

Vegetation Canopy Gap Size and Height: Critical Indicators for Wind Erosion Monitoring and Management[☆]



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ABSTRACT

Indicators of vegetation cover and structure are widely available for monitoring and managing rangeland wind erosion. Identifying which indicators are most appropriate for managers could improve wind erosion mitigation and restoration efforts. Vegetation cover directly protects the soil surface from erosive winds and reduces wind erosivity by extracting momentum from the air. The portion of the soil surface that is directly protected by vegetation is adequately described by fractional ground cover indicators. However, the aerodynamic sheltering effects of vegetation, which are more important for wind erosion than for water erosion, are not captured by these indicators. As wind erosion is a lateral process, the vertical structure and spatial distribution of vegetation are most important for controlling where, when, and how much wind erosion occurs on rangelands. These controlling factors can be described by indicators of the vegetation canopy gap size distribution and vegetation height, for which data are collected widely in the United States by standardized rangeland monitoring and assessment programs. In this paper we address why canopy gap size distribution and vegetation height are critical indicators of rangeland wind erosion and health. We review wind erosion processes to explain the physical role of these vegetation attributes. We then address the management implications including availability of data on the indicators on rangelands and needs to make the indicators and model estimates of wind erosion more accessible to the range management community.

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Introduction

Managing rangeland wind erosion is essential for maintaining healthy and productive agroecosystems, avoiding degradation of air quality, and mitigating dust hazards to human health (Middleton 2017). Recognition of this importance has triggered initiatives to monitor and forecast wind erosion and blowing dust so that negative impacts can be avoided, best management practices can be identified, and effectiveness of soil conservation efforts can be as-

sessed (UNEP, WMO, UNCCD 2016). Examples include establishment of the US National Wind Erosion Research Network (Webb et al. 2016), integration of drought monitoring with dust observation networks like the Australian DustWatch program (Leys et al. 2008), and establishment of the World Meteorological Organization (WMO) Sand and Dust Storm Warning, Advisory and Assessment System, SDS-WAS (WMO 2015). Key products of these efforts are the development of new tools and identification of indicators that enable managers to assess wind erosion risk (Webb et al. 2020).

A challenge in building capacity to monitor and assess rangeland wind erosion is the disconnect between the aeolian research community, comprising largely geographers, meteorologists, and soil scientists on the one hand, and the rangeland research and management community on the other. Concepts, approaches, and tools have not always been transferred effectively between domains. Perhaps the most important example affecting rangeland management is transfer of understanding of the role of vegetation in controlling wind erosion. In the aeolian literature, vegeta-

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tion effects on wind erosion are typically described through drag partition theory (e.g., [Raupach et al. 1993](#)), which can be inaccessible to those unfamiliar with the physical processes in boundary layer meteorology (e.g., within $\sim 1\,000$ m of the land surface). Differences in terminology have affected technology transfer of predictive models from the aeolian to rangeland community, as well as understanding within the rangeland community of how vegetation indicators can best be used to inform wind erosion management. This is evidenced by the scarcity of coordinated rangeland wind erosion monitoring and assessment at scales that can support management ([Webb et al. 2017](#)). In contrast, rangeland water erosion (e.g., [Nearing et al. 2011](#); [Williams et al. 2016](#)) and cropland wind erosion (e.g., [Wagner 2013](#); [Jarrah et al. 2020](#)) have established programs supporting land managers built over a longer history of engagement.

Vegetation and other factors controlling surface roughness, such as rock fragments and embedded litter, are regarded as the most important controls on aeolian (wind-driven) sediment transport ([Raupach et al. 1993](#)). In volume 73 of *Rangeland Ecology & Management*, [Zobell et al. \(2020\)](#) described vegetation attributes that control rangeland wind erosion. They evaluated critical criteria for “ground cover,” including how ground cover has been defined in methods and protocols used by assessment and monitoring programs implemented by agencies in the United States (e.g., [Herrick et al. 2018](#); [Pellant et al. 2020](#)). [Zobell et al. \(2020\)](#) noted that standing vegetation and the quantity, kind, and orientation of vegetation, including its spatial distribution, are important for wind erosion. However, these properties are not captured in the most common indicators of ground cover used by managers to assess wind erosion risk. Typical indicators instead focus on the fraction of land surface as viewed from above that is covered by vegetation and other elements, or the inverse of “bare ground” or “bare soil” depending on application ([Toebe et al. 2011](#)). While some fractional indicators of ground cover are good predictors of water erosion, they are demonstrably poor predictors of wind erosion ([Chappell et al. 2018](#)). This is because wind erosion is highly sensitive to the spatial distribution and height of ground cover ([Okin et al. 2006](#)). Here, we extend the review of [Zobell et al. \(2020\)](#) by describing the importance of indicators of vegetation structure and spatial arrangement—vegetation canopy gap size distribution and vegetation height—that enable first-order assessment of site susceptibility to wind erosion. We review wind erosion processes to define terminology, describe the importance of canopy gap size distribution and vegetation height as critical properties of ground cover for wind erosion, and identify management implications of developing more robust wind erosion assessments using data from existing rangeland monitoring programs.

