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RESEARCH ARTICLE

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The southwest Kalahari dune field does not emit dust post-fire despite a lack of vegetation and above-threshold winds

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Abstract

Vegetated sand dunes are not typically considered to be significant sources of dust because of coarse grain sizes and high vegetation cover. Yet, plumes of dust have been observed from vegetated dune fields, and wind tunnel experiments show the potential for interdunes to emit dust. The partially vegetated southwest Kalahari is one such dune field that is vulnerable to climate-driven land degradation and vegetation cover change and has been posited as a potential future dust source. In this study, we monitor the post-fire de-vegetated state of 11 interdunes to investigate the dust emission potential and erodibility controls on emission. Findings suggest that there is little emission of dust despite a fine-grain component (up to 30% of resident grains <62.5 μm) and a lack of vegetation, even with high velocity wind events (>7 m s^{-1}) post-fire. Erosive wind events were less frequent compared to other dust-producing regions, with wind speeds generally under 7 m s^{-1}. Five high wind speed events over 7 m s^{-1} were recorded in September 2022, the month immediately following burning, but even then, only one event had a concurrent increase in aerosol concentration. This is indicative of other erodibility factors limiting dust emission. These include high (>50%) burned debris cover in the immediate post-fire period and evidence of biological soil crusts that survived burning. Both protect the surface after fire whilst the natural vegetation cover recovers. Combined, the general low wind speeds, high initial surface cover, and the protective effect of biocrusts result in a low probability of the southwest Kalahari emitting dust post-fire. However, fine-grain sizes and low vegetation cover under drought and high grazing may lead to conditions conducive for dust emission.

KEYWORDS
biological soil crusts, fire, mineral dust, sand dunes, savanna biogeomorphology, wind erosion

1 | INTRODUCTION

Windblown dust is the most abundant atmospheric aerosol and is a critical component of the Earth's land-atmosphere–ocean-biosphere system (Adebiyi et al., 2023; Kok et al., 2017; Schepanski, 2018; Shao et al., 2011). Whilst airborne, dust has influence on the Earth's radiation balance and atmospheric chemistry, alongside issues for human health and air quality (Goudie, 2014; Hilly et al., 2025; Kok et al., 2023; Schepanski, 2018). Once deposited, it can be an important nutrient source for both terrestrial (Dong et al., 2020; von Suchodoletz et al., 2013; Winton et al., 2024) and marine (Dansie et al., 2022; Gittings et al., 2024; Jickells et al., 2005) ecosystems. Yet current understanding of the factors driving changes in the emission of dust, including the relative roles of wind speed, soil properties, changes in land use, sediment supply and vegetation cover, is poor (Bryant, 2013;Kok et al., 2023; Mahowald et al., 2024). These uncertainties have led to significant challenges in parameterising the amount of dust emitted into the atmosphere and its impact on environmental and climatic systems (Kok et al., 2023; Mahowald et al., 2024).

Vegetated dune fields are not typically considered to be large sources of dust, mainly because of low amounts of fine material (<100 μm) and high surface roughness due to vegetation cover. Vegetation stabilises the dunes but also reduces near-surface wind velocities and promotes deposition (Hesse & Simpson, 2006; Strong et al., 2010; Wiggs et al., 1994). However, vegetated sand dunes have resident fine grains (<62.5 μm) in the sediment matrix as a result of limited surface movement (Bullard et al., 2004). This stability allows for weak pedogenesis, increasing the fine-grain content of the dune field (Bhattachan et al., 2013; Bullard et al., 2008; Hesse, 2016). In addition, established vegetation and biological soil crusts (biocrusts) trap allochthonous sediment, further enhancing the fine portion of the dune field sediment texture (Garcia-Pichel et al., 2016; Hesse, 2016; Zhao & Lei, 2025). Biocrust communities of bacteria and algae in the top few millimetres of the soil cover around 25% of dryland soil surfaces (Rodríguez-Caballero et al., 2018, 2022). These biocrusts stabilise the surface where vegetation is limited or absent, and it is estimated that their presence reduces global atmospheric dust emissions by around 60% (Rodríguez-Caballero et al., 2018, 2022). Subsequently, when these systems are disturbed and de-vegetated, there are portions of fine sediment available to be eroded by the wind (Pye, 1989; Sweeney et al., 2023).

Within vegetated dune systems, it is the interdunes that are primarily considered to be the most likely source of dust because vegetation canopies trap aerosols advected across the dune field (Garcia-Pichel et al., 2016; Hesse, 2016; Zhao & Lei, 2025) and interdunes have larger proportions of fine sediment compared to dune crests or flanks (Bhattachan et al., 2012, 2013; Lancaster, 1986a; Strong et al., 2010). In the southwest Kalahari, interdunes frequently have a thin sand cover over extensive calcrete duricrusts, which are exposed in some places and a source of fine-grained material in the surface sediment matrix (Lancaster, 1988; Mabbutt, 1957; Nash, 2022). Bhattachan et al. (2012) used a dust impact generator in the partially vegetated dunes of the southwest Kalahari and found that only the interdune locations have the potential to emit dust. Interdunes were also posited to be the only dust-producing portion of the dune field by Strong et al. (2010) in the Simpson Desert, because of grain size and vegetation establishment.

Fires are common on vegetated dune landscapes and pose a disturbance event that triggers de-vegetation and exposes large portions of bare surface to the wind. Subsequently, post-fire dust emission events are becoming more frequently observed globally (Li et al., 2021; Meng et al., 2025; Wagenbrenner et al., 2013; Yu & Ginoux, 2022). Fire can further increase the erodibility of the surface by reducing inter-grain cohesion (Ravi et al., 2006; Ravi, D'Odorico, Zobeck, & Over, 2009). This occurs through the volatilisation of the organic component of plants when burned, which is then transported into the soil through strong temperature gradients, condensing around sand grains and creating a hydrophobic coating (DeBano, 2000; Ravi et al., 2007; Ravi, D'Odorico, Wang, et al., 2009).

Despite the effect of fires on surface conditions, few studies have reported post-fire dust plumes from interdune locations. Bullard et al. (2008) and McGowan & Clark (2008) both recorded dust events in the Simpson Desert in late 2003 using MODIS imagery, where one plume with origins within a dune field fire scar had a recorded size of 85,700 km^2. Yu & Ginoux (2022) used MODIS-derived dust optical depth (DOD) to identify increases in aerosols above burned land. The study observed increases over burned vegetated dune systems globally, but the events were rarely observed as distinct plumes of dust (Yu & Ginoux, 2022). Furthermore, Strong et al. (2010) measured higher than average total annual dust concentration at a meteorological station downwind of large fire scars seven years after burning in the Simpson Desert. The above-mentioned observations of post-fire dune dust emission all have difficulty in pinpointing the exact origins of these emissions within the dune landscape.

The southwest Kalahari Desert in southern Africa is ecologically and geomorphologically similar to the post-fire dust-producing Simpson Desert (Buckley, 1981). In addition, the southwest Kalahari burns frequently with a fire return time of less than 10 years (Huck et al., 2026). Yet, post-fire dust emissions have not been observed in the region despite some evidence of dust plumes originating from within the dune field (Eckardt et al., 2020; Vickery et al., 2013). Vickery et al. (2013) and Eckardt et al. (2020) both used the Meteosat Second Generation—Spinning Enhanced Visible and Infrared Imager (MSG – SEVIRI) to identify six plumes originating from the southwest Kalahari dune field over 13 years of observation, but none of these plumes were explicitly linked to burned areas. Such plumes can have ecologically important ramifications, with the iron-rich fallout providing nutrients to the south Atlantic (Dansie et al., 2017), the Madagascar Sea (Gittings et al., 2024) or the Southern Ocean (Bhattachan et al., 2012).

