Received: 7 January 2019 | Revised: 6 September 2019 | Accepted: 20 September 2019
DOI: 10.1111/aje.12700

SHORT COMMUNICATION

African Journal of Ecology WILEY

Ecosystem dynamics and aeolian sediment transport in the southern Kalahari

Nicholas P. Webb[1] | Gregory S. Okin[2] | Abinash Bhattachan[2] | Paolo D'Odorico[3] | Kebonye Dintwe[2,4] | Mokganedi Tatlhego[3]

[1]USDA-ARS Jornada Experimental Range, Las Cruces, NM, USA
[2]Department of Geography, University of California, Los Angeles, CA, USA
[3]Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA, USA
[4]Department of Environmental Science, University of Botswana, Gaborone, Botswana

Correspondence
Nicholas P. Webb, USDA-ARS Jornada Experimental Range, Las Cruces, NM, USA.
Email: nwebb@nmsu.edu

Funding information
National Science Foundation, Grant/Award Number: EAR-1147545 and EAR-1148334

1 | INTRODUCTION

Aeolian sediment transport processes are sensitive to dryland ecosystem change and can contribute to the transition of savannah grasslands to shrub-invaded and shrub-dominated states (Okin, Gillette, & Herrick, 2006; Ravi, Breshears, Huxman, & D'Odorico, 2010). In the southern Kalahari savannah, bush encroachment by *Senegalia mellifera* is a pervasive ecosystem change that creates mosaic landscapes of varying density grasses and bushes that can affect patterns of aeolian sediment transport (Thomas & Shaw, 1991). Herbaceous species losses and bush encroachment in the Kalahari have been associated with increased dune mobility (Wiggs, Thomas, Bullard, & Livingstone, 1995), degraded air quality (Witson, 2017) and potential reactivation of the region as a persistent dust source (Bhattachan et al., 2012). While accelerated wind erosion can be both driver and consequence of ecosystem change in the Kalahari (Bullard, Thomas, Livingstone, & Wiggs, 1997; Mayaud, Bailey, & Wiggs, 2017; Thomas & Leason, 2005), the role of aeolian processes and its regional impacts have not been fully established. Here, we examine preliminary data on the influence of southern Kalahari ecosystem changes on surface aerodynamic roughness and aeolian sediment transport as a basis for understanding their interactions.

Multiple drivers of ecosystem change have been identified in the Botswana Kalahari (Perkins & Thomas, 1993). These include the coincidence of land use pressures from livestock grazing and changing land tenure associated with the first Livestock Development Project (LDP1) in 1970 and the 1975 Tribal Grazing Lands Policy (TGLP; Dougill, Thomas, & Heathwaite, 1999), scarce groundwater resources, highly variable rainfall, altered fire regimes, increasing atmospheric CO_2 and regional warming (Saha, Scanlon, & D'Odorico, 2015). Research has investigated the impacts of these drivers on bush encroachment along livestock grazing gradients and at different scales (Dougill et al., 2016; Perkins, 2018; Porporato, Laio, Ridolfi, Caylor, & Rodriguez-Iturbe, 2003; Thomas, Sporton, & Perkins, 2000), building consensus that the Kalahari savannah is a nonequilibrium system with alternative ecological states (Figure 1).

Bush encroachment in the southern Kalahari typically occurs within areas of concentrated livestock grazing around boreholes and may be associated with a decline in total grass species and cover (Dreber, Rooyen, & Kellner, 2018; Rutherford & Powrie, 2010). Overgrazing can also result in herbaceous species loss without bush encroachment (Thomas & Shaw, 1991). Although grasses can re-establish after such changes (Bhattachan, D'Odorico, Dintwe, Okin, & Collins, 2014), without livestock exclusion affected areas can become mobile with active sand transport and dust emission (Wiggs, Livingstone, Thomas, & Bullard, 1994). Both fire and bush encroachment have previously been shown to influence surface wind speeds and microclimate in the Kalahari (Saha et al., 2015; Thomas et al., 2018; Wiggs, Livingstone, Thomas, & Bullard, 1996). We hypothesise that vegetation state transitions alter the aerodynamic roughness