Review of Wind Erosion Processes

Aeolian sediment transport includes processes of creep, saltation, and suspension (for definitions, see [Table 1](#)). These processes occur when the strength of the wind at the soil surface overcomes counteracting forces holding soil grains together at the surface. The total amount of sediment moving in saltation is called the *stream-wise* or *horizontal sediment mass flux*, which is often measured using Big Spring Number Eight (BSNE) or Modified Wilson and Cooke (MWAC) sediment samplers mounted at different heights above the soil surface (e.g., [Belnap et al. 2009](#); [Nauman et al. 2018](#); [Webb et al. 2019](#)). The amount of sediment moving up and away from the surface is called *dust emission*, or *vertical dust mass flux* ([Fig. 1](#)), which is linearly related to the horizontal sediment flux depending, in part, on the amount of silt and clay in the soil (see review by [Shao 2008](#)). Fine sandy soils tend to be most erodible due to their weak structure, while soils with larger silt and clay contents have greater potential to emit fine dust ($< 20\,\mu\text{m}$), but dust emis-

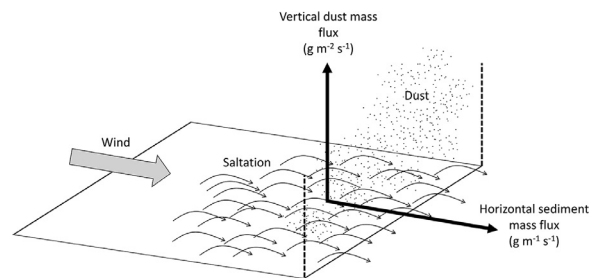


Fig. 1. Dominant modes of aeolian sediment transport: saltation, in which soil grains (typically $> 62.5\,\mu\text{m}$) leap or hop along the soil surface and are measured as the horizontal sediment mass flux, and dust emission, in which fine soil grains (typically $< 62.5\,\mu\text{m}$) are lifted by the wind up and away from the soil surface and are measured as the vertical dust mass flux.

sion is typically restricted by protective soil crusts and aggregates. Disturbance of fine-textured soils (e.g., by livestock trampling, off-highway vehicles, or drill-type seeders) dramatically increases dust emission potential ([Duniway et al. 2019](#)).

Despite the terms often being used interchangeably, wind erosion differs from aeolian sediment mass flux. Wind erosion is regarded as the net sediment flux for an area and can be calculated as the balance of sediment moving into and out of that area. Dust emission is regarded as part of the movement of sediment out of an area and typically results in loss of silt and clay particles and nutrients, as well as degradation of air quality (e.g., [Tong et al. 2017](#); [Pu and Ginoux 2018](#)). Horizontal sediment flux (rather than *net* horizontal sediment flux) simply quantifies how much sediment is moving through a point in the landscape and so, on its own, is best used as an indicator of soil and site stability rather than soil loss ([Webb et al. 2020](#)). This is different from the way we report water erosion, measured as the amount of sediment leaving an area and with the frequent assumption that the amount entering the area is zero, which is true for a watershed but not at the plot scale ([Nearing et al. 1994](#)). As rangeland wind erosion is not constrained by watersheds or fields, the net inputs and outputs must be considered but are difficult to measure and so are generally unknown. Numerous models have been developed to predict horizontal sediment flux (e.g., [Kawamura 1951](#); [Owen 1964](#); [Okin 2008](#)); dust emission (e.g., [Marticorena and Bergametti 1995](#); [Shao 2004](#); [Kok et al. 2014](#)); and net wind erosion of cropland fields (see review by [Jarrah et al. 2020](#)). Currently, there are no rangeland-specific *wind erosion* models due largely to the technical complexity and incomplete understanding of the processes that would make such a model robust across rangeland vegetation communities. A few models have been developed to address specific questions about interactions between dryland vegetation and aeolian sediment transport at small scales, but these have so far been constrained to research applications (e.g., [Mayaud et al. 2017a](#); [Zhang 2020](#)).

The amount of sediment that can be transported by the wind is controlled by the availability of loose erodible grains at the soil surface and the portion of the surface exposed to the wind. Sediment transport rates will then be determined by the strength of the wind at the exposed soil surface where it exceeds a soil entrainment threshold, defined as the wind strength required to mobilize soil grains ([Durán et al. 2011](#)). Ground cover is a first-order control on aeolian sediment transport and wind erosion because it 1) directly covers the soil surface, thereby controlling the portion of surface exposed to the wind; and 2) extracts momentum from the moving air, which has the effect of changing the distribution of wind strength (i.e., shear stress) at the soil surface ([Raupach et al. 1993](#); [Okin 2008](#)). As noted by [Zobell et al. \(2020\)](#), ground cover also traps sediment moving in creep, saltation, and suspension,

Table 1

Definitions of terms used in aeolian research to describe wind erosion processes.