This study investigates the post-fire environment of burned interdunes in the southwest Kalahari Desert to answer the following research questions: what is the potential of the interdune surfaces to produce dust (RQ1), and what are the controls on dust emission post-fire (RQ2)? To answer these questions, a primarily field-based study was conducted in the region. For RQ1, sediment grain size, wind speed and in-situ aerosol concentrations were recorded. For RQ2, we additionally undertook quantification of surface and biocrust cover, alongside measurements of soil hydrophobicity.

2 | STUDY SITE AND METHODS

2.1 | The southwest Kalahari linear dune field

The arid dune field in the southwest Kalahari is characterised by linear dunes that are broadly orientated from northwest to southeast (Lancaster, 1986b; Thomas & Wiggs, 2022). Dunes consist of unconsolidated aeolian sands, primarily composed of quartz and feldspar (Garzanti et al., 2022). Previous studies have found that there is fine material within the dune sediments, with fine silt and clay content ranging from 0% to 7% (Bhattachan et al., 2013; Livingstone et al., 1999; Stone & Thomas, 2008; Telfer, 2011).

The vegetation in this region is a mixture of trees, shrubs and grasses. Interdunes are dominated by the annual grass *Schmidtia kalahariensis* and sparsely distributed *Acacia mellifera* trees and shrubs. Wiggs et al. (1995) identified that the litter component of ground cover has much greater importance in protecting the surface from wind erosion than rooted vegetation. Fires occur most commonly in September through to December and are influenced by vegetation cover, which is linked to antecedent precipitation (Andela et al., 2019). Wet years allow for the build-up of biomass that senesces, generating dry flammable material in the subsequent dry season (Chen et al., 2017). Cyanobacteria-dominated biocrusts are common in the dune landscape, providing additional protection to the surface through the filamentous sheath material entangling grains and the secretion of extracellular polymeric substances, which agglutinate

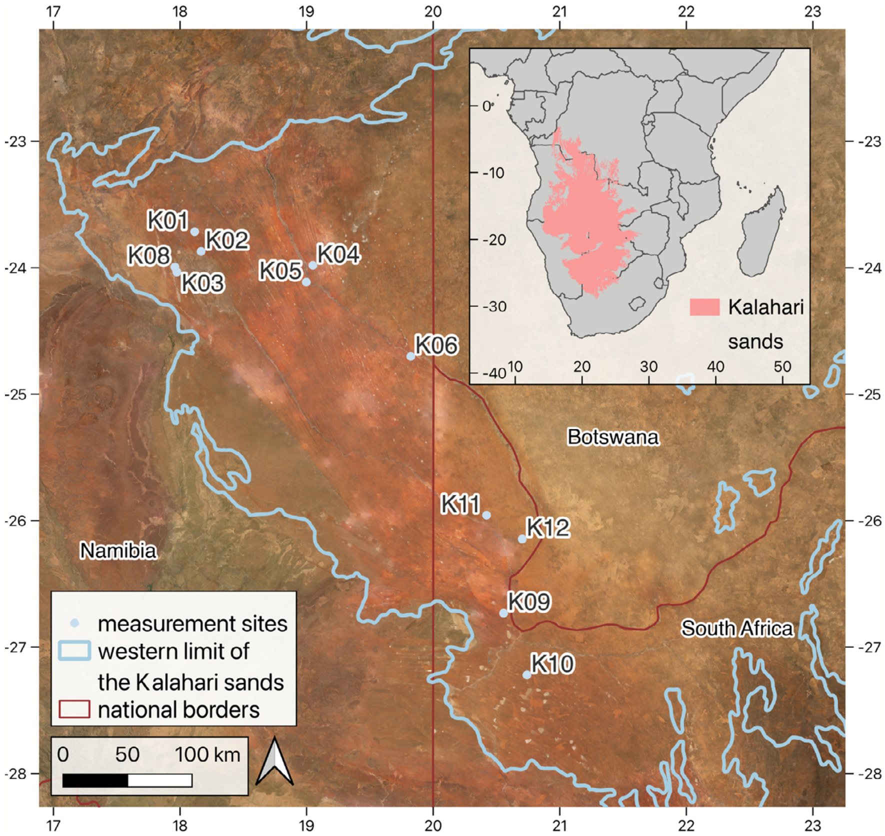

FIGURE 1 The location of the study sites in the southwestern Kalahari. Inset: the extent of Kalahari Sands in southern Africa. Background image © 2023 planet labs PBC (Planet, 2023). Kalahari sands extent from Southern African Science Service Centre for Climate Change and Adaptive Land Management.

particles (Thomas & Dougill, 2007). Biocrust cover is highly variable, depending on disturbance history covering between 11 to 95% of the ground surface of the Kalahari dune field (Thomas & Dougill, 2007).

2.2 | Study sites

To investigate what limits dust emission from the southwest Kalahari, measurements were conducted in three periods at 11 sites. The sites were then further divided into 22 plots (11 within fire scars and 11 co-located unburned interdunes; Figure 1 and Table S1). From herein, 'site' refers to the broader burned area and the co-located control area and 'plot' refers to the experimental area within a site in the interdune. Due to the inherent unpredictability of burning in the southwest Kalahari, sites chosen and measurements made were reactive to the presence of burning events. To maximise the likelihood of measuring a recently burned area, field studies were conducted mainly in September, which falls at the end of the dry season, when there is a higher likelihood of fire and dry and windy conditions most conducive to dust emission. Measurements were conducted during three field visits, in September 2022, June 2023 and September 2023, at sites (Figure 1) that had recently burned or represented older burned conditions. Measurements at burned sites were paired with equivalent data collection at nearby unburned sites, allowing comparison of key data in burned and unburned contexts.

The use of co-located control and burned plots aimed to reduce variations through differences in surface properties at each site (e.g., soil type or grazing density). Accordingly, the control and burned sites were either located on the same dune or with one dune separation. In farmed areas, the sites were located within the same fenced area. Sites where surface cover was first measured in September 2022 (K01 to K06, K08) were remeasured in September 2023 (Table 1). Sites K09 to K12 were only measured once, due to logistical constraints. The most recently burned sites (K01 and K02) were measured one month after the initial measurements (Table 1).

2.3 | Aerosol and wind speed measurements

To answer RQ1 and to identify any dust events that are not recorded by satellite remote sensing, aerosol concentrations were measured at the two most recently burned plots, K01 (3-day old fire scar) and K02 (one-month old fire scar), during September 2022. DustTrak DRX (TSI Inc.) aerosol monitors (Wang et al., 2009) were mounted on a tripod at 1.8 m height and located at least 500 m from the edge of the burn. Average aerosol concentrations (mg m^{-3}) were recorded at two-minute intervals at PM_1, $PM_{2.5}$ and PM_{10}.

For sediment to be mobilised, wind velocities must be sufficient to displace individual grains. To answer RQ1 and examine if erosive capability was limiting post-fire dust emissions, horizontal wind velocity and direction were measured at a frequency of two minutes during September 2022 using a Vector Instruments cup anemometer (A-100LK) and wind vane (W-200P) at the burned K02 plot at a height of 1.8 m (Figure 2). To maximise data collection and to best utilise fieldwork time, the burned K02 plot was chosen for both wind speed and aerosol measurements, as it was the most recently burned site available at the start of the measuring period and allowed for the longest continuous measurement duration.

