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Oil and gas development influences potential for dust emission from the Upper Colorado River Basin, USA

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Abstract

Wind erosion and dust emission from drylands have large consequences for ecosystem function and human health. Wind erosion is naturally reduced by soil crusting and sheltering by non-erodible roughness elements such as plants. Land uses that reduce surface roughness and disturb the soil surface can dramatically increase dust emission. Extraction of oil and gas is a common and growing land use in the western United States (US) that removes vegetation and other roughness elements for construction of well pads and unpaved access roads, resulting in thousands of small (1–4 ha), discrete patches of unprotected soil. Here, we use a satellite albedo-based model to assess the effect of oil/gas activity on surface roughness in the Uinta-Piceance Basin, an area of the Upper Colorado River Basin (UCRB) with dense oil and natural gas development and modelled how the change in surface roughness could impact aeolian sediment flux and dust emission. We also investigated how regional drought influences the response of surface roughness to well pads and access roads. Oil/gas activity reduced surface roughness and increased modelled aeolian sediment flux at the landscape scale across much of the study region, resulting in a modest increase of 10 139 kg of dust per year, which is small relative to dust loads from a single regional dust event observed in the region, but downwind impact could be significant. The magnitude of surface roughness reductions by oil/gas activity was generally consistent among land cover types. However, in parts of the basin that had high cover of annual forbs and grasses, oil/gas activity was associated with larger surface roughness and smaller potential dust emission. Drought decreased surface roughness across disturbed and undisturbed sites, but there was no interactive effect of oil/gas activity and drought on surface roughness. These results suggest that oil/gas activity may increase sediment fluxes and likely contributes to dust emission from landscapes in the UCRB. Understanding how drought and land use change contribute to dust emissions will benefit mitigation of undesirable impacts of wind erosion and dust transport.

KEYWORDS
aeolian modelling, drought, dust emission, land cover change, oil and gas, wind erosion

1 | INTRODUCTION

Wind erosion occurs naturally in global drylands (Field et al., 2010). Wind erosion processes (e.g., sediment flux and dust emission) can be intensified by land surface cover changes due to anthropogenic land uses, leading to cumulative effects on climate, ecosystems and human well-being (Webb & Pierre, 2018). While some global studies have estimated that anthropogenic dust contributions are small compared with climate-driven dust (<10%; Tegen et al., 2004), anthropogenic dust emission may significantly exceed climate-driven dust activity at local and regional scales, particularly in drylands where soil moisture is limited and vegetation recovery following disturbance can be slow (Copeland et al., 2019). Most studies of anthropogenic dust emission—defined here as dust emitted as a direct result of human-caused surface disturbance (Webb & Pierre, 2018)—have focused on grazing (e.g., Neff et al., 2008) or cropland expansion (e.g., Xi & Sokolik, 2016). However, other extensive surface-disturbing activities outside of grazing, such as energy development, may also significantly contribute to regional dust emission (Duniway et al., 2019), but this has not yet been quantified at landscape or regional scales.

Increased regional dust can contribute to reduced air quality and respiratory health in local communities (Achakulwisut et al., 2019; Achakulwisut, Mickley, & Anenberg, 2018), threaten highway safety by reducing visibility (Ashley et al., 2015; Tozer & Leys, 2013), and can and impact ecosystem productivity and function (Brahney et al., 2014, 2015) as well as ecosystem hydrology (Deems et al., 2013). For example, dust deposited on mountain snowpack can drive ecohydrological change through radiative forcing and accelerated snowmelt (e.g., Painter et al., 2010; Réveillet et al., 2022; Skiles et al., 2012). Subsequent changes in annual flow patterns of snow-fed streams can have serious implications for people living within the watersheds that depend on snowmelt (CRS, 2021; Siirila-Woodburn et al., 2021; Usha, Nair, & Babu, 2022). Atmospheric dust concentrations have increased across parts of the western United States (US) in recent decades (Hand et al., 2016). While some studies have tied US dryland dust emissions to increased aridity and changing wind speed due to climate change (Pu & Ginoux, 2017) and recurring patterns of climate variability (Achakulwisut, Shen, & Mickley, 2017; Tong et al., 2017), land cover change due to land use is also understood to be a driver (Nauman et al., 2023). Intensive cattle grazing has been linked to increases in dust emission from the region (Neff et al., 2008), but growth of urban development, recreation and energy development since the mid-20th century have compounded land cover changes in the Upper Colorado River Basin (UCRB; Copeland et al., 2017) and may also drive dust emissions.