Term	Definition
Creep	Movement of soil grains and aggregates in a rolling motion along the soil surface, typically grains > 150 μm diameter.
Drag	A force acting opposite to the relative motion of the land surface with respect to the air (wind) and influenced by the form and roughness of the surface.
Drag partition	Separation of drag and shear stress between roughness elements (e.g., vegetation) and the underlying substrate (soil) surface.
Dust emission (F)	Entrainment of fine soil particles and aggregates (dust), typically regarded as being smaller than 62.5 μm in diameter (e.g., silt and clays).
Erodibility	Susceptibility (or resistance) of soil to be entrained by the wind. Physically, erodibility is determined by the strength of forces holding soil grains and aggregates to the soil surface (e.g., due to crusting), as well as the amount of loose grains at the surface (that have weak binding forces).
Erosivity	Capacity of the wind to detach and transport loose soil grains and aggregates, physically defined as the wind shear stress or friction velocity.
Fractional ground cover	Proportion of the land surface that is covered by elements, such as vegetation, rock fragments, gravel, litter, and embedded litter. Components included in ground cover vary depending on application of the indicator.
Friction velocity (u_{*r})	Expression of wind shear stress in units of velocity (m s^{-1}).
Horizontal sediment mass flux (Q)	Mass of soil grains and aggregates in saltation per unit length per unit time (e.g., $\text{g m}^{-1} \text{s}^{-1}$).
Lateral cover (λ)	Also called roughness density or frontal area index, defined as the number of nonerodible roughness elements n multiplied by their basal area b and height h , divided by the surface area, s ($\lambda = nbh/s$)
Nonerodible roughness element	Any obstacle (e.g., vegetation, rock fragment, gravel, embedded litter, soil aggregate or crust that is too large, dense, and/or secure [i.e., rooted vegetation] to be moved by the wind).
Roughness length (z_0)	Theoretical height at which mean wind speed becomes zero when a measured logarithmic wind speed profile is extrapolated downward through the surface boundary layer (i.e., within 10s of m adjacent to the ground).
Saltation	Movement of soil grains and aggregates along the soil surface in a leaping or hopping motion, typically grains > 62.5 μm diameter and within ~ 1 m of the soil surface.
Shear stress (τ)	Component of force due to the wind that is coplanar with (i.e., blows across) an area of the land surface (N m^{-2}).
Streamwise	Direction of fluid motion (i.e., direction the wind is blowing).
Suspension	Particles held in the wind flow by turbulence, typically grains smaller than 62.5 μm .
Threshold shear stress	Amount of shear stress required to lift soil grains and aggregates from the soil surface and set them in motion.
Wind erosion	Net loss of soil from an area, considered the net sum of sediment fluxes out of the area (loss) and deposition (gain) of sediment into the area from upwind sources (e.g., t ha^{-1}).

thereby reducing the net movement of soil across a site (Wolfe and Nickling 1993; Raupach et al. 2001).

Importance of Canopy Gap and Height for Understanding Wind Erosion

The area of soil that is directly sheltered by nonerodible elements is adequately described by fractional ground cover indicators. Such indicators are typically calculated from data collected using the line-point intercept (LPI) method (e.g., Herrick et al. 2018) or by satellite remote sensing at regional scales (e.g., Guerschman and Hill 2018; Jones et al. 2018; Zhang et al. 2019; Zhou et al. 2020). However, the aerodynamic effects of ground cover (i.e., how vegetation structure influences air flow), which are most important for wind erosion, are not captured by these ground cover indicators.

Aeolian sediment transport is a lateral process, meaning that it is the wind acting across the soil surface that is the principal driver of sediment movement (Wolfe and Nickling 1993). As wind flows over the land surface and encounters vegetation and other nonerodible roughness elements, momentum is reduced by its drag (Fig. 2). Thus, in the lee (i.e., downwind side) of vegetation, a low-velocity zone is formed in which the exposed soil surface is aerodynamically sheltered. Within this sheltered area, the strength of the wind acting on the soil surface is reduced and then recovers with distance downwind from the obstacle (Raupach et al. 1993). Field measurements of wind in the lee of grasses, shrubs, and fences have shown that full recovery of wind strength occurs at distances between $10\times$ and $20\times$ the height of the upwind vegetation (e.g., Bradley and Mulhearn 1983; Leenders et al. 2011; Mayaud et al. 2017b). The sheltering effect of wind can therefore be determined as a function of distance from vegetation (x), normalized by vegetation height (h), and expressed as the scaled gap size x/h (Okin 2008). Thus, the recovery of wind strength downwind of vegetation depends on the length of bare gaps between roughness elements (i.e., canopy gap size distribu-

tion) and the height of the vegetation. This means that the protective effect of vegetation increases with increasing vegetation height (taller plants shelter larger areas) and decreasing gap size (small gaps are more sheltered than larger ones). Other factors such as the shape, porosity, and flexibility of vegetation influence the protective effects of vegetation, but vegetation canopy gap size and height are the most important controls (see review by Mayaud and Webb 2017).

The canopy gap size–vegetation height relationship has been established as a critical predictor of the vegetation sheltering effect (Li et al. 2013). The relationship can be used to explain differences in sediment transport among sites with different kinds, amounts, and proportions of vegetation, which are frequently characterized by different canopy gap size distributions and vegetation heights. For example, perennial grasslands with short vegetation height and small canopy gaps will experience high vegetation sheltering and little sediment transport, while shrubland sites with taller vegetation but large canopy gaps will experience less sheltering and larger sediment transport rates (e.g., Vest et al. 2013; Webb et al. 2014a). Unvegetated sites and sites with short vegetation height and large canopy gaps will be the most susceptible to wind erosion (Gillette et al. 2006). In any setting, the effect of canopy gap size on aeolian sediment transport will be dependent on the height of the upwind vegetation. In addition, changes in the canopy gap size distribution at fixed vegetation heights and fractional cover can have large effects on wind erosion and dust emission rates (Fig. 3).