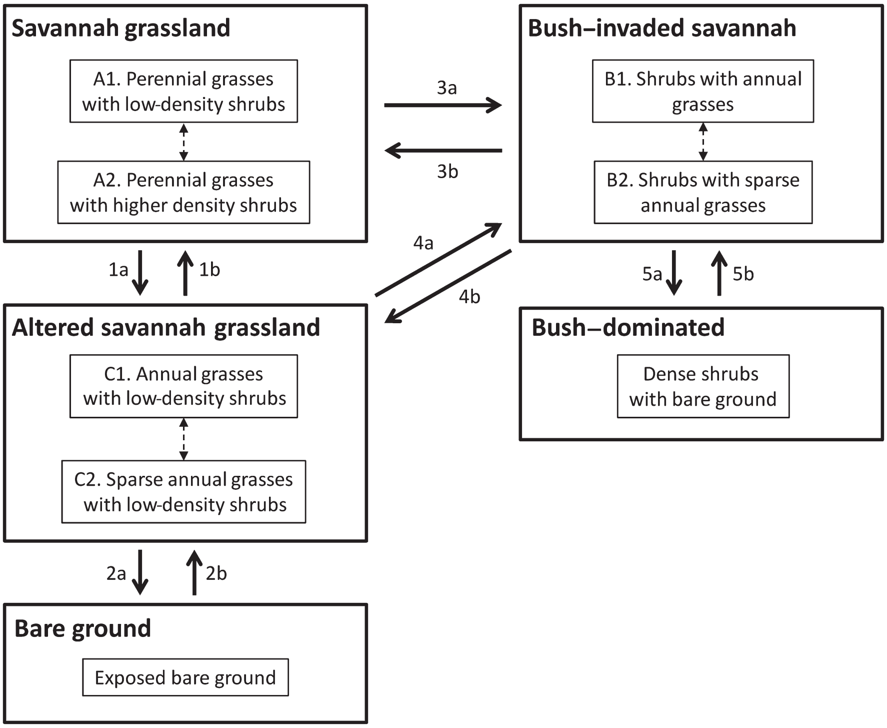


FIGURE 1 State-and-transition model (STM) for the southern Kalahari savannah rangelands (after Dougill et al., 1999). Five ecosystem states are identified for the savannah, excluding pans and playas. Large boxes represent states with distinct structures and rates of ecological and abiotic processes, like wind erosion. Solid arrows represent transitions between states. The ecosystem states may have different community phases (small boxes, e.g., A1, A2) that represent plant community assemblages, and dashed arrows represent pathways along which shifts among communities occur (Bestelmeyer et al., 2003). Description of transitions: 1a—Intensive grazing, drought, reduced fire frequency; 1b—Reduced grazing pressure, fire, perennial grass recovery. 2a—Sustained overgrazing, drought, heightened soil mobility; 2b—Exclosure to grazing, above-average rainfall. 3a—Intensive grazing, bush invasion, reduced fire frequency; 3b—Bush removal and/or dieback from intense fire, reduced grazing pressure, perennial grass recovery. 4a—Persistent intensive grazing, bush invasion, competition by bushes; 4b—Bush removal and/or dieback from intense fire. 5a—Sustained overgrazing, drought, heightened soil mobility; 5b—Exclosure to grazing, above-average rainfall

(z_0) of Kalahari landscapes, producing hot spots of aeolian transport that may reinforce alternative vegetation states. There is a need to understand the interactions at a system level to identify thresholds of ecosystem change, potentially negative impacts, and where and when management interventions could help.

2 | MATERIALS AND METHODS

2.1 | Study sites

Fourteen study sites were established across private cattle ranches near Bokspits and Spaarwater, communal grazing land near Kolonkwaneng, and two private game ranches (Bartrek and Phirima) in southern Botswana in August 2013 (Figure 2). Sites were selected to represent ecosystem states and plant community phases in the southern Kalahari savannah (Table 1). Plant community composition varied among sites, with *Senegalia mellifera* the dominant tree species followed by *Vachellia erioloba*. Perennial grasses included *Eragrostis*, *Aristida* and *Stipagrostis* species (Van Rooyen, 2001).

2.2 | Data collection and analysis

Foliar cover of grasses, bushes and trees were estimated in September 2014 using the line-point intercept method (Herrick et al., 2018) along three parallel 100 m transects at each site. Transects were 20 m apart, and readings were made every 1 m to give 300 readings per site. Five surface soil samples (0–1 cm) were collected from plant interspaces at each site for texture analysis using a Beckman Coulter LS 13 320 laser particle size analyser following Bhattachan, D'Odorico, Okin, and Dintwe (2013). Wind speed profile data were collected using a meteorological tower centrally located at each site. The tower was instrumented with RM Young 3101 cup anemometers at 0.75, 1.17, 1.7, and 2.7 m and an RM Young 3002 at 5.2 m height. Measurements were acquired at each site for ~48 to 52 hr under wind conditions from all directions. Data were sampled at 1 Hz and logged every 1 min on a Campbell Scientific CR1000 data logger. We estimated z_0 following the Prandtl-von Kármán logarithmic velocity profile law:

$$\frac{U_z}{u_*} = \frac{1}{k} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

