growth.

Parameter description	Default (calibrated)
Soil water lower limit	0.5 (0.49)
Curve number retention parameter	1 (1.5)
Runoff curve number initial abstraction	0.2 (0.4)
Soil water content at wilting point[1]	0.08–0.17 (0.03–0.17)
Soil water content at field capacity[1]	0.16–0.25 (0.09–0.25)
Hargreaves PET equation exponent	0.6 (0.5)
Optimal temperature for plant growth	30 (27)
Minimum temperature for plant growth	10 (6.5)
Maximum potential leaf area index	1.35 (1)
Fraction of growing season when leaf area declines	0.99 (0.8)
First point on optimal leaf area development curve	5.05 (5.1)
Second point on optimal leaf area development curve	50.8 (70.95)
Leaf area index decline rate parameter	1 (0.01)
Maximum crop height	(0.8)
Plant population for crops & grass-1st Point on curve	120.88 (400.95)
Plant population for crops & grass-2nd Point on curve	20.13 (10.06)
Potential heat Units	4254

[1] The range shows the parameter values across the soil layer.

4.2.2. Parameters related to vertical particle transport

Vertical particles transport rate is proportional to streamwise saltation flux but the proportionality depends on soil texture and soil plastic pressure (Shao, 2004). Fig. 8 shows low values of soil plastic pressure (loose soils) that tended to result in high vertical particle transport estimates. The influence of the soil plastic pressure on selected values above 10,000 Pa was minimal on simulated vertical particle transport. The vertical particle transport coefficient and the shape factor for particle size distribution parameters strongly influenced the vertical particles transport (Fig. 8). As suggested by Shao et al. (2011), a significant kappa coefficient value represents a soil with particle coats and aggregates, which are easily broken, while a small kappa value represents the opposite.

4.3. Evaluation of calibrated model performance

Hydrologic monitoring data at the location were unavailable to evaluate simulated outputs directly. Therefore, we conducted a qualitative evaluation of the model. Table 3 lists APEX1905 parameters that were calibrated manually. The calibrated APEX1905 model results indicated that a considerable portion of annual precipitation (i.e., 88%) returns to the atmosphere through evapotranspiration. This is in agreement with Templeton et al. (2014), in which the authors noted a strong correlation between precipitation and evapotranspiration during summer months in the study area.

Similarly, a robust linear relationship (r = 0.82) was found between precipitation and simulated evapotranspiration, indicating that the manually calibrated APEX1905 model performed well on estimating water balances for the study field (Fig. 9). The model suggested that the study field had low surface runoff volume, which is well supported by hydrologic properties of the area, such as sandy soil texture having high infiltration potential and a low slope gradient. In general, simulated hydrologic outputs from the APEX1905 were consistent with underlying controlling factors and reported values in the region for the routine developed and keeping the parameters within acceptable ranges.

Fig. 10 depicts the comparison of simulated monthly LAI with observed LAI from MODIS from 2015 through 2017. Overall, the APEX1905 simulated monthly LAI dynamics matched well with MODIS LAI, r = 0.86, and their agreement further improved when aggregated seasonally. The APEX1905 model over (under) estimates the peak (minimum) LAI values compared to the MODIS estimates during the summer (winter) months. The MODIS LAI data has a 500 m pixel size, while the Jornada Experimental Range site has a 100-m by 100-m plot size. Thus, the LAI estimation error may be partly attributable to the difference in the spatial scale of sampling domains between simulated and observed values. Scarcity of local hydrologic data due to low rainfall under an arid and semi-arid climate was a prodigious challenge in calibrating the APEX1905 on water balances and plant growth simulation. However, these modeling simulations demonstrated that the APEX1905 performance is acceptable after keeping parameters within viable parameter value ranges even with limited observation data. The ability to simulate local soil moisture dynamics and plant growth responses to local weather in an arid climate is a key feature of APEX1905 as a wind erosion simulator. This new development accounts for local weather, soil, and vegetation conditions in simulating aeolian transport processes. Furthermore, the holistic model approach of the APEX1905 enables model users to evaluate the effect of various land management practices on wind erosion.