To situate the month-long meteorological station data within the broader context of regional wind patterns, daily mean wind speeds and wind gust data for 2000 to 2023 inclusive were obtained using ERA5-Land reanalysis daily aggregate data, which has a horizontal

TABLE 1 Locations of measurement sites on the Kalahari linear dunes. Measurement time since fire (TSF) also reveals the number of measurements made at each site.

Site	Land use	Burned interdune latitude	Burned interdune longitude	Date of fire	Time since fire (months)
K01	Farm	−23.7227	18.1100	2022-09-01	0*3,1*,12
K02	Farm	−23.8606	18.1507	2022-07-26	1*,2*,13
K03	Farm	−24.0422	17.9812	2022-06-18	4*, 15
K04	Farm	−23.9825	19.0172	2021-11-29	10*, 22
K05	Farm	−24.1159	18.9966	2021-11-16	10*, 22
K06	Farm	−24.6889	19.8223	2020-10-27	25*, 37
K08	Farm	−23.9961	17.9593	2021-12-18	9*, 21
K09	Farm	−27.2211	20.7403	2023-01-21	6
K10	Farm	−26.7354	20.5562	2022-10-18	10
K11	NP	−25.9571	20.4206	2021-12-27	18
K12	NP	−26.1460	20.7030	2022-09-09	10

Abbreviation: NP, National Park.
*No biocrust cover or water drop penetration time assessed, but aerosol and wind speed measurements.
[3]Site K01 was initially recorded three days after burning.

FIGURE 2 In-situ measurements of dust using a DustTrak monitor and meteorological station at site K02 burned interdune in September 2022.

resolution of around 9 km (Muñoz-Sabater et al., 2021). Wind gusts (m s^{-1}) are defined as the maximum value, within the hourly observation period, and were chosen for analysis due to previous research finding good correlation between wind gusts and dust emission (Engelstaedter & Washington, 2007). ERA5-Land data are a commonly used method for reanalysis of southern African climate (e.g., Chikoore et al., 2024; Mwangala et al., 2024; Parsons et al., 2022; Roffe & van der Walt, 2023; Wallum et al., 2025), with Gadal et al. (2022) finding that ERA5-Land can reliably be used for wind speed analysis in southern Africa.

2.4 | Grain size distribution

Surface sediment samples were collected from each burned and control plot to answer RQ1 and establish (1) if resident erodible fines were contained within the interdunes and (2) if there was evidence of a reduction in fines post-fire due to wind erosion. Resident fine material is described by Bullard et al. (2004) as particles under 125 μm that can be released as dust during sand saltation. In this study, sediment under 62.5 μm is considered as the resident fine material benchmark as this size bin is a key component of dust (Adebiyi et al., 2023; Sweeney et al., 2023).

Samples of sediment exposed to the wind (up to 2 cm maximum depth) were collected at each experimental plot. These were returned to the laboratory for grain-size analysis, with three replicate grain size distributions measured for each sample and a mean value calculated. The grain size analyses were conducted using a Malvern Mastersizer Hydro 2000MU laser diffraction particle size analyser. Before analysis, samples were oven dried overnight and sieved to under 2 mm and exposed to 10 seconds of ultrasonic dissolution. Samples were determined using the classification system of the United States Department of Agriculture (USDA), where clay is <2 μm, silt is 2 μm to 50 μm and sand is 50 μm to 2000 μm. In addition, sediment was further classed into two size classes: under 10 μm, where particles are typically considered to be inhalable, and the size which is used in most dust models (Mahowald et al., 2014; Middleton, 2020), and under 62.5 μm, where recent evidence shows transport of this super-coarse dust (Adebiyi et al., 2023; Sweeney et al., 2023).

Lancaster (1986a) investigated sediment size characteristics of the southwest Kalahari. The study concluded that the interdunes have more fine material than the dune crest because of the differential movement of grains of different sizes (Lancaster, 1986a). Should the resident fine material be emitted from the surface as dust, then a coarsening in grain size between control to burned surfaces could be indicative of dust emissions from the plots. This assumes the interdunes are fine-grained supply-limited. This is likely the case for the Kalahari because of the lack of large recharge events replenishing the supply (Bhattachan et al., 2012). Yet some interdune sand layers are so thin that they interact with the underlying calcrete, providing some fine material. These calcrete-influenced interdunes are characteristically lighter in colour than the unconsolidated red sands, and this sediment was not sampled in this study. Subsequently, we assume that the interdune sediment is supply-limited. A comparative method

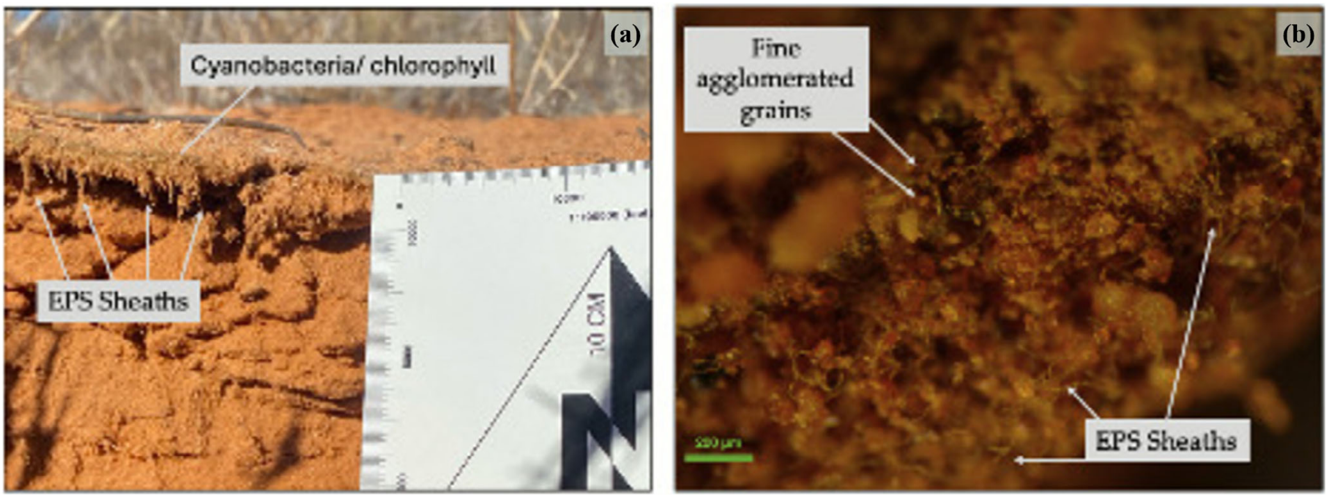

FIGURE 3 Biological soil crusts in the Kalahari. (A) a sediment profile trench at control interdune plot K11 where biological soil crust is present. Extracellular polymeric substances (EPS) sheaths and greened cyanobacteria/chlorophyll are highlighted. (B) Microscopy of a biological soil crusts displaying the EPS sheaths and the diverse grain sizes present within the crust.

for paired burned and unburned plots was used to assess for any sediment coarsening that resulted from the removal of fine material as dust from the burned plots. Wilcoxon rank-sum tests were chosen to assess for any statistical differences between the burned and control plots because of the paired and skewed nature of the dataset.