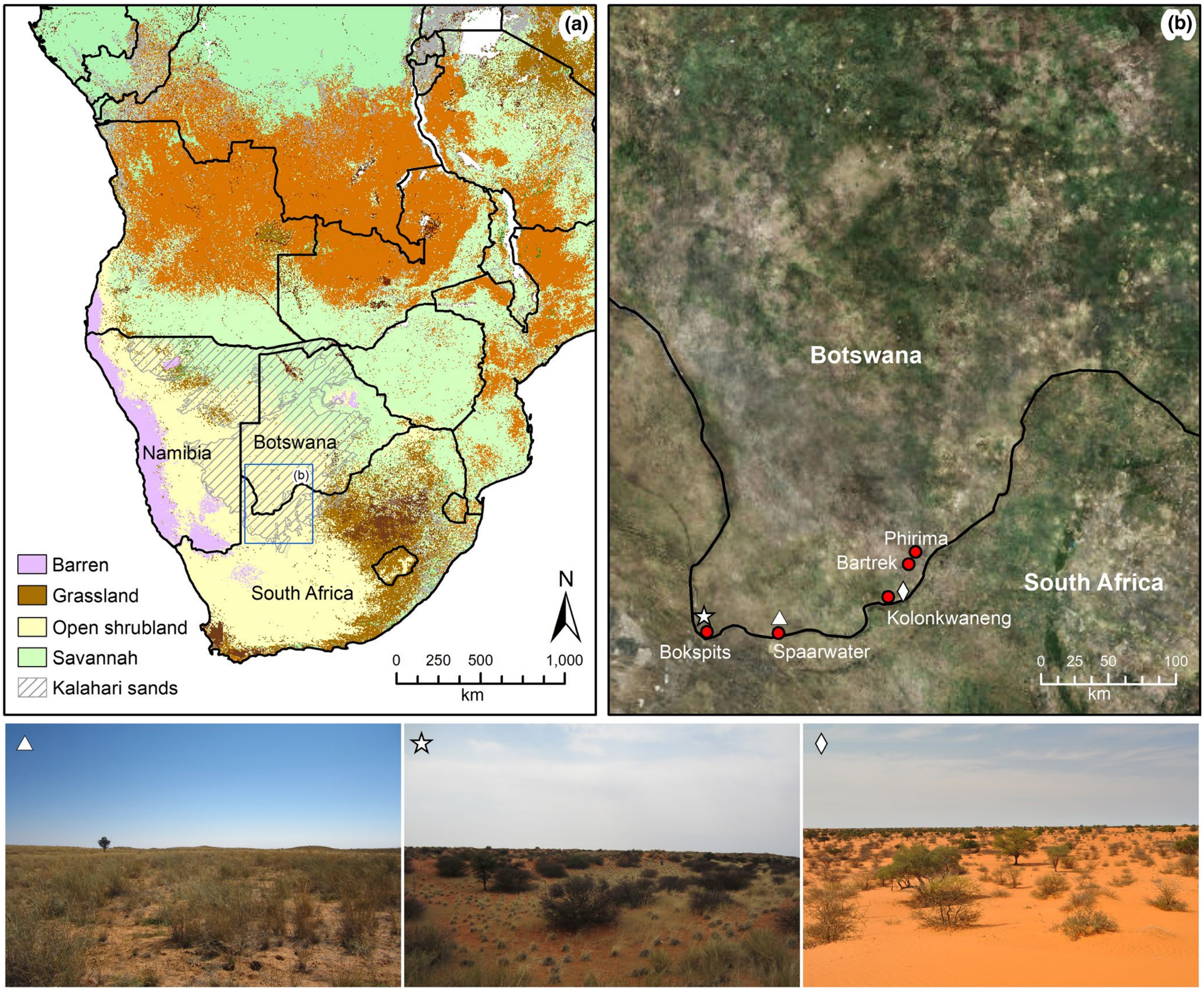


FIGURE 2 Map showing the distribution of International Geosphere-Biosphere Program (IGBP) land cover types across southern Africa (a) and heterogeneity of Landsat 8 surface reflectance across the Kalahari Desert (b) that is indicative of the large spatial variability in vegetation. Photographs illustrate three common ecological states (grassland savannah, bush-invaded and bush-dominated) of the southern Kalahari [Colour figure can be viewed at wileyonlinelibrary.com]

where U_z is the wind speed (m/s) at height z (m), u_* is the wind friction velocity (m/s) and k is von Kármán's constant (0.4). We did not estimate the zero-plane displacement height (d) of the profiles due to the lack of a robust method for its calculation in the presence of patchy vegetation (Wiggs et al., 1996). Estimates of z_0 were obtained using the linear regression approach of Wiggs et al. (1996):

$$U_z = m.\ln(z) + c \quad (2)$$

where $u_* = km$ and $z_0 = e^{-c/m}$. Data were resampled to 15 min averages prior to analysis, and filters were applied to ensure wind speeds at all heights (U_z) ≥ 2 ms^{-1} and fits had r^2 ≥ .97. Estimates of z_0 for vegetation community phase C2 (sparse annual grasses with low-density shrubs) were unreliable due to the tall surrounding bushes and so are not reported.