Careful consideration of how the canopy gap size–vegetation height relationship affects sheltering clearly illustrates differences in aeolian sediment transport among rangeland sites that may not be apparent from fractional ground cover indicators alone. Sites with similar fractional ground cover may have different vegetation heights and canopy gap size distributions that result in quite different aeolian transport rates. Early approaches in the aeolian research community to characterize effects of vegetation (e.g., Raupach et al. 1993; Marticorena and Bergametti 1995) used lat-

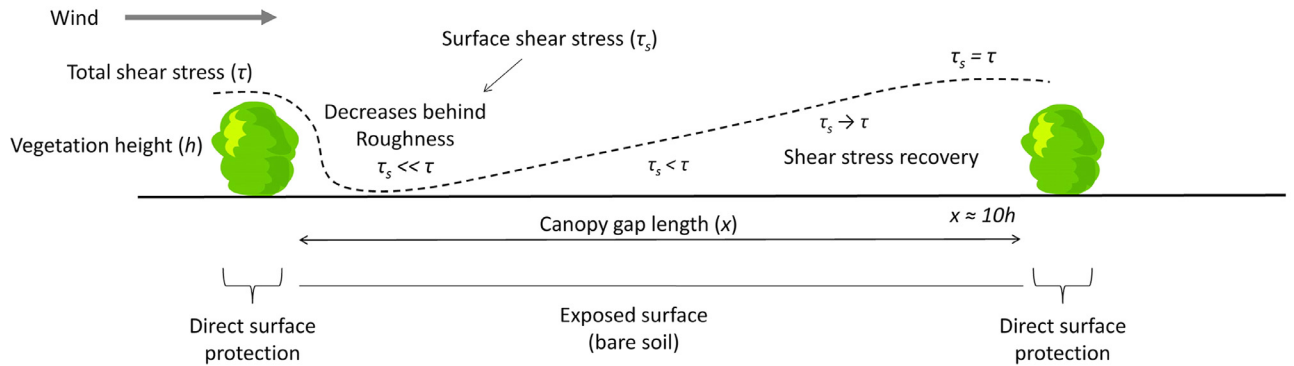
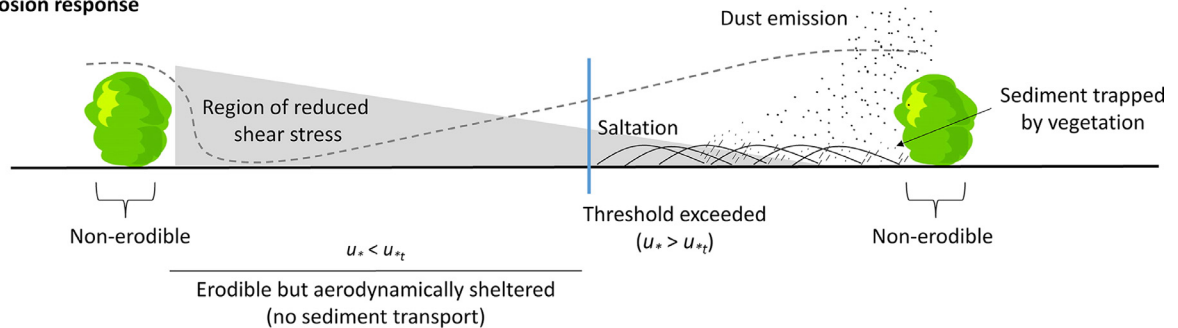
(a) Wind shear stress recovery behind vegetation**(b) Wind erosion response**

Fig. 2. Factors controlling rangeland wind erosion including **(a)** the influence of vegetation on the reduction and recovery of wind shear stress over the exposed soil surface and **(b)** the wind erosion response where wind strength recovers sufficiently to exceed the threshold required to move soil particles.

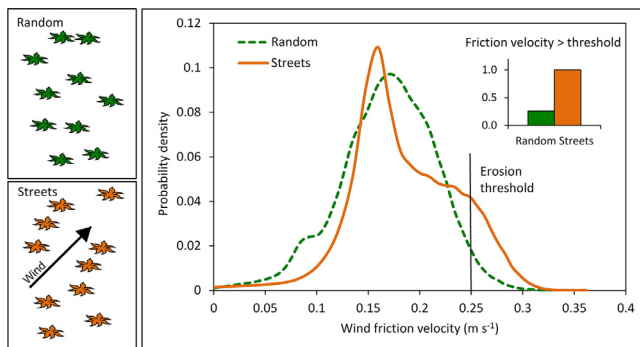


Fig. 3. Graphs showing the effect of canopy gap size distribution on the distribution of wind shear stress (expressed as friction velocity, u_*) at the same fractional vegetation cover, height, and wind speed (8.7 m s^{-1}). Inset graph shows the proportion of shear stress in excess of a nominal threshold for aeolian sediment transport ($u_{*t} = 0.25 \text{ m s}^{-1}$) that is typical of loose sand. Canopy gap size distributions are for a random orientation of roughness elements ("Random") and orientation with large gaps ("Streets") typical of mesquite (*Prosopis glandulosa* Torr.) shrublands in the northern Chihuahuan Desert (Gillette et al. 2006). Changing the canopy gap size distribution can have a large effect on the wind erosivity, producing similarly large differences in wind erosion. Data used in this figure were obtained from wind tunnel experiments of Brown et al. (2008) as reported in Webb et al. (2014b).

eral cover and aerodynamic roughness lengths (see Table 1 for definitions) to estimate aeolian sediment transport. However, while these approaches accounted for vegetation height, they did not represent the spatial distribution of vegetation. Intuitively, the effect can be understood by visualizing two cases that have the same lateral cover, but very different distributions (Fig. 4). In the first case, a telephone pole stands in the middle of a field. In the second, an identical telephone pole is cut into short cylinders that are

spread across the field. The lone telephone pole hardly protects the field from erosion at all, while the short cylinders provide greater protection of the surface from the wind. If the spatial distribution of vegetation is not explicitly accounted for with its height, estimates of aeolian sediment transport may be inaccurate by over an order of magnitude (Li et al. 2013; Webb et al. 2014b).