Fig. 11 compares observed and simulated horizontal sediment transport between 2015 and 2017. The calibrated benchmark model explains 58% of the observed variability in the horizontal sediment transport with low bias (2.6%), indicating a good simulation. It is evident from the measured data that the study area has a considerable temporal dynamic in horizontal sediment transports ranging from 2 to

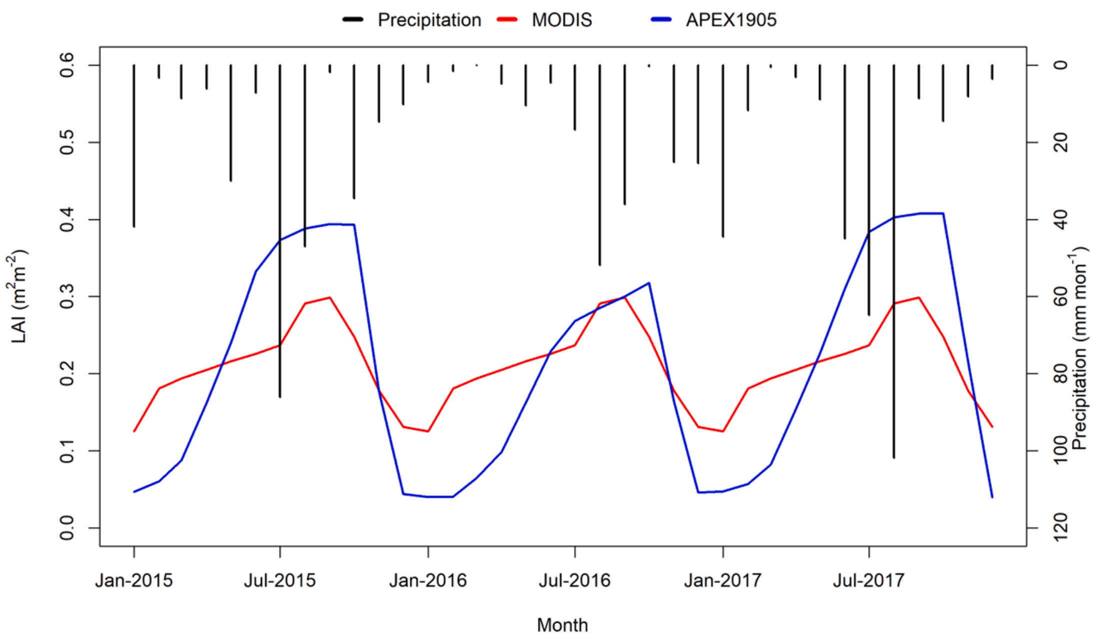

Fig. 10. Seasonal dynamics of MODIS and APEX simulated LAI from 2015 through 2017.

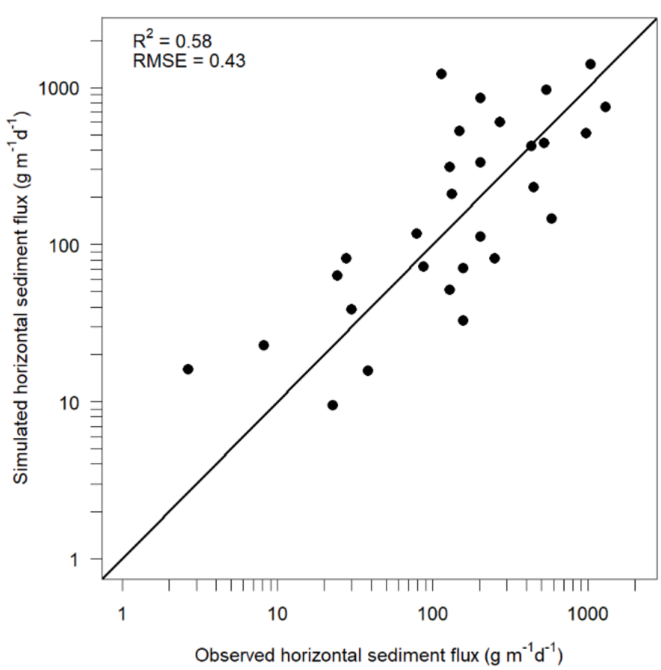

Fig. 11. Comparison of horizontal sediment transport simulated by the APEX1905 Landscape Wind Erosion benchmark model and observations from Jornada Experimental Range, National Wind Erosion Network site. Both axes are log-transformed.