2.5 | Ground cover surveys

A 10 m transect line ground cover surveys were conducted at each interdune area to address RQ2 using the line-intercept method (Canfield, 1941). This method is an established technique to assess ground cover (Brun & Box, 1963; Canfield, 1941; Etchberger & Krausman, 1997; Hesse & Simpson, 2006), with Etchberger & Krausman (1997) finding that the line-intercept method was the most close estimate to the real census of vegetation in the Sonoran Desert. The line-intercept measurement method was chosen to accommodate the need for instantaneous measures of both surface cover and bare ground without instrumentation of the plots. At each plot, a tape measure was placed on the surface and, at 1 cm resolution, every ground cover classification in contact with the tape was recorded. This included bare ground (including cyanobacterial and algal crusts, which were not easily distinguishable from bare ground), vegetation height, class (for example, perennial grass, annual grass, shrub, forb, tree), basal cover, litter, burned vegetation and burned detritus.

2.6 | Sediment profile trenches

Biological soil crusts are known to limit dust emissions from desert regions (Rodríguez-Caballero et al., 2022) and need to be quantified to answer RQ2. The visual delineation of biocrusts is difficult, and mapping the surface cover from above is hard (Bullard et al., 2022). Many biocrusts in the Kalahari are early successional stage cyanobacterial crusts, which do not have any surface discolouration. To circumvent inaccurate surface cover estimates, one to three 10 cm-deep pits were dug at each plot when measurements were made in 2023 to describe the surface, the structure of the top few centimetres and ascertain any surface crusting through identification of conglomerations of sediment (Figure 3).

2.7 | Soil hydrophobicity

To assess the role of post-fire sediment hydrophobicity on dust emissions and address RQ2, a water drop penetration time (WDPT) test was conducted at each site (Doerr, 1998; Ravi et al., 2012; Ravi, D'Odorico, Wang, et al., 2009; Tinebra et al., 2019). Using a pipette held approximately 1 cm above the surface, a drop of water was released onto the ground. The time required for the drop to penetrate the surface was recorded. Measurements were taken every 50 cm along each transect, generating 20 measurements at each site.

3 | RESULTS

3.1 | Wind conditions

24-year ERA5-Land data reported an average mean wind speed of 4.29 m s^{-1} for September 2022. The wind gust data are presented in Figure 4 and situates September 2022 within the broader context of regional wind patterns. September 2022, with wind gusts of 6.81 m s^{-1}, was above average for the month of September in the period 2000–2023. However, January, October, November and December, with average wind gusts of 6.64, 6.92, 7.07 and 7.19 m s^{-1}, respectively, proved to be windier months overall (Figure 4).

When compared, the ERA5-Land and the site K02 meteorological station data correlated with an R^2 value of 0.326 and can be used comparatively. Data from the meteorological station, with a temporal resolution of two minutes, recorded five high wind speed days during the recording period. During these events, winds surpassed 7 m s^{-1} which is a commonly used threshold above which aeolian sediment transport can begin (Yang et al., 2012).

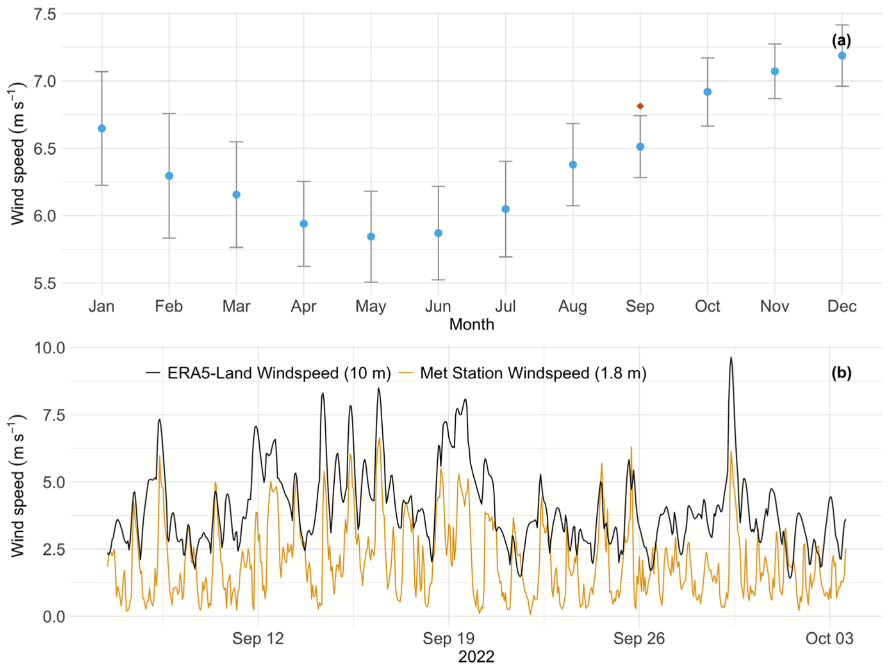

FIGURE 4 Wind measurement from the site. Panel (A) shows monthly mean wind gusts (m s^{-1}) from 2000 to 2023. Mean values are reported in blue with ± one standard deviation. The ground survey month (September 2022) is highlighted in the orange diamond and showed higher than average wind gusts for September (2000–2023). Panel (B) displays the good correlation between 10 m ERA5-land hourly wind speed in black and the in-situ meteorological station at 1.8 m data in yellow during the measurement period in September 2022.

3.2 | In-situ aerosol concentrations

Despite five events where wind speeds were greater than 7 m s^{-1}, there were a limited number of coincident increases in aerosol concentration measured by the DustTrak. Figure 5a show aerosol concentration at the burned plots K01 and K02 from 2022-09-04 to 2022-10-03 alongside the meteorological station wind speed. In the recording period, there were four events where wind speed and aerosol concentration increased at the same time (2022-09-07, 2022-09-13, 2022-09-14 and 2022-09-29). Yet, there were also days that recorded strong wind speeds but had no increase in aerosols (2022-09-16, 2022-09-17, 2022-09-24, 2022-09-25). Other days experienced minor increases in wind speed (<4 m s^{-1}) with no aerosol concentration increase (e.g., 2022-09-12 and 2022-09-21), or aerosol concentrations increased without a recent (in the previous 3 hours) wind speed increase (2022-09-24 and 2022-09-15). These results suggest a poor correlation between wind speed and aerosol concentration and, when tested, the R^2 values were 0.036 and 0.029 at K01 and K02, respectively (Figure S1).

The four days where aerosol concentration increased coincident with wind speed were deemed potential dust emission events sourced from the site surfaces (Figure 5 b,c,d,e). These events on 2022-09-07, 2022-09-13, 2022-09-14 and 2022-09-29 occurred in the early morning, approximately 3 hours after sunrise, where wind speeds were above 6 m s^{-1} for 0, 2, 12 and 66 minutes, respectively, reaching maximum 2-minute wind speeds of 4.19, 6.56, 6.585, 7.414 m s^{-1}. In these events, the winds were mainly from the north (Figure S2) and aerosol concentration remained low, peaking at 0.0636 mg m^{-3} at K01 and 0.072 mg m^{-3} at K02 both on 2022-09-29.

3.3 | Sediment particle-size characteristics

Grain size distribution data for the study site sediments are presented in Table 2. The median D_{50} grain size from all sites was 249 μm, indicating that the sediments were largely sand-sized, as expected for a dune field. Fine-grained sediments (<62.5 μm) were present (mean: 8.7% range: 1.3% to 30.0%) at all the measured interdunes, with the highest proportion (30.0%) at the burned K01 plot. When comparing the control and burned plots, there was no overall coarsening in grain size for the burned plots, and any difference between the pairs of data was not significant ($p > 0.05$) when the data are tested using a Wilcoxon rank-sum test.