Management Implications

Fractional indicators of foliar and basal ground cover have been used to manage wind erosion for the past 80 yr (e.g., Chepil 1944). However, due to vegetation height and canopy gap size distribution effects on surface sheltering, such cover thresholds are specific to vegetation types (e.g., Pi et al. 2020) and inadequate on their own for managing rangelands with mixed plant communities (Chappell et al. 2018). The sole use of fractional ground cover thresholds risks underprotecting soils at some sites, increasing erosion and air quality risks, while overprotecting other sites (see Fig. 3). These unintended outcomes result in misallocation of valuable management resources at best and irreversible land degradation at worst. Using fractional ground cover indicators alone is therefore inadequate for managing trade-offs among goals such as maintaining soil and site stability and livestock production. Alternatively, retooling management frameworks to explicitly consider the effects of vegetation canopy gap size distribution and height will ensure that rangeland wind erosion monitoring and assessment are supported by the best available science.

An additional benefit of using canopy gap size and vegetation height information to support wind erosion management is that these properties are key indicators of ecosystem structure and connectivity, which influence the movement of water and organisms (Okin et al. 2015) and the "landscape of fear" experi-

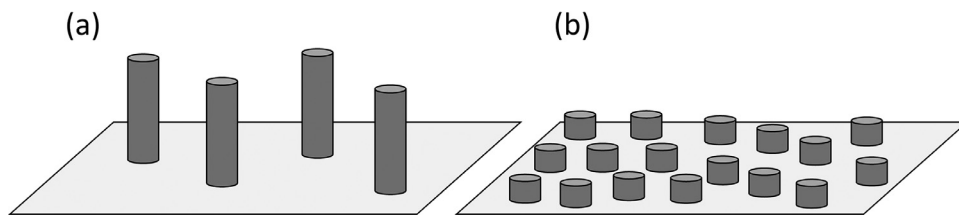


Fig. 4. “Telephone pole problem.” Both surfaces (a) and (b) have the same lateral cover (λ) of vegetation, where lateral cover is calculated as the number of elements (n) multiplied by their basal area (b) and height (h), divided by the surface area (s) they occupy ($\lambda = nbh/s$). Surface (a) has four elements, which in (b) are partitioned into 16 elements that are one-quarter the height. Early wind erosion models using lateral cover would estimate that both a and b have the same sediment transport rates, while in reality the greater aerodynamic sheltering of the surface by the dispersed objects in (b) would result in substantially smaller wind strength at the soil surface and a smaller sediment transport rate. Figure redrawn after Okin (2008).

enced by prey in structurally complex landscapes (e.g., [Laundré et al. 2014](#); [Bleicher and Dickman 2020](#)). Ecological state transitions within ecological sites, comprising changes in the kinds, amounts, and proportions of vegetation at a site, often exhibit structural changes that can be described by changes in vegetation canopy gap size distribution and height ([Webb et al. 2020](#)). These indicators can therefore be used to identify critical thresholds for ecological state changes, as well as functional thresholds for wind erosion, and so serve as dual indicators of ecosystem structure (pattern) and function (process) that can be linked to conservation practices ([Bestelmeyer 2006](#)). Critical structural and functional thresholds can be used as benchmarks to support assessments of wind erosion risk alongside other indicators of ecosystem services of management interest ([Webb et al. 2020](#)).

Fortunately, in the United States, data needed to assess rangeland wind erosion are now widely available. Large standardized monitoring programs like the Bureau of Land Management’s Assessment, Inventory and Monitoring (AIM) strategy, Natural Resources Conservation Service’s National Resources Inventory (NRI), and National Park Service’s Inventory and Monitoring (I&M) program collect canopy gap and vegetation height data alongside fractional ground cover following the core methods of [Herrick et al. \(2018\)](#). Approaches using high-resolution aerial imagery captured by drones and machine learning analysis techniques are also being developed to estimate these structural indicators of ground cover (e.g., [Gillan et al. 2016](#); [Zhang et al. 2019](#); [Gillan et al. 2020](#)). However, while the canopy gap intercept method ([Herrick et al. 2018](#)) was incorporated into rangeland monitoring programs and is recommended to support the Interpreting Indicators of Rangeland Health assessment protocol ([Pellant et al. 2020](#)) to address wind erosion, there has not been a recognized context for managers to use the data. Information about the relation between vegetation canopy gap size and height and wind erosion are needed in ecological site descriptions (ESDs) and reference sheets used to inform rangeland health and other assessments of rangeland status, condition, and trend. In the absence of site-specific information, managers could refer to available studies that identify wind erosion thresholds for canopy gap size and vegetation height (e.g., [Okin et al. 2009](#); [Webb et al. 2014a, 2020](#)). Further efforts are now needed to improve accessibility of wind erosion information and these indicators to managers through monitoring databases, ESDs, and quantitative models so that the many impacts of rangeland wind erosion can be effectively addressed.