1305 g m^{-1} d^{-1}. There is a comparable range in the LWE benchmark model simulated with the horizontal sediment transports (9 – 1393 g m^{-1} d^{-1}) for the same period, indicating the capacity of the APEX1905 to simulate sediment flux under extreme conditions in rangelands. The monthly average vertical particle transport rate ranges from close to 0.0 to 0.38 g m^{-2} d^{-1}, and the average is 0.081 g m^{-2} d^{-1}. These estimates are comparable to reported vertical particle transport estimates for the Cactus Flats monitoring site, New Mexico of 0.015 g m^{-2} d^{-1} (shrubland) and 0.0083 g m^{-2} d^{-1} (grassland) g m^{-2} d^{-1} (Breshears et al., 2003).

4.4. *Comparison of the benchmark model with APEX1905*

As described in Section 3.3, the sole difference between the LWE benchmark model and APEX1905 used to simulate the Jornada Experimental Range site data is the temporal resolution of time-series input data, with the latter being much coarser. Fig. 12 illustrates simulated horizontal sediment transport and vertical particle transport using the LWE benchmark model and APEX1905. Despite less data-intense inputs than the benchmark model, the APEX1905 reproduced both the horizontal sediment transport and vertical particle transport well without further refining parameters. The results are R^2 of 0.77 and 0.81, respectively. The biases in APEX1905 are low, with RMSE less than 1.0.

Given the substantial simplification and approximation in the input data preparation, the APEX1905 model was not expected to replicate measured horizontal sediment transport from individual wind erosion events. However, the model simulated monthly and annual average sediment transports as shown in Figs. 12 and 13. In Fig. 13, simulated average annual horizontal sediment transports from 2002 to 2017 lay within the observed interquartile range (IQR), indicating the reliability of the model output in simulating long-term periods.

4.5. *Benefits of the enhanced APEX1905 model to simulate landscape wind erosion in rangelands*

Continuous simulation of horizontal sediment transport and vertical particle transport using a stand-alone aeolian erosion model (e.g., Okin 2008) often requires detailed field properties such as vegetation height, canopy gap, vegetation cover fraction, soil moisture condition and wind speed distribution, which is uncommon in the U.S. Monitoring these properties for long periods is expensive and labor-intensive. The gaps in data availability make it worthwhile to integrate a landscape-scale wind erosion model into the APEX1905 agro-hydrological watershed model. The integrated model offers a cost-effective tool to simulate horizontal sediment transport and vertical particle without intensive data collection.

Fig. 14 presents the mean canopy gap, mean vegetation height, and vegetation cover fraction estimated by APEX1905 for the Jornada Experimental Range site. The model simulation shows a relatively big canopy gap and small vegetation cover during the winter than during growing seasons in summer and fall. Although grasses show seasonal

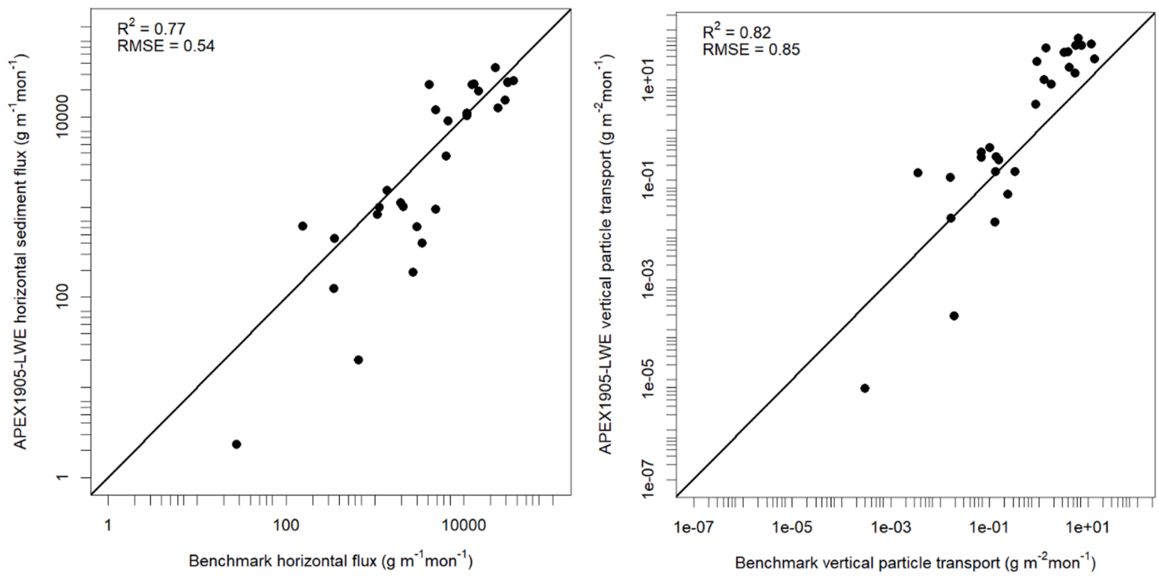

Fig. 12. Comparison of the benchmark model simulated horizontal sediment transport with APEX1905 simulations. Note that the main difference between the two models is their input data only.