3.4 | Patterns of surface cover

Analysis of the ground cover surveys was divided into the initial post-fire period (0–4 months) and the remaining post-fire measurements (6 months onwards). The data presented in Figure 6 show the initial post-burn period in 2022 and the plot measurements made in 2023 when the region was experiencing a drought. Initially, after burning there is a high cover of burned debris. Burned debris cover was 70.4% at plot K01 three days after the fire. This cover then reduces to the lowest cover observed at the burned K02 plot two months after fire with 3.8% of the surface covered. Of the control plots, litter (which mainly consisted of the dead annual grass *Schmidtia kalahariensis*) provided the most surface cover. The older burned plots (6–37 months) measured lower surface cover than the co-located control plots, but cover is again dominated by litter. The lower coverage on burned plots indicates that these plots have difficulty retaining cover under the drought conditions of the measurement period.

3.5 | Biological soil crust presence

Biocrusts are ubiquitous with the Kalahari landscape (Thomas & Dougill, 2007) and were identified at 95% of interdune plots and 100% of burned interdune plots when trenches were dug (Table 3). A total of 65.2% of these crusts were early successional stage crusts with no surface discolouration or micro-topographical changes.

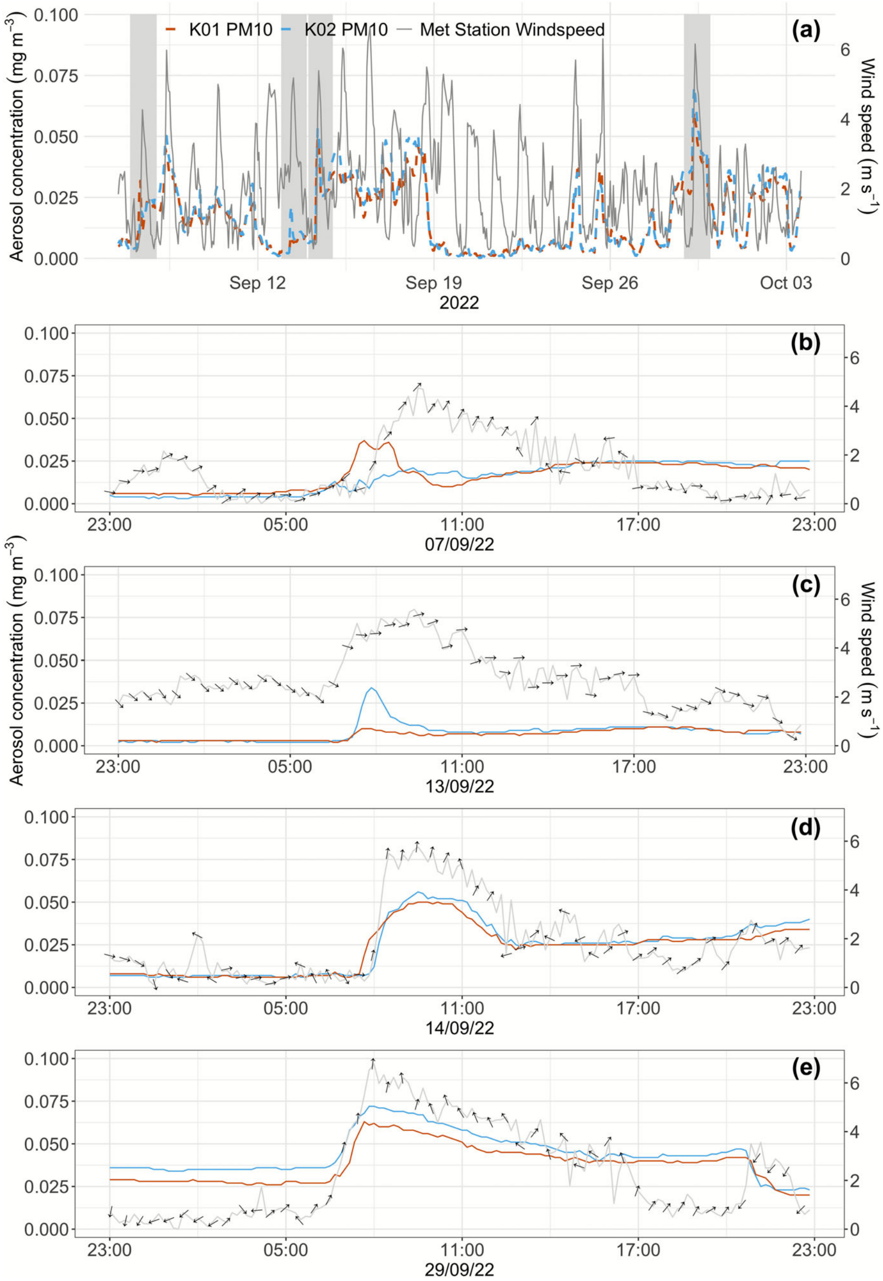

FIGURE 5 A 24-hour time series of measured aerosol concentration (PM_{10}, mg m^{-3}) with measurements from plot K01 in blue and K02 in brown. Panel (A) is throughout the full monitoring period, with the grey background denoting periods of increased aerosol concentration with coincidental increases in wind speed. Details of these events over 24 hr periods are shown in panels (B), (C), (D) and (E), which include ten-minute weighted average wind speed (m s^{-1}) displayed with arrows indicating the 30-minute median direction of wind travel.

4 | DISCUSSION

4.1 | What is the potential for dust emission?

4.1.1 | Resident fine grains in the interdunes

All interdunes sampled contained resident fine material (Table 2) with a maximum of 30% of the grains being below 62.5 μm. Grains under 62.5 μm are a key component of dust and having resident material under this size indicates that if the dunes become de-vegetated fine grains could be susceptible to wind erosion. This release of the fine grains driven by the sand saltation process has been suggested as a likely initial mechanism for dust emission on sand dunes prior to abrasion-produced fine sediment dominating the dust flux (Bullard et al., 2004; Sweeney et al., 2023). An average of 6.87% of sediment being less than 62.5 μm indicates that the system is not supply-limited in terms of dust emission potential.

4.1.2 | Low overall wind speed

Overall, the recorded wind speeds were below the threshold for dust emission compared to other dust-producing regions. In the Taklimakan Desert, Yang et al. (2012) investigated dust emissions from an interdune using a piezoelectric saltation sensor (Sensit) to calculate an average U_t of 7 m s^{-1}. When examining the 2-minute meteorological station wind data recorded in the current study, this threshold was only exceeded in three wind events (2022-09-16, 2022-09-24 and 2022-09-29) and was not sustained for a period longer than 6 minutes. Due to the low wind speeds during the recording period of this study (Figure S4), it is unlikely that dust emissions would have been observed apart from on 2022-09-29. On the 2022-09-29, an increase in aerosol concentration was recorded at the site.

By contextualising the September 2022 meteorological station data with the 24-year record from ERA5-Land data, it is evident that September is not the windiest month of the year. On average,

TABLE 2 Grain size data for samples from the study plots. X ~ delineates the mean.