One anthropogenic land use with potential to impact dust emission is extraction of oil and natural gas (hereafter oil/gas activity). This land use creates numerous discrete, small-scale (1–4 ha) and abrupt ecosystem changes in the form of well pads and unpaved access roads (Villarreal et al., 2023). Oil/gas activity has substantially increased in parts of the US interior since the year 2000 (Allred et al., 2015; Copeland et al., 2017), and there are now over 117 000 developed wells within the UCRB (Villarreal et al., 2023). Oil/gas activity is expected to continue in the UCRB in the foreseeable future due to large untapped mineral resources in the region (USGS, 2003; Whidden et al., 2012; USGS, 2016), which will require further development of well pads and access roads to support drilling equipment (Di Stéfano et al., 2021).

Well pads in western US drilling fields are constructed by clearing and levelling the site surface, which removes non-erodible surface elements (e.g., vegetation; Di Stéfano et al., 2021) that play a key role in attenuating wind erosivity (Okin, 2008; Raupach, Gillette, & Leys, 1993). Non-erodible surface elements (hereafter 'surface roughness') protect the surface from wind erosion by extracting momentum from wind and by physically protecting a portion of the surface, such that the wind friction velocity acting on the exposed soil surface (u_{S*}) is reduced (Raupach, Gillette, & Leys, 1993; Webb, Okin, & Brown, 2014). In the absence of surface roughness, the total wind friction velocity (u_*) acts on the soil surface (such that $u_* = u_{S*}$), which increases the likelihood that u_{S*} will exceed the threshold (u_{*t}) required for sediment entrainment (Okin, Gillette, & Herrick, 2006; Webb, Okin, & Brown, 2014). Thus, land clearing for drilling activities may increase wind erosion from the landscape (e.g., Duniway et al., 2019).

Previous studies suggest that drilling fields may be sources of dust. In the Bakken well field of the northern Great Plains, US, Gebhart et al. (2018) detected large concentrations of fine dust and coarse mass aerosols measured at air quality monitoring sites downwind of recently drilled oil and gas wells. In the same region, Creuzer et al. (2016) measured large increases in dust loading in areas with recent oil/gas development, particularly around gravel roads used to access well pads. Another recent study of dust in the Great Plains detected an increase in coarse-mode aerosol optical depth in western Oklahoma, US from 2008 to 2018, which coincided with a period of growth of oil/gas development in that area (Lambert et al., 2020). Brahney et al. (2015) found that trends in total suspended particles calculated for oil/gas activity in the Pinedale Anticline of southwestern Wyoming, US agreed with dust deposition in downwind alpine lake sediments. While these studies suggest that energy development can accelerate dust emission, there is great opportunity to investigate cumulative impacts of oil/gas activity on dust emission through the lens of land surface change through removal of surface roughness, a first-order physical control on wind erosion and dust emission.

In the UCRB, land uses like oil/gas activity may interact with the current megadrought that began at the turn of the 21st century (Williams, Cook, & Smerdon, 2022) to influence surface roughness and dust emission in unpredictable ways. Drought conditions are expected to persist in the region for the remainder of the century (Cook, Ault, & Smerdon, 2015) and are expected to drive reductions in surface roughness as herbaceous cover declines and is replaced by bare ground (Edwards et al., 2019; Li et al., 2007; Munson, Belnap, & Okin, 2011). If drought conditions reduce surface roughness across a landscape developed for energy extraction, the difference in roughness between well pads and rangeland may be reduced, and during a wet year, the difference may increase. Such context is important for understanding the relative effect of oil/gas activity on potential wind erosion and dust emission.

In this study, we aimed to characterize how numerous, small-scale and discreet land surface changes created by oil/gas activity modify a first-order control on wind erosion and quantify the contribution of this land use type to dust emissions from drylands. Our study objectives were to (1) determine if there is a cumulative response of surface roughness to oil/gas activity, (2) evaluate whether the surface roughness modifications of oil/gas activity have a significant effect on simulated aeolian sediment flux and dust emission and (3) determine how chronic regional drought attenuates the surface roughness response to oil/gas activity. We expect that vegetation removal and recontouring of land for oil/gas extraction will result in a cumulative decrease of surface roughness, which will, in turn, increase the potential for wind erosion and dust emission. We also expect that the effect of oil/gas activity on surface roughness will be offset during drought periods because of regional-scale reductions in roughness during drought periods.