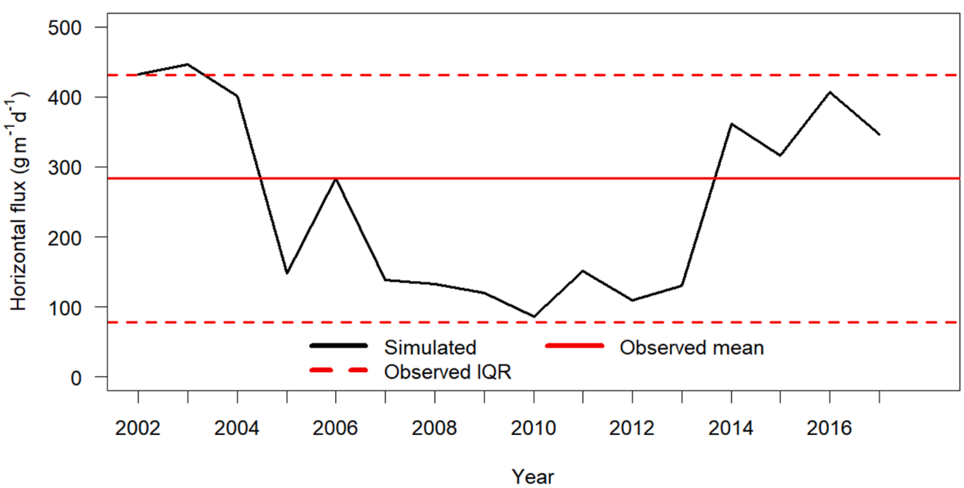

Fig. 13. Average annual horizontal transport simulation using APEX1905 from 2002 to 2017. The red lines represent the mean (solid line) and the Interquartile Range (IQR) (broken line) of the observed horizontal transport between 2015 and 2017 (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

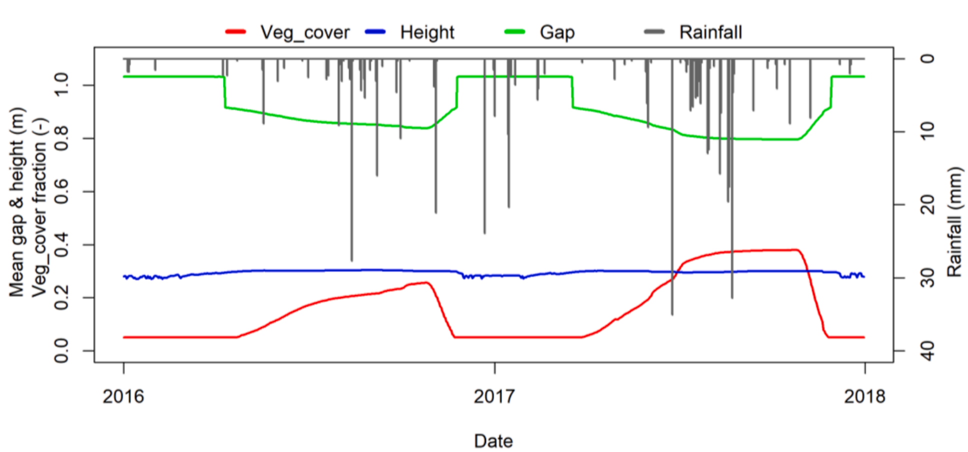

Fig. 14. Simulated mean gap, height, and vegetation cover fraction between 2016 and 2017 for the USDA-ARS New Mexico Jornada experimental range site.