	% of sample																			
	Clay				Silt				Sand				<10 µm				<62.5 µm			
	x ~	Max.	Min	SD	x ~	Max.	Min.	SD	x ~	Max.	Min.	SD	x ~	Max.	Min.	SD	x ~	Max.	Min.	SD
Burned	0	0.090	0	0.022	5.466	25.254	1.446	6.656	94.534	98.554	74.655	6.674	1.688	8.907	0.155	2.244	6.873	29.965	2.068	7.928
Control	0	0	0	0	5.381	11.928	0.963	2.872	94.619	99.037	88.072	2.872	1.649	3.386	0.062	1.021	6.637	14.722	1.360	3.563

maximum wind speeds are higher in October, November, December and January. In these months, maximum wind gusts frequently exceed 7 m s^{-1}; subsequently, the wind speeds in these months may exceed the threshold for erosion, and dust may be emitted from the interdune locations. However, in interior southern Africa, the wet season begins from approximately November onwards. These strong winds coincide with the wet season when moisture is more likely to inhibit aeolian transport directly through surface wetting or the growth of vegetation.

On the 2022-09-29, there was an increase in aerosol concentration and concurrent increase in wind speed, which remained above 6 m s^{-1} for 66 minutes and peaked at 7.41 m s^{-1} in the 2-minute recordings. During this event, the recorded increase in aerosol concentration peaked at 0.078 mg m^{-3} and remained above background levels for 14 hours. This increase may have been the local mobilisation of dust. However, without further information, it is not possible to confirm if the increase in PM_{10} recorded by the DustTrak was the local emission of the fine material found in the surface sediment, allochthonous aerosol advected across the plot or the local remobilisation of burned debris. The removal of burned debris was recorded at the plot during the DustTrak monitoring period (discussed below; Figure 7). Because of the low correlation between wind speed and aerosol concentration ($R^2 = 0.036$ and 0.029 at K01 and K02, respectively; Figure S1) and lack of confirmed dust events, thresholds for dust emission were not calculated in this study.

4.1.3 | No definitive emissions recorded

A coarsening of the surface grain size between the control and the burned surfaces would be indicative of dust emissions from the burned plots, removing finer components. No statistically significant difference between the co-located surfaces was apparent. In its unburned state, the Kalahari is an availability-limited system, as vegetation and biocrusts prevent sediment from being available for erosion by the wind. When vegetation is removed through burning, the fine sediment identified in this study may become available for aeolian erosion. In this scenario, the system switches from availability-limited to supply-limited as there is no recharge of fine grains in the southwest Kalahari dunes, unlike areas that have fluvial inflows. Thus, dust-sized particles from the dune field would become depleted as the surface is eroded (Bhattachan et al., 2012; Li et al., 2009), resulting in a reduction in fine grains at the burned plots compared to control plots. There was no consistent coarsening in grain size found in the study sites, even in plots which had burned some years prior (e.g., K05, K06 and K08; Table 2). Therefore, it is unlikely that dust has been emitted from the dunes post-fire, even though the vegetation ostensibly limiting such wind erosion has been removed.

The relationship between wind speed and aerosol concentration was not strong (Figure S1). Only four events showed distinct increases in aerosol concentrations with an increase in wind power, which suggests some form of local emission, but whether this is dust or remobilised burned debris is unknown. Within these four events, the relationship between wind speed and aerosol concentration also remained poor with R^2 values of 0.239 at site K01 and 0.571 at site K02 (Figure S3). During the events, PM_{10} concentrations remained below previously defined dust concentration thresholds for emission

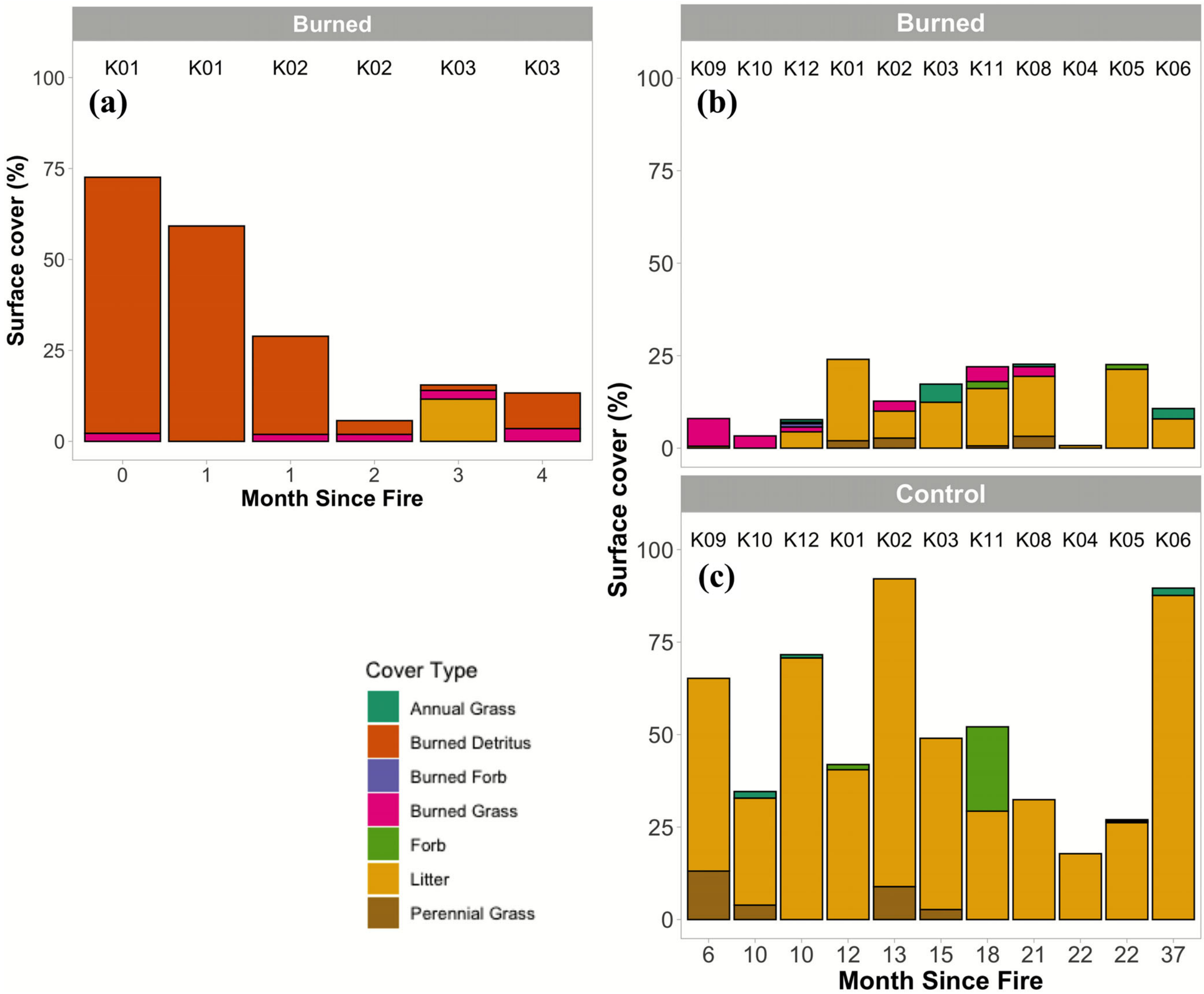

FIGURE 6 Surface cover of burned and control plots: each column represents a specific site for each month, indicated by the labels at the top of the graphs. (A) Displays the immediate post-fire period (0–4 months) where surface cover is dominated by burned material, which is gradually translocated. (B) and (C) are measurements from less recently burned plots measured during a drought in 2023 (6–37 months post-fire). Here, the surface cover is dominated by litter with the burned plots having much less surface cover than the co-located control plots.

TABLE 3 Biocrust presence in the trenches. Biocrust stage is determined using (Dougill & Thomas, 2004).