2 | METHODS

To assess the effect of oil/gas activity on landscape-scale surface roughness, we modelled surface wind friction velocity scaled by 10-m wind speeds from MODIS land surface albedo (Moderate Resolution Imaging Spectroradiometer product MCD43A3, version 6.1; Schaaf & Wang, 2021) and compared this metric between 500-m MODIS pixels with and without oil and gas infrastructure. We then modelled aeolian sediment flux from the scaled surface wind friction velocity for a range of environmental conditions. Data generated during this study are published and available (Tyree et al., 2024).

2.1 | Study area

Our study focused on the Uinta-Piceance Basin (hereafter 'UP'), located on the northern Colorado Plateau in the UCRB (Figure 1). The UP is a sedimentary basin that is particularly rich in oil and natural gas resources with five major total petroleum systems spanning the Uinta Basin and Wasatch Plateau in northeastern Utah and the Piceance Basin in western Colorado ([USGS] United States Geological Survey, 2003). This basin has experienced a sharp increase in oil/gas drilling activity since 2000 (Figure 1), and further extraction is expected for the foreseeable future ([USGS] United States Geological Survey, 2003). The UP has a cold desert climate characterized by low and variable precipitation (mean annual precipitation 13 to 46 cm; Woods et al., 2001), warm summers (mean maximum temperatures 29–38°C; Woods et al., 2001) and cold winters (mean minimum temperatures −18°C to −9°C; Woods et al., 2001). Wind speeds follow a seasonal pattern with the highest daily averages and maxima occurring in the spring (March–May), with a southwesterly prevailing wind direction. Soils within the basin are highly heterogenous but are dominated by loamy, finer-textured and saline soils in the basin floor and rockier, shallower soils at higher elevations (Nauman et al., 2022).

2.2 | Time series of oil/gas activity

A map of active well pad footprints and access roads developed by the U.S. Geological Survey (USGS; Villarreal et al., 2023) was used to represent oil/gas activity across the study region from 2001 to 2016. Details of the map development process can be found in Villarreal et al. (2023). Additionally, we retrieved point data of wells that were plugged and abandoned (no longer active) from state databases for Colorado and Utah (COECMC, 2020; UTOGM, 2020) to exclude past as well as concurrent oil/gas activity from control sites (process outlined below in Section 2.4).