Aeolian transport was measured with five Modified Wilson and Cooke (MWAC) sediment sampler masts at each site (Goossens, Offer, & London, 2000). The samplers trapped sediment at 0.1, 0.25, 0.5 and 0.85 m heights, with the five masts located in the middle of plant interspaces surrounding site centres. Samplers were deployed from September 2013 to August 2014. Sediment in each trap was extracted in December 2013, May 2014, and August 2014 and weighed. Sample losses reduced the data to 58 complete mass flux profiles (samples at ≥3 heights) across the sites and sampling periods. Exponential functions were fitted using nonlinear least squares regression to the sediment masses, normalised by the MWAC inlet area (0.4715 cm^2), and the sampling period (q), from each MWAC mast with complete profiles:

$$q(z) = ce^{(az^2 + bz)} \quad (3)$$

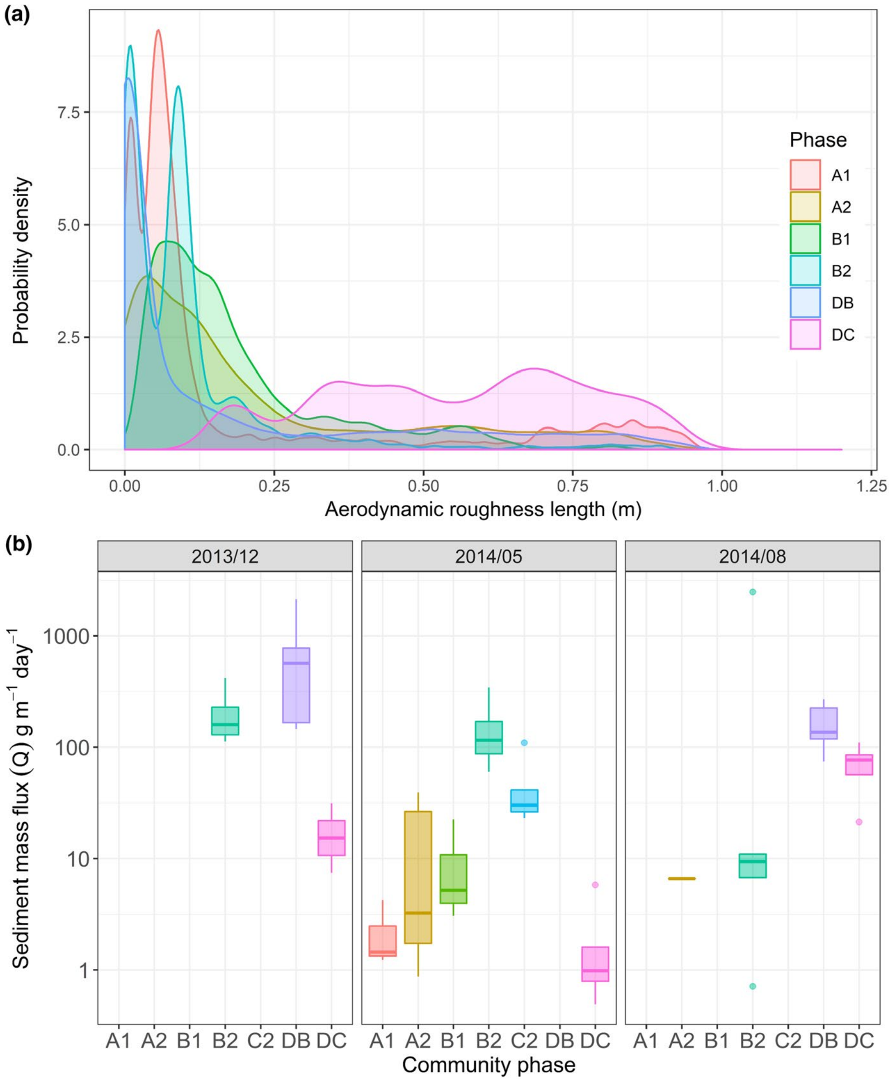
where a, b and c are coefficients of the fitted function and z is the height above the surface (in cm). The fit provided an average R^2 of

TABLE 1 Summary of the study site locations and their respective vegetation community phases, vegetation foliar cover characteristics and soil particle size distributions