	Biocrust present in trench (%)	Stage 1 (%)	Stage 2 (%)
Burned	100	73	37
Control	91	82	9

events (Bergametti et al., 2022; Leys et al., 2011; Wang et al., 2008; Wiggs et al., 2022). Furthermore, there were four events (2022-09-24, 2022-09-25, 2022-09-26, 2022-09-15) where 2-minute wind speeds surpassed 7 m s^{-1}, but there were no recorded increases in aerosol concentrations. The breakdown in this relationship between wind speed and aerosol concentration indicates that other factors are limiting the availability of sediment for erosion. The data suggest that this is not because of a lack of fine material available; instead, other factors such as low wind speed, biological soil crusts or surface cover play an important role in suppressing dust emission post-fire in the region.

4.2 | Are there post-fire erodibility controls on emission?

The duration that a surface can emit dust post-fire is inherently linked to the duration of reduced surface cover. Immediately after a fire, there is a high surface cover because of the production of burned debris. This material is then removed (Figure 7), most likely by aeolian activity, until 2 months after fire, when there is low overall surface cover (Figure 6). Therefore, in the immediate post-fire window, emission of dust may be low because of surface cover by burned debris. The immediate post-fire period was the same time in which the meteorological and DustTrak stations were monitoring, and are an explanation for why (a) there were few instances of increased aerosols recorded and (b) we cannot be certain any measured increases in aerosol were driven by local dust emissions rather than local remobilisation of the burned debris. The photographs of the DustTrak station at the burned K01 plot in Figure 7 and satellite imagery of the sites (Figure 8) are evidence that there is remobilisation of this burned material during the immediate post-fire stage.

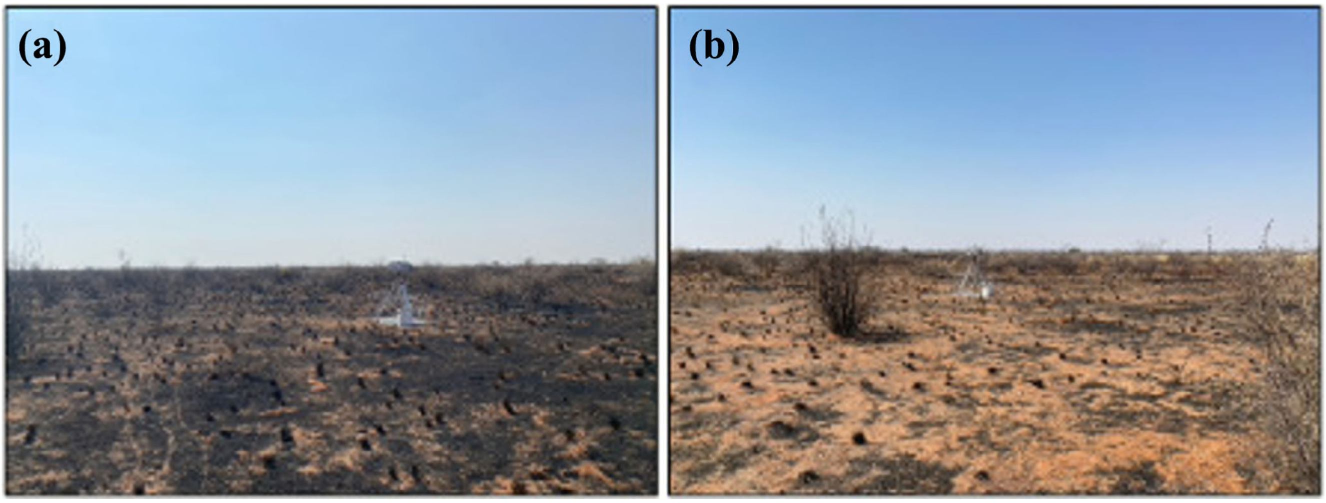

FIGURE 7 Burned plot K01 with the DustTrak (A) three days after burning at the start of the recording period and (B) 32 days after burning before recording ended. In image (A), the surface is largely covered by burned debris and some burned grass stubble. Much of this burned debris had been translocated by the time image B was taken.

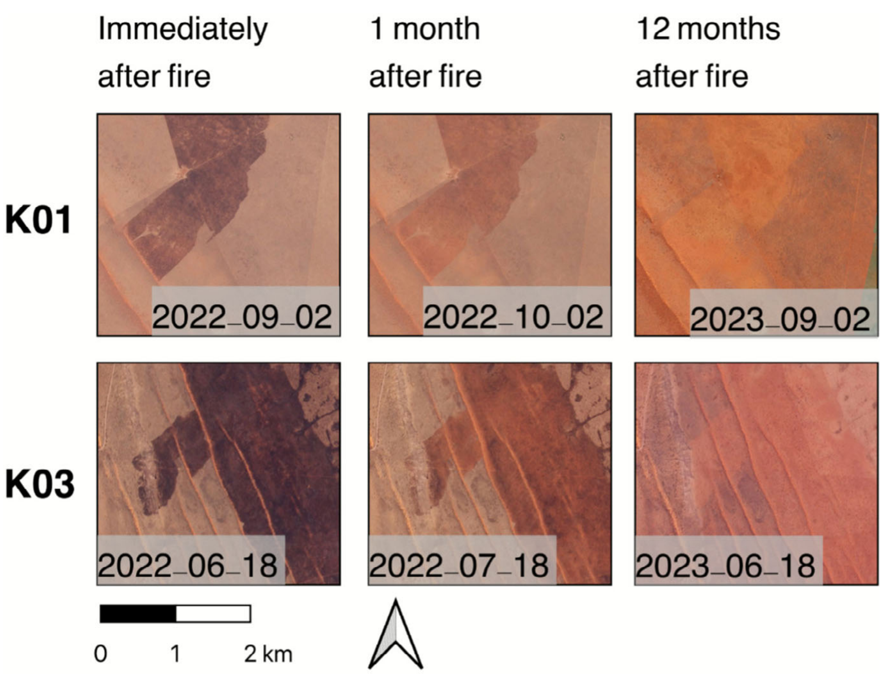

FIGURE 8 Satellite imagery one day, one month and twelve months after fire at sites K01 and K03. The black burned material is blown away within this one-year timeframe. Imagery 2023 planet labs PBC (Planet, 2023).

Once the burned material has been eroded, the period in which the resident fine sediment is likely to be emitted as dust is linked to the vegetation regrowth. The rate of vegetation recovery is controlled by larger climate cycles, which provide moisture to the region (Smit et al., 2024). The ground cover measurements made in 2023 under drought conditions show that the burned surfaces are less resilient to drought conditions than unburned surfaces (Figure 6B), with burned plots remaining under 25% surface cover (Figure 6C) during the drought – regardless of time since fire. There have been very few studies into the response of dune systems to fire and how long the de-vegetated states persist, particularly in relation to surface cover levels below which aeolian erosion can occur. Previous work in the southwest Kalahari by Wiggs et al. (1994) found that increased sand activity occurred for five years post-burn. In the Great Victoria Desert dune system in Australia, Levin et al. (2012) found that effective vegetation cover returns within one to five years post-fire, whilst full recovery occurs within 25–30 years. Further, in the Simpson Desert in Australia, dust emission was observed from fire scars 27 months after burning (Bullard et al., 2008; McGowan & Clark, 2008). Bullard et al. (2008) attributed the combination of fire and drought to the causation of the dust events. Drought-induced vegetation reduction has been linked to dust emissions from sandy soils in southern Africa (Eckardt et al., 2020).