This paper attempts to link the aeolian and rangeland communities by addressing the need to integrate canopy gap size, vegetation height, and fractional ground cover indicators for wind erosion assessment. The ability to acquire wind erosion indicators using accessible core methods (e.g., [Herrick et al. 2018](#)) and remote sensing (e.g., [Chappell et al. 2018](#); [Zhang et al. 2019](#)) may be attractive to managers and agencies running monitoring programs that lack data needed for wind erosion assessments or who are already collecting these data but have not fully realized their utility. Ap-

plication of the methods is also not limited to rangelands. The National Wind Erosion Research Network effectively employs the LPI, canopy gap intercept, and vegetation height methods of [Herrick et al. \(2018\)](#) on croplands, as well as rangeland sites ([Webb et al. 2016](#)). The approach of integrating multiple indicators collected by monitoring programs to develop new indicators and tools (e.g., physically-based models) has great potential for extending the utility of monitoring datasets to address a wider range of ecosystem attributes and processes than are typically incorporated into agroecosystem management (e.g., [Toevs et al. 2011](#); [LaRue et al. 2019](#)). Broad adoption of the canopy gap size, vegetation height, and fractional ground cover indicators could support international efforts to manage wind erosion hazards (e.g., [WMO 2015](#)) and meet sustainable development goals.

Declaration of Competing Interest

None.

References

- Belnap, J., Reynolds, R.L., Reheis, M.C., Phillips, S.L., Urban, F.E., Goldstein, H.L., 2009. Sediment losses and gains across a gradient of livestock grazing and plant invasion in a cool, semi-arid grassland, Colorado Plateau, USA. *Aeolian Research* 1, 27–43.
- Bestelmeyer, B.T., 2006. Threshold concepts and their use in rangeland management and restoration: The good, the bad, and the insidious. *Restoration Ecology* 14, 325–329.
- Bleicher, S.S., Dickman, C.R., 2020. On the landscape of fear: shelters affect foraging by dunnarts (*Marsupialia, Sminthopsis* spp.) in a sandridge desert environment. *Journal of Mammalogy* 101, 281–290.
- Bradley, E.F., Mulhearn, P.J., 1983. Development of velocity and shear-stress distributions in the wake of a porous shelter fence. *Journal of Wind Engineering and Industrial Aerodynamics* 15, 145–156.
- Brown, S., Nickling, W.G., Gillies, J.A., 2008. A wind tunnel examination of shear stress partitioning for an assortment of surface roughness distributions. *Journal of Geophysical Research* 113, F02S06.
- Chappell, A., Webb, N.P., Guerschman, J.P., Thomas, D.T., Mata, G., Handcock, R.N., Leys, J.F., Butler, H.J., 2018. Improving ground cover monitoring for wind erosion assessment using MODIS BRDF parameters. *Remote Sensing of Environment* 204, 756–768.
- Duniway, M.C., Pfenningwerth, A.A., Fick, S.E., Nauman, T.W., Belnap, J., Barger, N.N., 2019. Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. *Ecosphere* 10, e02650.
- Durán, O., Claudin, P., Andreotti, B., 2011. On aeolian transport: grain-scale interactions, dynamical mechanisms and scaling laws. *Aeolian Research* 3, 243–270.
- Gillan, J.K., Karl, J.W., Barger, N.N., Elaksher, A., Duniway, M.C., 2016. Spatially explicit rangeland monitoring using high-resolution digital aerial imagery. *Rangeland Ecology & Management* 69, 95–107.
- Gillan, J.K., Karl, J.W., van Leeuwen, J.D., 2020. Integrating drone imagery with existing rangeland monitoring programs. *Environmental Monitoring and Assessment* 192, 269.
- Gillette, D.A., Herrick, J.E., Herbert, G., 2006. Wind characteristics of mesquite streets in the northern Chihuahuan Desert, New Mexico, USA. *Environmental Fluid Mechanics* 6, 241–275.
- Guerschman, J.P., Hill, M.J., 2018. Calibration and validation of the Australian fractional cover product for MODIS collection 6. *Remote Sensing Letters* 9, 696–705.
- Herrick, J.E., Van Zee, J.W., McCord, S.E., Courtwright, E.M., Karl, J.W., Burkett, L.M., 2018. Monitoring manual for grassland, shrubland, and savanna ecosystems, vol. 1: core methods, 2nd ed.. USDA-ARS Jornada Experimental Range, Las Cruces, NM, USA, p. 86.