Site	Site ID[a]	Latitude	Longitude	Community phase	September 2014 foliar cover (%)			Soil texture			Texture class
					Herbaceous	Bush and tree	Trees	Clay (%)	Silt (%)	Sand (%)	
Bokspits	TMG	26.8231°S	20.6789°E	B1	47	10	1	0.62	1.60	97.78	Sand
	TMNG	26.8242°S	20.6779°E	B2	29	12	2	0.69	2.61	96.70	Sand
	DCG	26.8249°S	20.6768°E	DC	64	2	0	0.65	1.03	98.32	Sand
Spaarwater	DCG	26.8399°S	21.0795°E	DC	42	3	0	0.65	0.87	98.48	Sand
	DCNG	26.8464°S	21.0817°E	DB	1	0	0	0.70	1.93	97.37	Sand
	IDG	26.8411°S	21.0789°E	A1	60	1	0	0.73	1.35	97.92	Sand
Kolonkwaneng	TMNG	26.6319°S	21.9891°E	B2	–	–	–	0.66	2.12	97.22	Sand
	DCNG	26.6319°S	21.9875°E	DB	–	–	–	0.64	1.06	98.30	Sand
Phirima	TMNG	26.2599°S	22.1262°E	A2	18	14	5	0.99	2.04	96.97	Sand
	TMG	26.2426°S	22.1311°E	A2	46	4	4	1.16	2.70	96.14	Sand
	DCNG	26.1837°S	22.0247°E	B2	39	4	2	0.74	0.54	98.72	Sand
	DCG	26.1528°S	22.0154°E	B1	47	4	1	0.88	1.16	97.96	Sand
	TNG	26.2091°S	22.0254°E	C2	40	5	5	1.07	1.90	97.03	Sand
	TG	26.1772°S	21.9986°E	A1	38	5	5	0.97	1.61	97.42	Sand

[a]Site IDs are trees with mellifera (*Senegalia mellifera*) and grass (TMG), trees with mellifera and no grass (TMNG), trees with grass (TG), trees with no grass (TNG), dune crest with grass (DCG) and dune crest with no grass (DCNG). Grasses included *Eragrostis lehmanniana*, *Aristida meridionalis*, *Stipagrostis amabilis* and *Schmidtia kalahariensis* species. Bush and tree species included *Vachellia erioloba* and *Senegalia mellifera*.

FIGURE 3 Measured (a) aerodynamic roughness lengths (z_0) summarised by vegetation community phase for the savannah grassland (phases A1 and A2), bush-invaded savannah (phases B1 and B2) and dune crest sites with grass cover (DC) or without (DB); and (b) sediment mass flux (Q) for the sample collections in December 2013 (2013/12), May 2014 (2014/05) and August 2014 (2014/08). Sampling commenced September 2013 [Colour figure can be viewed at wileyonlinelibrary.com]



.98 across all the profiles for the sites. Vertically integrated horizontal sediment mass fluxes (Q) were calculated by integrating the exponential functions from the surface (0 cm) to 100 cm height:

$$Q = \int_0^{100} q(z)dz \quad (4)$$

where Q was expressed with units of g cm^{-1} day^{-1}. Estimates of z_0 and Q were summarised by plant community phase (Table 1) to examine potential effects of ecosystem change (Figure 1) on aeolian sediment transport. We separated community phases DC (dune crests with grass) and DB (bare dune crests) from the other phases as measured dune crest locations tended to support different grass species (i.e., *Stipagrostis* sp.) to the interdune savannah.

3 | RESULTS

Soils at the study plots had >96% sand in the surface horizon (0–1 cm depth). Soil surfaces were loose at all sites suggesting that, with similar texture, the soils would have similar thresholds for entrainment by wind (Gillette, Adams, Endo, Smith, & Kihl, 1980). Herbaceous vegetation cover ranged from 1% at the Spaarwater bare dune crest site to 64% at the Bokspits vegetated dune crest site (Table 1). Herbaceous cover was high across the sites following the relatively wet 2013/2014 wet season (Dougill et al., 2016). Bush and tree cover ranged from 4% to 14% at nondune crest sites.

Aerodynamic roughness showed large variability within and among the vegetation community phases (Figure 3a). Vegetated dune crests (DC) had largest z_0 of 0.57 ± 0.22 m (median ± standard deviation), with loss of vegetation from dune crests (DB) resulting in a reduction in z_0 to 0.01 ± 0.26 m. Increasing shrub density within savannah grassland sites appeared to increase z_0 from phase A1 (0.06 ± 0.27 m) to A2 (0.12 ± 0.24 m), while reducing grass cover within bush-invaded savannah sites appeared to reduce z_0 from phase B1 (0.14 ± 0.15 m) to B2 (0.08 ± 0.14 m). Overall, our results suggest the transition from savannah grassland to bush-invaded savannah may reduce the surface aerodynamic roughness within bush interspaces and in areas that have experienced a loss of grass cover.

Our measurements of Q appear to reflect differences in measured z_0 among the vegetation states and community phases (Figure 3b). Aerodynamically smooth sites (small z_0) are more exposed to erosive winds that can transport sediments than sites that are aerodynamically rough (large z_0). The largest Q was measured on bare dune sites, whereas the smallest Q was measured on savannah grassland sites with perennial grasses and little bush cover (phase A1). The sediment transport rates appeared to be larger for grassland savannah sites with a higher density of shrubs (phase A2) and increased for bush-invaded savannah sites with annual grasses (phase B1) and sparse annual grasses (phase B2), respectively. Measurements from the May 2014 collection suggest that altered savannah grassland sites (phase C2) may experience sediment transport rates larger than sites in the savannah grassland state (phases A1 and A2). Like z_0, the sediment transport rates had large spatiotemporal variability. The measured magnitude differences in Q suggest that the evaluated vegetation states and phases may have functionally different aeolian sediment transport rates.