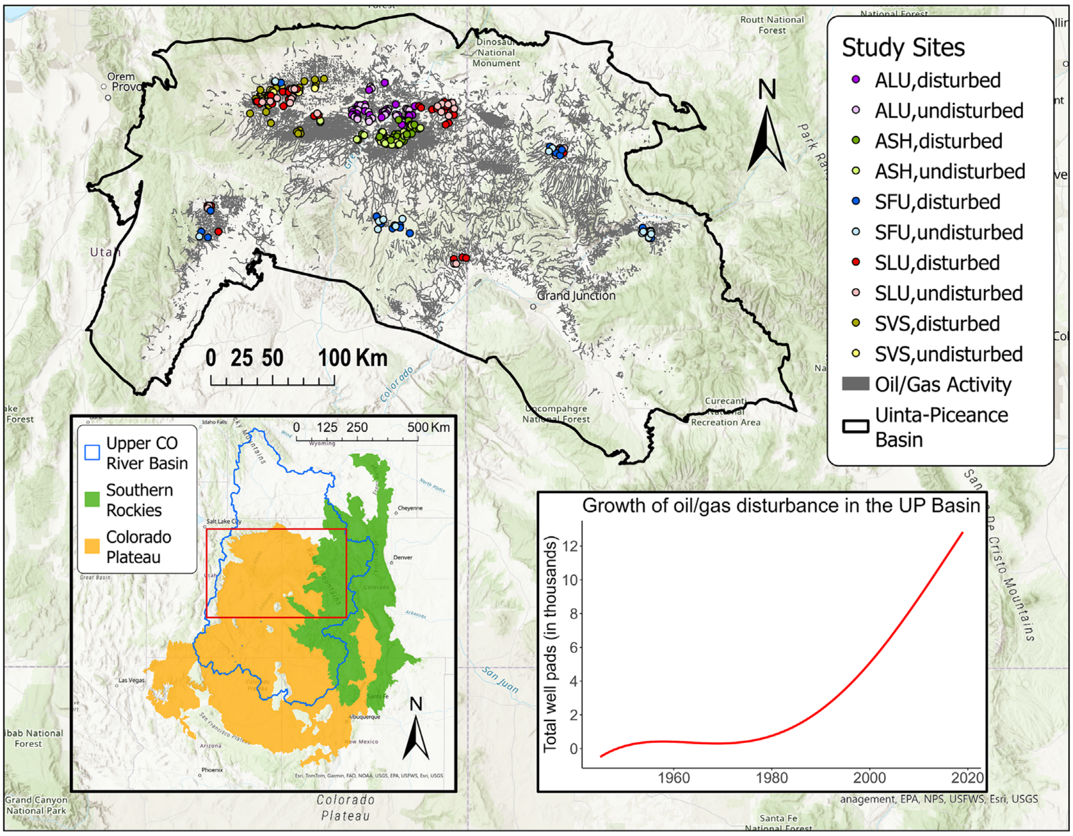

FIGURE 1 The Uinta-Piceance Basin (red box of inset map) with study sites, mapped well pads and access roads (Villarreal et al., 2023) and time series of oil/gas activity (inset graph). ALU = Arid Loamy Uplands, ASH = Arid Saline Hills, SFU = Semiarid Finer Uplands, SLU = Semiarid Loamy Uplands and SVS = Semiarid Very Shallow. MODIS pixels (500 m) designated as 'disturbed' contain at least one active well pad and associated access roads, whereas those designated 'undisturbed' contain no well pads (active or abandoned) and no access roads. Ecoregions and boundary of the Upper Colorado River Basin in the inset map are from Omernik & Griffith (2014) and Steeves & Nebert (1994), respectively.

2.3 | Controlling for variation in surface roughness with edaphic, topographic and climatic data

To control for variation of surface roughness due to soil, topographic and climatic variability, we stratified the study region by climate zones and soil-geomorphic units that capture key ecological boundaries between vegetation communities in the UCRB (Nauman et al., 2022). We rescaled the 30-m climate zone and soil-geomorphic unit data (Nauman & Duniway, 2021) to 500 m to match the MODIS albedo data (see Section 2.5 for details) and masked out aggregated pixels that were <90% homogenous. When combined, the aggregated and masked climate zone and soil-geomorphic unit layers produced 21 strata. We overlaid the strata layer with the oil/gas map to identify those that contained enough active well pad disturbance for a robust sample (≥1% of the 500-m aggregated pixels in the stratum contained active well pad disturbance; Table 1). Five strata met this criterion and were used in subsequent analysis: Arid Saline Hills (ASH), Arid Loamy Uplands (ALU), Semiarid Loamy Uplands (SLU), Semiarid Finer Uplands (SFU) and Semiarid Very Shallow (SVS). Table 1 describes soil and vegetation characteristics of the five study strata as well as the extent of oil/gas disturbance in each within the UP. We also masked open water, perennial ice and snow, developed open space, high-intensity development, wetlands, pasture and cropland from the sampling region using the 2019 National Land Cover Database (Dewitz, 2019).

2.4 | Sample design and selection of reference pixels

We identified disturbed and undisturbed sites from each stratum of the study area to compare the effect of oil/gas activity on modelled surface roughness. The 500-m aggregated pixels were considered disturbed if they contained at least 3500 m^2 of active well pad, which is the median area of mapped active well pads in the UP (Villarreal et al., 2023). A minimum distance of 1000 m was set between the sampled pixels. We selected undisturbed pixels based on the following criteria: they had to be from the same stratum, 1000–4000 m from the disturbed pixel, contain no oil/gas disturbance (including plugged and abandoned pads and access roads) and could not be directly adjacent to another identified reference pixel. We visually inspected pixels that met these criteria in Google Earth Pro (Google Earth version 7.3, 2018) to ensure that none included unmapped development and that they were reasonably comparable with undeveloped areas of disturbed pixels in the same stratum.