The impact of surface roughness on surface erodibility was not accounted for in this investigation. Vegetation is frequently not fully incinerated at the study sites, leaving behind stubble at the surface that acts as a form of surface roughness. Sub-daily changes in burned vegetation structure as vegetation regrows result in dynamic levels of roughness at the burned sites, which are difficult to parameterise. Future work should investigate how the burned stubble impacts the aerodynamic roughness, potentially using techniques such as Terrestrial Laser Scanning.

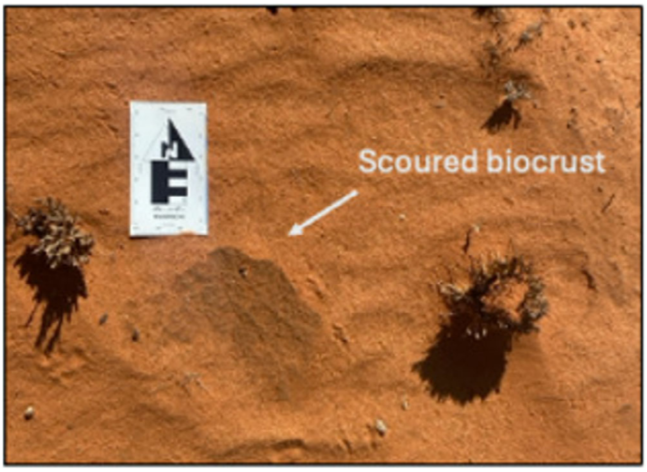

FIGURE 9 Evidence of scouring of biological soil crust at the burned K09 plot.

During the post-fire low-surface cover period, biological soil crusts likely play a large role in limiting dust emissions. Our data show that biocrusts were found in all of the burned interdune plots (Table 3), which demonstrates the ability of biocrusts to survive fire and afford protection to the surface. The post-fire presence of biocrusts means that even though cover provided by grasses and shrubs is limited, the fine sediment in the soil composition is still not available to be eroded as it is bound together in biological soil crusts. Previous studies have found that even at low coverage, biocrusts can reduce wind erosion in sandy deserts (Belnap & Gillette, 1997, 1998; Zhang et al., 2006, 2008). For example, in the Gurbantunggut Desert in China, Zhang et al. (2006) found a reduction in wind erosion with as little as 20% biocrust surface cover. As biocrusts are present in the Kalahari, it is likely that the crust is also reducing the emission of dust. Globally, there is no consensus on the fate of biocrusts after fire (Palmer et al., 2020), with recorded increases in cover post-fire in the Columbia Basin (Dettweiler-Robinson et al., 2013) and Oregon (Bowker et al., 2004), and decreases in cover in Utah (Evangelista et al., 2004) and Australia (Strong et al., 2010). The data presented in this study show that in the Kalahari, biocrusts are withstanding burning and continue to provide protection to the surface.

In the Kalahari, it has been observed that, post grazing disturbance, biocrusts possess a relatively quick recovery rate. Thomas & Dougill (2007) recorded biocrust recovery from 0% to up to 99% cover over a period of 15 months. Data from the current study suggest that biocrusts survive fire, but mortality may increase should a fire be followed by intense drought or higher grazing pressure. The increased mortality of biocrusts was observed at the burned K09 plot, which was measured 6 months after burning. At the plot, there was evidence of scoured biocrusts (Figure 9) which indicated that the biocrust provided a high degree of surface protection immediately after the fire, but, with the slow recovery rate of vegetation due to drought conditions, the biocrust began to deteriorate from sand abrasion.

Surface moisture is a further factor that can impact the erodibility of the surface and was not measured during this study. Soil hydrophobicity has been linked to increased rates of soil erosion in other non-dune desert landscapes after fire (Ravi et al., 2012; Ravi, D'Odorico, Zobeck, & Over, 2009). Soil hydrophobicity was not evident on any surface in this investigation, with rapid water infiltration being recorded at all sites. The lack of evidence for soil hydrophobicity indicates that the organic compounds in the grasses are not volatilised when burnt and are not transported into the soil. The lack of post-fire soil hydrophobicity is also evidence that the fires in the region burn cool and do not transfer much heat into the ground (Lentile et al., 2006). This offers an explanation as to why the biocrusts are not killed by burning in the southwest Kalahari dune system.

The abundance of resident fine-grains in the dunes offers the opportunity for dust emissions to occur when the surface is devegetated. However, the importance of wind speed and biological soil crusts in controlling actual emissions should not be overlooked. The Kalahari is predicted to get hotter and drier through the 21st century, accompanied by changing patterns in precipitation (Attwood et al., 2024; Dunning et al., 2018; Engelbrecht et al., 2015). These changes may lead to conditions that result in reduced vegetation and biocrust cover (Lawal et al., 2019; Rodríguez-Caballero et al., 2022), which potentially increases the potential for dust emission. However, climate models do not predict future increases in wind speed (Ashkenazy et al., 2012; Fant et al., 2016; IPCC, 2023), so that it may be posited that dust emissions would be limited to rare above-threshold wind events when the resident fines would quickly be exhausted.

5 | CONCLUSIONS

This study aimed to examine the post-fire environment of burned interdunes in the southwest Kalahari, and focused on two research questions examining the potential of the interdune surfaces to produce dust (RQ1) and determining the controls on dust emission post-fire (RQ2). The findings from this research suggest that there is little emission of dust, despite the lack of vegetation after burning, the significant proportion of fine grains available for erosion and occasional above-threshold wind events.

In relation to RQ1, the results show that the Kalahari does have fine grains present within interdunes, with up to a maximum of 30.0% of sediment recorded as finer than 62.5 µm. Yet, crucially, there was no statistical difference between burned and control (unburned) plots, indicating no loss of the resident fines in the form of emissions. Overall, the wind speeds recorded in this study are low and largely below threshold when compared to other dusty regions of the world. However, there were four events where there were concurrent increases in wind speed and aerosol concentration. But these events had low concentrations of aerosols, meaning that there may be other factors controlling emissions in the southwest Kalahari. The reduction in burned debris 2 months after the fire indicates that the measured increases in aerosols recorded cannot be explicitly linked to the emission of mineral dust. Instead, we suggest they could be the local remobilisation of burned material.

In relation to RQ2, high burned debris cover (>50%) was found after fire, limiting the erodibility of the surface. Biocrusts were recorded at 100% of burned interdune plots, affording protection to the surface for the roughly 10-month duration of the reduced vegetation period post-fire. Subsequently, sediment is not available to be eroded by the wind after fire, and this explains why post-fire emissions are very rarely observed from the landscape. However, evidence has shown that biocrusts are vulnerable to climate and land use change (Rodríguez-Caballero et al., 2022) and should the biocrusts die-back because of changing environmental conditions, the fine grains found in the interdunes may become available for erosion in periods of high wind velocity. Future work should quantify the role of biocrusts in preventing dust emissions in the Kalahari dune field under varying environmental conditions (i.e., drought, post-fire and high grazing pressures).

AUTHOR CONTRIBUTIONS

Rosemary Huck: Writing—original draft, Writing—review and editing, Conceptualisation, Formal Analysis, Investigation, Methodology, Visualisation. **David Thomas:** Writing—review and editing, Conceptualisation, Methodology, Supervision. **Giles Wiggs:** Writing—review and editing, Conceptualisation, Methodology, Supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The ground cover survey, grain size distribution, ground wind speed and aerosol concentration data have been placed on an open-access repository and can be found at the following DOI: 10.5281/zenodo.15463851. ERA5-Land data can be downloaded from Copernicus (https://cds.climate.copernicus.eu/; accessed on 19 May 2025).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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