4 | DISCUSSION

Dryland ecosystem change, including shrub invasion of savannah grasslands, can alter landscape aerodynamics and accelerate aeolian sediment transport (Ravi et al., 2010). Differences in z_0 among vegetation states are produced by changes in vegetation cover, structure and spatial distributions that increase surface wind friction velocities that can entrain loose sediments (Okin et al., 2006). For example, conversion of former Chihuahuan Desert grasslands to shrublands has significantly altered z_0 and sediment transport (Bergametti & Gillette, 2010; Gillette, Herrick, & Herbert, 2006; Gillette & Pitchford, 2004). At the same time, aeolian processes are an important abiotic feedback driving grassland to shrubland transitions (Bestelmeyer et al., 2018; Okin et al., 2009). Accelerated aeolian transport increases the impacts of soil mobilisation, nutrient losses, and dust emissions from affected ecosystems and on communities within them (e.g., Alvarez, Epstein, Li, & Okin, 2012; Li, Okin, Alvarez, & Epstein, 2007; Webb, Herrick, & Duniway, 2014). Our preliminary data suggest that ecosystem changes occurring in the southern Kalahari modify surface aerodynamic roughness and aeolian transport and, therefore, have potential to impact spatial patterns of dune mobilisation and dust emission.

Elucidating whether aeolian processes are a driver of ecosystem change is necessary for understanding the dynamics and feedbacks of bush encroachment and herbaceous species losses in the Kalahari, as well as other drylands, at the systems level (e.g., Stringer et al., 2017). Earlier studies show vegetation removal due to fire, overgrazing, and drought can result in mobilisation of Kalahari sands and contribute to the persistence of a bare ground state (e.g., Bullard et al., 1997; Lancaster, 1988; Wiggs et al., 1994). Our data suggest state changes can result in changes in aerodynamic roughness and aeolian transport. Nonetheless, information is still lacking on how aeolian processes feed back onto bush encroachment and bush dominance in the Kalahari compared to other drylands where this process is better understood.

Debate also remains open as to whether the Kalahari dunefield could mobilise under future climate change (Ashkenazy, Yizhaq, & Tsoar, 2012; Thomas, Knight, & Wiggs, 2005). Models used on either side of the debate have generally considered only herbaceous species cover and not how changes in plant functional types (e.g., bush encroachment) might play into dunefield activation or interactions among them (e.g., Mayaud et al., 2017). Understanding how aeolian processes influence and respond to vegetation state changes is essential for projecting future Kalahari dune activity and dust emissions.

To the extent that the Kalahari is representative of other savannah systems, this research extends our understanding more generally of vegetation-geomorphic process feedbacks that create and enforce alternative stable states. Future research is needed to measure z_0 and aeolian transport across vegetation states within different precipitation regimes and to establish how aeolian processes impact vegetation directly, through burial/deflation and abrasion, and indirectly, through changes in nutrients and soil water. This new research would allow deeper understanding of observed ecosystem changes in the context of the roles of aeolian processes in the degradation and development of the Kalahari savannah.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation through grants EAR-1147545 and EAR-1148334. We thank the Department of Forestry and Range Resources, Botswana for granting us a research permit, and Alana Ayasse, Laura McNerney, and Onkagetse Mathata for assistance in the field. We are most grateful to Mr. Abraham Jood, Mr. Johannes Martin, the kgosi of Kolonkwaneng, Mr. Thomas van Zyl, Mr. Richard Thomas and Ms. Carol Thomas for access to the study sites for this research. We also thank the late Jill Thomas for logistical support and looking after us so well.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Nicholas P. Webb https://orcid.org/0000-0001-9355-5512

REFERENCES

Alvarez, L., Epstein, H. E., Li, J., & Okin, G. S. (2012). Aeolian process effects on vegetation communities in an arid grassland ecosystem. *Ecology and Evolution*, *2*, 809–821. https://doi.org/10.1002/ece3.205

Ashkenazy, Y., Yizhaq, H., & Tsoar, H. (2012). Sand dune mobility under climate change in the Kalahari and Australian Deserts. *Climatic Change*, *112*, 901–923. https://doi.org/10.1007/s10584-011-0264-9

Bergametti, G., & Gillette, D. A. (2010). Aeolian sediment fluxes measured over various plant/soil complexes in the Chihuahuan desert. *Journal of Geophysical Research*, *115*(F3), F0304. https://doi.org/10.1029/2009JF001543.