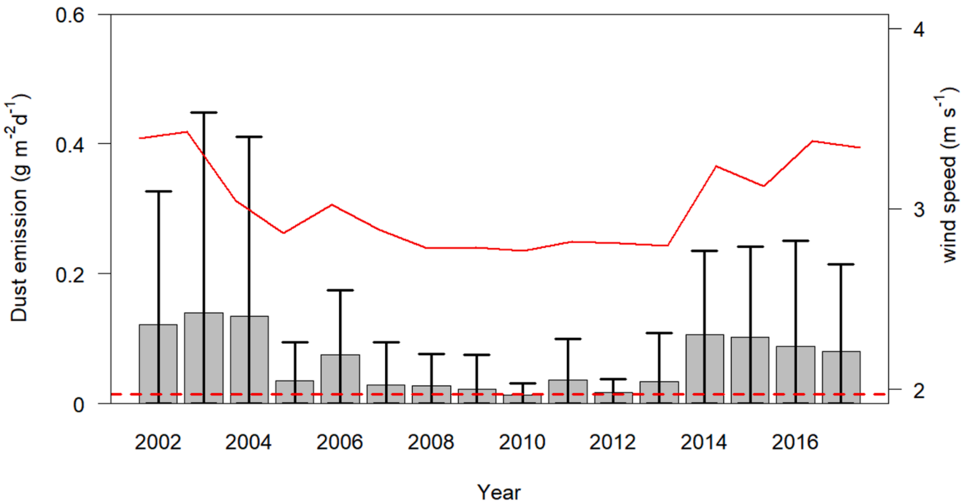

Fig. 15. APEX1905 simulated average annual (bars) and intra-annual variation (vertical lines) of vertical particle transport from 2002 to 2017. No field data are available for vertical particle transport; the measured values (broken red line) from a site near Carlsbad, New Mexico (Breshears et al., 2003) are used as a reference (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

variation in canopy height, the simulated canopy height presents little temporal variability. This is attributed to the minimal variation of canopy height for matured honey mesquite trees that grow interspersed with black grama grasses.

The APEX1905 model provides the capability to simulate long-term vertical particle transport, as shown in Fig. 15. As expected, estimated vertical particle transport is significantly driven by wind speed in the long term. The years with high wind speed generally had high vertical particle transport rates.

4.6. Limitations and future research

In this study, the APEX1905 model was evaluated at the USDA-ARS New Mexico Jornada Experimental Range National Wind Erosion Network site. Availability of additional data would ensure its applicability and reliability on simulating aeolian transport processes under a wide range of climatic conditions as more data becomes available. The APEX1905 model could be a valuable tool to evaluate the efficacy of land management practices on controlling wind erosion as a decision aid for land managers and policymakers for both croplands and rangelands.

5. Conclusion

This study presented an integration of landscape wind erosion (LWE) processes to the APEX model for simulating wind-driven horizontal sediment transport and vertical particle transport for rangelands. For the integration, we selected aeolian modeling schemes that are process-based and require minimal data because aeolian data are scarce in the United States and other countries. The model's capabilities were evaluated using measured data, and ranges for their representative parameters were identified. We also tested the APEX1905 simulated horizontal sediment transport and vertical particle transport against the benchmark model. Overall, the benchmark model could reproduce 58% of the observed horizontal sediment transport variability between 2015 and 2017 with an RMSE of 2.6. Although the APEX1905 was not expected to capture intra-day variability in measured horizontal sediment transport due to daily averaging in wind speed and gap distribution data, the model simulated horizontal and vertical particle transport well compared with the benchmark model ($R^2 = 0.77$ and 0.81, respectively). The performance metric of the APEX1905 model improved when outputs were evaluated at the monthly or the annual time scale, suggesting that APEX1905 can be helpful to assess long-term land management practices and restoration efforts as well as climatic impacts at a coarse time interval. The enhanced APEX model can be applied to any rangeland to simulate soil erosion driven by winds. This model is a crucial application tool in rangelands where monitoring vegetation characteristics, soil moisture, and sub-daily wind speed is limited, labor-intensive, and expensive.

Reliable and comprehensive modeling tools provide a means to understand the implications of rangeland soil erosion and/or land-use change and evaluate the effect of various soil and water management practices and environmental policies. Simulation models help acquire critical insights on the environmental impacts of alternative management or climate change over different periods. The integration of aeolian processes to account for landscape wind erosion on rangelands into the APEX model will provide model users and land and policy managers with the capability to evaluate land management practices and restoration efforts to reduce wind-driven soil erosion.

CRediT authorship contribution statement

Tadesse A: Data curation, Writing – original draft, Visualization, Software. **Jaehak Jeong:** Conceptualization, Methodology, Software. **Colleen H.M. Green:** Conceptualization, Writing – review & editing, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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