2.5 | Modelling surface roughness from MODIS black-sky albedo

Surface roughness was modelled by assuming that shadow is proportional to shelter (Raupach, 1992; Raupach, Gillette, & Leys, 1993). With the use of a ray-casting approach, Chappell et al. (2010) showed that shadow of surface roughness is proportional to the wake interference of wind acting on the roughness. Chappell & Webb (2016) calibrated that ray-casting shadow against wind tunnel measurements of wind friction velocity. The ray-casting approximated the directional-hemispherical reflectance (DHR), the integration of reflected light with a directional source across the outgoing hemisphere (Schaepman-Strub et al., 2006). The BSA or DHR is the albedo with direct illumination, in the absence of a diffuse component and is a function of solar zenith angle. The MCD43A3 (v61) Albedo Product (MODIS/Terra Albedo Daily L3 Global 500 m SIN Grid) provides the BSA (at local solar noon) for MODIS bands 1–7 as well as for three broad bands (0.3–0.7, 0.7–5.0 and 0.3–5.0 μm at 500-m daily resolution; Schaaf & Wang, 2021). By taking the inverse of BSA, we obtain shadow (ω). The spectral dependency of that shadow is removed by normalizing it by the isometric parameter of the MODIS Bidirectional Reflectance Distribution Function (f_{iso}). In other words, we remove the spectral reflectance component of surface characteristics unrelated to surface structure that influence albedo, such as soil moisture and colour (Coulson & Reynolds, 1971). The model then rescales ω_n between 0.0001 and 0.1 to match the calibration data from Marshall (1971) to get the normalized scaled shadow (ω_{ns}). This metric has a strong empirical inverse relationship with wind tunnel measurements of surface wind friction velocity u_{S*} scaled by the wind speed at a given height (U_h) (Chappell & Webb, 2016), which is calculated as:

$$\frac{u_{S*}}{U_h} = 0.0306\left(2.7183^{\frac{-\omega_{ns}^{1.1202}}{0.0125}}\right) + 0.0072. \quad (1)$$

The coupled metric $\frac{u_{S*}}{U_h}$ must then be multiplied by a wind speed ($m\,s^{-1}$) to obtain the wind friction velocity acting on the exposed soil surface (u_{S*}), which can then be used to calculate the horizontal sediment flux (Q) for a given threshold friction velocity (u_{*t}) and dust emission (F). Monthly mean $\frac{u_{S*}}{U_h}$ for each year of the study period was used to calculate probability distributions of $\frac{u_{S*}}{U_h}$ for disturbed and undisturbed sites (i.e., pixels) within each stratum.

We ran Chappell & Webb's (2016) model (Gorelick et al., 2017) using data from MODIS Band 1 (red; 620–670 nm). We used band 1 because Chappell et al. (2018) showed that by normalizing by f_{iso} and removing the spectral signature, the structure-dominated signal is comparable across MODIS bands. All MODIS data were filtered using the quality assurance layer supplied for band 1. Pixels contaminated by snow cover were masked prior to modelling using the MODIS MOD10A1 Version 6 Terra Snow Cover Dataset (Hall, Salomonson, & Riggs, 2016).

2.6 | Estimating oil/gas impacts on potential horizontal sediment flux and dust emission

To determine how the effect of oil/gas activity on surface roughness could influence horizontal sediment flux (Q), we modelled Q from $\frac{u_{S*}}{U_h}$ for simulations of environmental conditions using four wind speeds (6, 8, 10 and 12 $m\,s^{-1}$) and five threshold wind friction velocities (u_{*t} set to 0.20, 0.25, 0.30, 0.35 and 0.40 $m\,s^{-1}$). These wind speeds are within the ranges of daily average wind speeds and 2-min daily maximum wind speeds for the UP (Figure S1), and the u_{*t} values are within the range of u_{*t} typical for disturbed sandy to loamy soils in desert environments (Gillette et al., 1980; Marticorena et al., 1997). While this range falls far below u_{*t} typical of many desert soils, particularly those with high content of fines (clay > 10% or clay + silt > 10%), gravel or salts (Gillette et al., 1980), widespread surface disturbance in US rangelands (Schwinning et al., 2008), make it important to

TABLE 1 Descriptions of climate-soil groups used as strata in this study. Listed are distinguishing soil, vegetative and ecological change properties of the selected climate-soil groups. We also list the extent of oil/gas disturbance within each stratum within the Uinta-Piceance Basin (UP). Soil, vegetative and ecological change data summarized from Nauman et al., 2022, tabs. 4, A2 and A3.