- Jarrah, M., Mayel, S., Tatarko, J., Funk, R., Kuka, K., 2020. A review of wind erosion models: data requirements, processes, and validity. *Catena* 187, 104388.
- Jones, M.O., Allred, B.W., Naugle, D.E., Maestas, J.D., Donnelly, P., Metz, L.J., Karl, J., Smith, R., Bestelmeyer, B., Boyd, C., Kerby, J.D., McIver, J.D., 2018. Innovation in rangeland monitoring: annual, 30 m, plant functional type percent cover maps for US rangelands, 1984–2017. 9. *Ecosphere*, p. e02430.
- Kawamura, R., 1951. Study of sand movement by wind, Hydraulic Engineering Laboratory Report HEL-2-8. University of California, Berkeley, CA, USA, p. 57.
- Kok, J.F., Mahowald, N.M., Fratini, G., Gillies, J.A., Ishizuka, M., Leys, J.F., Mikami, M., Park, M.-S., Park, S.-U., Van Pelt, R.S., Zobeck, T.M., 2014. An improved dust emission model—part 1: model description and comparison against measurements. *Atmospheric Chemistry and Physics* 14, 13023–13041.
- LaRue, E.A., Hardiman, B.S., Elliott, J.M., Fei, S., 2019. Structural diversity as a predictor of ecosystem function. *Environmental Research Letters* 14, 114011.
- Laundré, J.W., Hernández, L., López Medina, P., Campanella, A., López-Portillo, J., González-Romero, A., Grajales-Tam, K., Burke, A.M., Gronemeyer, P., Brown, D.M., 2014. The landscape of fear: the missing link to understand top-down and bottom-up controls of prey abundance? *Ecology* 95, 1141–1152.
- Leenders, J.K., Sterk, G., van Boxel, J.H., 2011. Modelling wind-blown sediment transport around single vegetation elements. *Earth Surface Processes and Landforms* 36, 1218–1229.
- Leys, J.F., McTainsh, G.H., Strong, C.L., Heidenreich, S., Biesaga, K., 2008. DustWatch: using community networks to improve wind erosion monitoring in Australia. *Earth Surface Processes and Landforms* 33, 1912–1926.
- Li, J., Okin, G.S., Herrick, J.E., Belnap, J., Munson, S.M., Miller, M.E., Vest, K., Draut, A.E., 2013. Evaluation of a new model of aeolian transport in the presence of vegetation. *Journal of Geophysical Research* 118, 1–19.
- Marticorena, B., Bergametti, G., 1995. Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme. *Journal of Geophysical Research* 100, 415–416, 430.
- Mayaud, J.R., Bailey, R.M., Wiggs, G.F.S., 2017a. A coupled vegetation/sediment transport model for dryland environments. *Journal of Geophysical Research: Earth Surface* 122, 875–900.
- Mayaud, J.R., Wiggs, G.F.S., Bailey, R.M., 2017b. A field-based parameterization of wind flow recovery in the lee of dryland plants. *Earth Surface Processes and Landforms* 42, 378–386.
- Mayaud, J.R., Webb, N.P., 2017. Vegetation in drylands: effects on wind flow and aeolian sediment transport. *Land* 6, 64.
- Middleton, N.J., 2017. Desert dust hazards: a global review. *Aeolian Research* 24, 53–63.
- Nauman, T.W., Duniway, M.C., Webb, N.P., Belnap, J., 2018. Elevated aeolian sediment transport on the Colorado Plateau, USA: the role of grazing, vehicle disturbance, and increasing aridity. *Earth Surface Processes and Landforms* 43, 2897–2914.
- Nearing, M.A., Lane, L.J., Lopes, V.L., 1994. Modeling soil erosion. In: Lal, R. (Ed.), *Soil erosion research methods*. Soil and Water Conservation Press, St. Lucie, FL, USA, pp. 127–156.
- Nearing, M.A., Wei, H., Stone, J.J., Pierson, F.B., Spaeth, K.E., Wertz, M.A., Flanagan, D.C., Hernandez, M., 2011. A rangeland hydrology and erosion model. *Transactions ASABE* 54, 1–8.
- Okin, G.S., Gillette, D.A., Herrick, J.E., 2006. Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments. *Journal of Arid Environments* 65, 253–275.
- Okin, G.S., 2008. A new model of wind erosion in the presence of vegetation. *Journal of Geophysical Research* 113, F02S10.
- Okin, G.S., Parsons, A.J., Wainwright, J., Herrick, J.E., Bestelmeyer, B.T., Peters, D.P.C., Fredrickson, E.L., 2009. Do changes in connectivity explain desertification? *BioScience* 59, 237–244.
- Okin, G.S., Moreno-de las Heras, M., Saco, P.M., Throop, H.L., Vivioni, E.R., Parsons, A.J., Wainwright, J., Peters, D.P.C., 2015. Connectivity in dryland landscapes: shifting concepts of spatial interactions. *Frontiers in Ecology* 13, 20–27.
- Owen, P.R., 1964. Saltation of uniform grains in air. *Journal of Fluid Mechanics* 20, 225–242.
- Pellant, M., Shaver, P., Pyke, D.A., Herrick, J.E., Lepak, N., Riegel, G., Kachergis, E., Newingham, B.A., Toledo, D., Busby, F.E., 2020. Interpreting indicators of rangeland health, version 5. Tech Ref 1734-6. US Department of the Interior, Bureau of Land Management, National Operations Center, Denver, CO, USA.
- Pi, H., Webb, N.P., Huggins, D.R., Sharratt, B., 2020. Critical standing crop residue amounts for wind erosion control in the inland Pacific Northwest, USA. *Catena* 195, 104742.
- Pu, B., Ginoux, P., 2018. Climatic factors contributing to long-term variations in surface fine dust concentration in the United States. *Atmospheric Chemistry and Physics* 18, 4201–4215.
- Raupach, M.R., Gillette, D.A., Leys, J.F., 1993. The effect of roughness elements on wind erosion threshold. *Journal of Geophysical Research* 98, 3023–3029.
- Raupach, M.R., Woods, N., Dorr, G., Leys, J.F., Cleugh, H.A., 2001. The entrainment of particles by windbreaks. *Atmospheric Environment* 35, 3373–3383.