Bestelmeyer, B. T., Brown, J. R., Havstad, K. M., Alexander, R., Chavez, G., & Herrick, J. E. (2003). Development and use of state-and-transition models for rangelands. *Journal of Range Management*, *56*, 114–126. https://doi.org/10.2307/4003894

Bestelmeyer, B. T., Peters, D. P. C., Archer, S. R., Browning, D. M., Okin, G. S., Schooley, R. L., & Webb, N. P. (2018). The grassland-shrubland regime shift in the southwestern United States: Misconceptions and their implications for management. *BioScience*, *68*, 678–690. https://doi.org/10.1093/biosci/biy065

Bhattachan, A., D'Odorico, P. D., Baddock, M. C., Zobeck, T. M., Okin, G. S., & Cassar, N. (2012). The Southern Kalahari: A potential new dust source in the Southern Hemisphere? *Environmental Research Letters*, *7*, 024001. https://doi.org/10.1088/1748-9326/7/2/024001

Bhattachan, A., D'Odorico, P. D., Dintwe, K., Okin, G. S., & Collins, S. L. (2014). Resilience and recovery potential of duneland vegetation in the southern Kalahari. *Ecosphere*, *5*, art2. https://doi.org/10.1890/ES13-00268.1

Bhattachan, A., D'Odorico, P. D., Okin, G. S., & Dintwe, K. (2013). Potential dust emissions from the southern Kalahari's dunelands. *Journal of Geophysical Research: Earth Surface*, *118*, 307–314. https://doi.org/10.1002/jgrf.20043

Bullard, J. E., Thomas, D. S. G., Livingstone, I., & Wiggs, G. S. F. (1997). Dunefield activity and interactions with climatic variability in the Southwest Kalahari Desert. *Earth Surface Processes and Landforms*, *22*(2), 165–174. https://doi.org/10.1002/(SICI)1096-9837(199702)22:2<165:AID-ESP687>3.3.CO;2-0

Dougill, A. J., Akanyang, L., Perkins, J. S., Echardt, F. D., Stringer, L. C., Favretto, N., … Mulale, K. (2016). Land use, rangeland degradation and ecological changes in the southern Kalahari, Botswana. *African Journal of Ecology*, *54*, 59–67. https://doi.org/10.1111/aje.12265

Dougill, A. J., Thomas, D. S. G., & Heathwaite, A. L. (1999). Environmental change in the Kalahari: Integrated land degradation studies for nonequilibrium dryland environments. *Annals of the Association of American Geographers*, *89*, 420–442. https://doi.org/10.1111/0004-5608.00156

Dreber, N., van Rooyen, S. E., & Kellner, K. (2018). Relationship of plant diversity and bush cover in rangelands of a semi-arid Kalahari savannah, South Africa. *African Journal of Ecology*, *56*, 132–135.

Gillette, D. A., Adams, J., Endo, A., Smith, D., & Kihl, R. (1980). Threshold velocities for input of soil particles into the air by desert soils. *Journal of Geophysical Research*, *85*, 5621–5630. https://doi.org/10.1029/JC085iC10p05621

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. https://doi.org/10.1007/s10652-005-6022-7

Gillette, D. A., & Pitchford, A. M. (2004). Sand flux in the northern Chihuahuan desert, New Mexico, USA, and the influence of mesquite-dominated landscapes. *Journal of Geophysical Research*, *109*, F04003. https://doi.org/10.1029/2003JF000031

Goossens, D., Offer, Z. Y., & London, G. (2000). Wind tunnel and field calibration of five aeolian sand traps. *Geomorphology*, *35*, 233–252. https://doi.org/10.1016/S0169-555X(00)00041-6

Herrick, J. E., Van Zee, J. W., McCord, S. E., Courtright, E. M., Karl, J. W., & Burkett, L. M. (2018). *Monitoring manual for grassland, shrubland, and savanna ecosystems, volume 1: Core methods* (2nd ed.). Las Cruces, NM: USDA-ARS Jornada Experimental Range.

Lancaster, N. (1988). Controls of eolian dune size and spacing. *Geology*, *16*, 972–975. https://doi.org/10.1130/0091-7613(1988)016<0972:COEDSA>2.3.CO;2

Li, J., Okin, G. S., Alvarez, L., & Epstein, H. (2007). Quantitative effects of vegetation cover on wind erosion and soil nutrient loss in a desert grassland of southern New Mexico, USA. *Biogeochemistry*, *85*, 317–332. https://doi.org/10.1007/s10533-007-9142-y

Mayaud, J. R., Bailey, R. M., & Wiggs, G. F. S. (2017). Modelled responses of the Kalahari Desert to 21st century climate and land use change. *Scientific Reports*, *7*, 3887. https://doi.org/10.1038/s41598-017-04341-0

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*(2), 253–275. https://doi.org/10.1016/j.jaridenv.2005.06.029

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. https://doi.org/10.1525/bio.2009.59.3.8

Perkins, J. S. (2018). Southern Kalahari piospheres: Looking beyond the sacrifice zone. *Land Degradation and Development*, *29*, 2778–2784. https://doi.org/10.1002/ldr.2968