Stratum	Soils	Vegetation	Ecological changes	Stratum area in UP (ha)	Percent area disturbed by oil/gas[a]	Oil/gas disturbance (ha)	Number of disturbed sites	Number of undisturbed sites
Arid Saline Hills (ASH)	Saline and sodic soils; loamy to clayey surface textures; high water erodibility	Mixed saltbush scrubland dominated by *Atriplex* spp.; low production and cover; even mix of grasses and shrubs	Water erosion; loss of grasses; woody encroachment; annual invasion with site disturbance	92 550	3.48	3221	33	29
Semiarid Finer Uplands (SFU)	Loamy to fine-loamy surface textures; clay content 20–30%	Savannahs and shrublands dominated by *Artemisia tridentata ssp. Wyomingensis* and perennial grasses; PJ production comparable with SVS	Loss of grasses; annual invasion; woody encroachment; increased bare ground cover; increased erosion risk	84 325	2.49	2100	22	18
Arid Loamy Uplands (ALU) and Semiarid Loamy Uplands (SLU)	Sandy to loamy soils that can have $CaCO_3$; highly susceptible to wind erosion	Grasslands and savannahs; may be dominated by *Artemisia tridentata*	Severe wind erosion with drought and surface disturbance; loss of grasses; annual invasion; woody encroachment	ALU: 25 600 SLU: 83 875	ALU: 14.75 SLU: 4.92	ALU: 3776 SLU: 4127	ALU: 23 SLU: 34	ALU: 27 SLU: 26
Semiarid Very Shallow (SVS)	Soil depths < 30 cm; loamy surface textures; surfaces rocky and rugged	Low total production; mix of trees/tall shrubs (PJ), smaller shrubs and grasses; drought-prone due to shallow soils	Annual invasion; loss of grasses; loss of woody species with drought; bare ground states; water erosion	52 075	1.73	901	26	24

[a]Oil/gas activity is considered as a 25-ha site (500-m pixel) containing at least one active well pad and associated disturbance (e.g., access roads).

understand the relative effect of oil/gas on potential Q within disturbed landscapes.

For each sample site and year, we modelled Q ($g\,m^{-1}\,s^{-1}$) from $\frac{u_{S*}}{U_h}$ for a given wind speed following Chappell and Webb (2016; adapted from Shao, Raupach, & Findlater, 1993):

$$Q = A\left(\frac{\rho_a}{g}\right)\sum_{u_{S*}} u_{S*}\left(u_{S*}^2 - u_{*t}^2\right), \quad (2)$$

in which A is a scaling parameter set to 0.54, ρ_a is the air density at sea level (1225 $g\,m^{-3}$) and g is gravitational acceleration (9.81 $m\,s^{-1}$). We then weighted Q by the probability of a given value of $\frac{u_{S*}}{U_h}$ for grouped disturbed and undisturbed sites and summed the weighted values to get total modelled Q. The magnitude of the effect of oil/gas activity on modelled Q was determined from the ratio of $Q_{Disturbed}$ to $Q_{Undisturbed}$ for each stratum in each year.

To estimate of the potential contribution to dust emission by oil/gas activity, we calculated the dust emission flux (F; $g\,m^{-2}\,s^{-1}$) from the horizontal aeolian sediment flux following Marticorena & Bergametti (1995):

$$F = Q\left(10^{(0.134 * clay\%) - 6}\right), \quad (3)$$

in which $clay\%$ is the percent clay fraction of the soil at the surface. Based on mean soil surface clay content among common soil types within the soil-geomorphic units (Nauman et al., 2022), we estimated the surface soil percent clay fraction to be 15% for ALU, SLU and SVS, which typically have loamy sands to fine sandy loams at the soil surface, and 20% for ASH and SFU, which typically have finer-textured surface soils (Table 1). F was estimated for the total area of each stratum within the UP in the absence of oil/gas activity ($F_{Undisturbed}$ calculated from $Q_{Undisturbed}$ for each unit area) and in the presence of oil/gas activity ($F_{Disturbed}$ scaled by the percent area of each stratum disturbed by well pads and access roads).

To better understand how oil/gas activity might influence aeolian sediment flux over time under real environmental conditions, we also calculated total Q of disturbed and undisturbed sites for a 16-year data set of 10-m daily average wind speeds and daily 5-s maximum wind speeds collected at the Vernal, UT Municipal Airport (40.44002, −109.5355, elevation: 1629.2 m, available from https://www.ncei.noaa.gov/access/search/data-search/global-hourly; Figure S1). The daily data were used for calculating probabilities of wind speeds from March to October from 2001 to 2016. The wind speeds were multiplied with $\frac{u_{S*}}{U_h}$ calculated for the stratified disturbed and undisturbed sites to obtain u_{S*} weighted by the combined probability of the roughness $\left(\frac{u_{S*}}{U_h}\right)$ and the wind speed (U_h), which was used to weight modelled Q. We modelled total Q for a set of u_{*t} (0.20–0.40 $m\,s^{-1}$ for daily average wind speeds and 0.20–3.0 $m\,s^{-1}$ for daily 5-s maximums) to capture how oil/gas activity might affect sediment mass flux across a range of erodibility conditions.