- Shao, Y., 2004. Simplification of a dust emission scheme and comparison with data. *Journal of Geophysical Research* 109, D10202.
- Shao, Y., 2008. *Physics and modelling of wind erosion*. Kluwer Academic Publishers, London, p. 452.
- Toevs, G.R., Karl, J.W., Taylor, J.T., Spurrier, C.S., Karl, M., Bobo, M.R., Herrick, J.E., 2011. Consistent indicators and methods and a scalable sample design to meet assessment, inventory, and monitoring information needs across scales. *Rangelands* 33, 14–20.
- Tong, D.Q., Wang, J.X.L., Gill, T.E., Lei, H., Wang, B., 2017. Intensified dust storm activity and Valley fever infection in the southwestern United States. *Geophysical Research Letters* 44, 4304–4312.
- UNEP, WMO, UNCD, 2016. *Global assessment of sand and dust storms*. United Nations Environment Programme, Nairobi, Kenya.
- Vest, K.R., Elmore, A.J., Kaste, J.M., Okin, G.S., Li, J., 2013. Estimating total horizontal aeolian flux within shrub-invaded groundwater dependent meadows using empirical and mechanistic models. *Journal of Geophysical Research* 118, 1132–1146.
- Wagner, L.E., 2013. *A history of Wind Erosion Prediction Models in the United States*. Department of Agriculture: the Wind Erosion Prediction System (WEPS). *Aeolian Research* 10, 9–24.
- Webb, N.P., Herrick, J.E., Duniway, M.C., 2014a. Ecological site-based assessments of wind and water erosion: informing accelerated soil erosion management in rangelands. *Ecological Applications* 24, 1405–1420.
- Webb, N.P., Okin, G.S., Brown, S., 2014b. The effect of roughness elements on wind erosion: the importance of surface shear stress distribution. *Journal of Geophysical Research: Atmospheres* 119, 6066–6084.
- Webb, N.P., Herrick, J.E., Van Zee, J.W., Courtright, E.M., Hugenholtz, C.H., Zobeck, T.M., Okin, G.S., Barchyn, T.E., Billings, B.J., Boyd, R., Clingan, S.D., Cooper, B.F., Duniway, M.C., Derner, J.D., Fox, F.A., Havstad, K.M., Heilman, P., LaPlante, V., Ludwig, N.A., Metz, L.J., Nearing, M.A., Norfleet, M.L., Pierson, F.B., Sanderson, M.A., Sharratt, B.S., Steiner, J.L., Tatarko, J., Tedela, N.H., Toledo, D., Unnasch, R.S., Van Pelt, R.S., Wagner, L., 2016. The National Wind Erosion Research Network Building a standardized long-term data resource for aeolian research, modeling and land management. *Aeolian Research* 22, 23–36.
- Webb, N.P., Van Zee, J.W., Karl, J.W., Herrick, J.E., Courtright, E.M., Billings, B.J., Boyd, R., Chappell, A., Duniway, M.C., Derner, J.D., Hand, J.L., Kachergis, E., McCord, S.E., Newingham, B.A., Pierson, F.B., Steiner, J.L., Tatarko, J., Tedela, N.H., Toledo, D., Van Pelt, R.S., 2017. Enhancing wind erosion monitoring and assessment for US rangelands. *Rangelands* 39, 85–96.
- Webb, N.P., Chappell, A., Edwards, B.L., McCord, S.E., Van Zee, J.W., Cooper, B.F., Courtright, E.M., Duniway, M.C., Sharratt, B., Tedela, N., Toledo, D., 2019. Reducing sampling uncertainty in aeolian research to improve change detection. *Journal of Geophysical Research Earth Surface* 124, 1366–1377.
- Webb, N.P., Kachergis, E., Miller, S.W., McCord, S.E., Bestelmeyer, B.T., Brown, J.R., Chappell, A., Edwards, B.L., Herrick, J.E., Karl, J.W., Leys, J.F., Metz, L.J., Smarik, S., Tatarko, J., Van Zee, J.W., Zwicke, G., 2020. Indicators and benchmarks for wind erosion monitoring, assessment and management. *Ecological Indicators* 110, 105881.
- Williams, C.J., Pierson, F.B., Spaeth, K.E., Brown, J.R., Al-Hamdan, O.Z., Wertz, M.A., Nearing, M.A., Herrick, J.E., Boll, J., Robichaud, P.R., Goodrich, D.C., Heilman, P., Guertin, D.P., Hernandez, M., Wei, H., Hardegree, S.P., Strand, E.K., Bates, J.D., Metz, L.J., Nichols, M.H., 2016. Incorporating hydrologic data and ecohydrologic relationships into ecological site descriptions. *Rangeland Ecology & Management* 69, 4–19.
- WMO, 2015. *Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS): Science and Implementation Plan 2015–2020*. In: Nickovic, S., Cuevas, E., Baldasano, J., Terradellas, E., Nakazawa, T., Baklanov, A. (Eds.), *WWRP Report 2015-5*. World Meteorological Organization, Geneva, Switzerland, p. 37.
- Wolfe, S.A., Nickling, W.G., 1993. The protective role of sparse vegetation in wind erosion. *Progress in Physical Geography* 17, 50–68.
- Zhang, J., 2020. A new ecological-wind erosion model to simulate the impacts of aeolian transport on dryland vegetation patterns. *Acta Ecologica Sinica* doi:10.1016/j.chnaes.2020.06.004, Accessed 5 Sept 2020.
- Zhang, J., Okin, G.S., Zhou, B., 2019. Assimilating optical satellite remote sensing images and field data to predict surface indicators in the western US: assessing error in satellite predictions based on large geographical datasets with the use of machine learning. *Remote Sensing of Environment* 233, 111382.
- Zhou, B., Okin, G.S., Zhang, J., 2020. Leveraging Google Earth Engine (GEE) and machine learning algorithms to incorporate in situ measurement from different times for rangelands monitoring. *Remote Sensing of Environment* 236, 111521.
- Zobell, R.A., Cameron, A., Goodrich, S., Huber, A., Grandy, D., 2020. Ground cover—what are the critical criteria and why does it matter? *Rangeland Ecology & Management* 73, 569–576.