Perkins, J. S., & Thomas, D. S. G. (1993). Spreading deserts or spatially confined environmental impacts? Land degradation and cattle ranching in the Kalahari Desert of Botswana. *Land Degradation and Development*, *4*, 179–194. https://doi.org/10.1002/ldr.3400040307

Porporato, A., Laio, F., Ridolfi, L., Caylor, K. K., & Rodriguez-Iturbe, I. (2003). Soil moisture and plant stress dynamics along the Kalahari precipitation gradient. *Journal of Geophysical Research*, *108*(D3), 4127. https://doi.org/10.1029/2002JD002448

Ravi, S., Breshears, D. D., Huxman, T. E., & D'Odorico, P. (2010). Land degradation in drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology*, *116*, 236–245. https://doi.org/10.1016/j.geomorph.2009.11.023

Rutherford, M. C., & Powrie, L. W. (2010). Severely degraded dunes of the southern Kalahari: Local extinction, persistence and natural re-establishment of plants. *African Journal of Ecology*, *48*, 930–938. https://doi.org/10.1111/j.1365-2028.2009.01194.x

Saha, M. V., Scanlon, T. M., & D'Odorico, P. (2015). Examining the linkage between shrub encroachment and recent greening in water-limited Southern Africa. *Ecosphere*, *9*(6), 156. https://doi.org/10.1890/ES15-00098.1

Stringer, L. C., Reed, M. S., Fleskens, L., Thomas, R. J., Le, Q. B., & Lala-Pritchard, T. (2017). A new dryland development paradigm grounded in empirical analysis of dryland systems science. *Land Degradation and Development*, *28*, 1952–1961. https://doi.org/10.1002/ldr.2716

Thomas, A. D., Elliott, D. R., Dougill, A. J., Stringer, L. C., Hoon, S. R., & Sen, R. (2018). The influence of trees, shrubs, and grasses on microclimate, soil carbon, nitrogen, and CO2 efflux: Potential implications of shrub encroachment for Kalahari rangelands. *Land Degradation and Development*, *29*, 1306–1316.

Thomas, D. S. G., Knight, M., & Wiggs, G. F. S. (2005). Remobilization of southern African desert dune systems by twenty-first century global warming. *Nature*, *435*, 1218–1221. https://doi.org/10.1038/nature03717

Thomas, D. S. G., & Leason, H. C. (2005). Dunefield activity response to climate variability in the southwest Kalahari. *Geomorphology*, *64*(1–2), 117–132. https://doi.org/10.1016/j.geomorph.2004.06.004

Thomas, D. S. G., & Shaw, P. A. (1991). *The Kalahari environment*. Cambridge, UK: Cambridge University Press.

Thomas, D. S. G., Sporton, D., & Perkins, J. (2000). The environmental impact of livestock ranches in the Kalahari, Botswana: Natural resource use, ecological change and human response in a dynamic dryland system. *Land Degradation and Development*, *11*, 327–341. https://doi.org/10.1002/1099-145X(200007/08)11:4<327:AID-LDR395>3.0.CO;2-V

Van Rooyen, N. (2001). *Flowering plants of the Kalahari dunes*. Newlands, South Africa: Botanical Society of South Africa.

Webb, N. P., Herrick, J. E., & Duniway, M. C. (2014). Ecological site-based assessments of wind and water erosion: Informing accelerated soil erosion management in rangelands. *Ecological Applications*, *24*, 1405–1420. https://doi.org/10.1890/13-1175.1

Wiggs, G. F. S., Livingstone, I., Thomas, D. S. G., & Bullard, J. E. (1994). Effect of vegetation removal on airflow patterns and dune dynamics in the southwest Kalahari Desert. *Land Degradation and Rehabilitation*, *5*, 13–24. https://doi.org/10.1002/ldr.3400050103

Wiggs, G. F. S., Livingstone, I., Thomas, D. S. G., & Bullard, J. E. (1996). Airflow and roughness characteristics over partially vegetated linear dunes in the southwest Kalahari Desert. *Earth Surface Processes and Landforms*, *21*, 19–34. https://doi.org/10.1002/(SICI)1096-9837(199601)21:1<19:AID-ESP508>3.0.CO;2-P

Wiggs, G. F. S., Thomas, D. S. G., Bullard, J. E., & Livingstone, I. (1995). Dune mobility and vegetation cover in the southwest Kalahari Desert. *Earth Surface Processes and Landforms*, *20*, 515–529. https://doi.org/10.1002/esp.3290200604

Witson, M. (2017). Status of air pollution in Botswana and significance to air quality and human health. *Journal of Health and Pollution*, *7*, 8–17. https://doi.org/10.5696/2156-9614-7.15.8

How to cite this article: Webb NP, Okin GS, Bhattachan A, D'Odorico P, Dintwe K, Tatlhego M. Ecosystem dynamics and aeolian sediment transport in the southern Kalahari. *Afr J Ecol*. 2020;58:337–344. https://doi.org/10.1111/aje.12700