2.7 | Climate data and analysis of drought effects

To understand how drought influences the effect of oil/gas activity on surface roughness during the year of a drought event and in the years following, we compared time series of anomalies (deviations from the 20-year mean) of the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano, Santiago Beguería, & López-Moreno, 2010) and of August mean $\frac{u_{S*}}{U_h}$ using a lag correlation. The SPEI considers both precipitation and potential evapotranspiration when determining drought conditions and thus captures how increasing temperatures affect water demand, making the index particularly useful for understanding drought impacts in drylands (e.g., Barnard et al., 2021; Bunting et al., 2017). Values of 1-year aggregated SPEI from the GridMet CONUS Drought Indices collection (4 km; Abatzoglou, 2013; Gorelick et al., 2017) were correlated with monthly mean $\frac{u_{S*}}{U_h}$ of disturbed and undisturbed pixels of each stratum with lags of 0–8 years. The lag correlations were conducted with mean $\frac{u_{S*}}{U_h}$ and 1-year aggregated SPEI for the month of August to capture the end of the growing season, when drought would have the maximum effect on surface roughness. We also assessed the effect of same-year and lagged-year drought on $\frac{u_{S*}}{U_h}$ using linear regression models.

3 | RESULTS

3.1 | Differences in distributions of $\frac{u_{S*}}{U_h}$ between disturbed and undisturbed sites

We found a large degree of overlap between probability distributions of surface roughness (approximated by $\frac{u_{S*}}{U_h}$) for disturbed and undisturbed sites across all strata (Figure 2). However, results for four of the five groups (ASH, SFU, SLU and SVS; Table 1) indicated that sites disturbed by oil/gas activity often had smaller surface roughness (i.e., large $\frac{u_{S*}}{U_h}$) than undisturbed sites. Among ALU sites, we found a greater probability of smaller surface roughness among undisturbed sites relative to disturbed sites. The difference in the probability of smoother conditions was most pronounced among ASH sites and subtler among SFU, SLU and SVS sites.

3.2 | Influence of oil/gas disturbance on potential aeolian horizontal sediment flux and dust emission

For most simulations, modelled aeolian sediment fluxes (Q) for disturbed sites were larger than modelled Q for undisturbed sites under the same wind and entrainment conditions (Figures 3, S2 and S13). Differences in Q for disturbed and undisturbed sites $\left(\frac{Q_{Disturbed}}{Q_{Undisturbed}}\right)$ generally increased as the entrainment threshold (u_{*t}) increased, though this pattern was strongest among ASH sites. Disturbed ALU sites had smaller modelled Q than undisturbed sites in most years, following the distribution results for $\frac{u_{S*}}{U_h}$ (Figure 3). SVS sites also showed smaller modelled Q at disturbed than at undisturbed sites, though the effect was subtler than that observed for ALU sites.

Generally, differences in modelled Q between disturbed and undisturbed sites were largest when wind speed and roughness produced a surface wind friction velocity (u_{S*}) close to u_{*t}. Differences in modelled Q decreased for simulations in which u_{S*} far exceeded u_{*t} (Figure S2). For example, at an 8 $m\,s^{-1}$ wind speed and u_{*t} = 0.20 $m\,s^{-1}$, modelled Q of disturbed SFU sites was larger than for undisturbed SFU sites, but as wind speed (U_h) increased relative to u_{*t}, the difference in modelled Q declined such that the ratio approached 1 (Figure S3). This result indicates that oil/gas activity

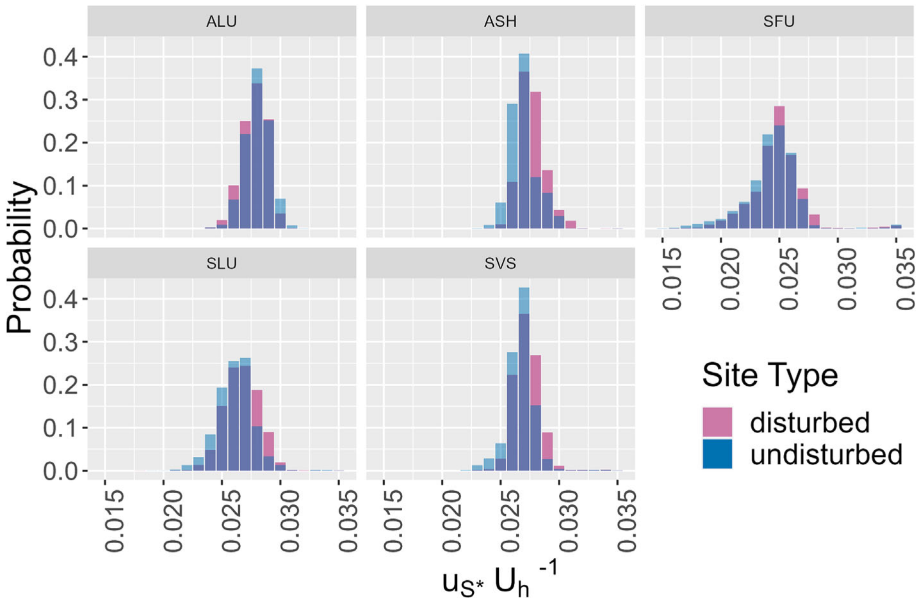

FIGURE 2 Probability distributions of approximated surface roughness $\left(\frac{u_{S*}}{U_h}\right)$ of disturbed and undisturbed sites by climate-soil stratum (Table 1) for the 16-year period (larger values indicate smaller surface roughness, i.e., larger continuous bare soil cover and less vegetation structure). Light blue bars represent $\frac{u_{S*}}{U_h}$ of only undisturbed sites, and dark blue bars represent overlapping $\frac{u_{S*}}{U_h}$ of both disturbed and undisturbed sites.

could have the largest effect on aeolian sediment flux during low-intensity wind events, which occur with much larger frequency than high-intensity wind events. ALU showed little change in $\frac{Q_{Disturbed}}{Q_{Undisturbed}}$ across u_{S*} produced from different wind speeds and roughness as well as across u_{*t}.

For most cases in which $Q_{Disturbed}$ was much larger than $Q_{Undisturbed}$, modelled total Q for disturbed sites was very small (<1.5 g m^{-1} s^{-1}; Figure 3). That is, when well pads and access roads had the largest impact on modelled aeolian sediment flux (Q), modelled aeolian sediment flux for both disturbed and undisturbed sites was minimal. Conversely, for simulations in which absolute modelled aeolian sediment flux for disturbed sites was large (>10 g m^{-1} s^{-1}), there were much smaller differences in modelled aeolian sediment flux between disturbed and undisturbed sites (median $\frac{Q_{Disturbed}}{Q_{Undisturbed}} < 2$ across strata; Figures 3 and S3). For example, among ASH sites when $U_h = 12$ m s^{-1} and $u_{*t} = 0.20$ m s^{-1}, median $Q_{Disturbed}$ was 29.00 g m^{-1} s^{-1}, but $Q_{Disturbed}$ was only 19% larger than $Q_{Undisturbed}$. When $U_h = 12$ m s^{-1} and $u_{*t} = 0.35$ m s^{-1}, Q of disturbed ASH sites was 133% larger than Q of undisturbed ASH sites, but median $Q_{Disturbed}$ was only 0.04 g m^{-1} s^{-1}.

For Q modelled from a 16-year data set of daily average and maximum wind speeds collected at the Vernal, UT airport, aeolian sediment fluxes of disturbed sites consistently exceeded that from undisturbed sites across all strata except for ALU (Figure 4). In most cases, the effect of oil/gas activity increased as the entrainment threshold increased; however, change in $\frac{Q_{Disturbed}}{Q_{Undisturbed}}$ with increasing u_{*t} was often nonlinear, particularly among ASH and SVS sites under average wind speeds (Figure 4). These results suggest that, across a range of real-world wind speeds and entrainment thresholds, most landscapes in the UCRB disturbed by oil/gas activity can be expected to produce larger aeolian sediment fluxes than most undisturbed landscapes.

Our calculations of vertical sediment flux (dust emission) from Q showed that for an entrainment threshold of 0.20 m s^{-1}, the total stratified area of the UP (338 425 ha or 3384.25 km^2), oil/gas activity increased dust emission by 1.30 kg day^{-1} for a 12 m s^{-1} wind event (Table 2). This small increase is due to the offset of a high-emission zone (ASH sites, which contribute 24.38 kg/day) with a negative-emission zone (ALU sites, in which oil/gas activity reduced modelled emissions by 24.35 kg day^{-1}; Table 2). Additionally, small amounts of modelled dust emission from SFU and SLU sites (1.30 and 2.10 kg day^{-1}, respectively) were offset by a dust emission reduction of 2.12 kg day^{-1} from SVS sites (Table 2). As a percentage of total F in the absence of oil/gas activity, the greatest magnitude of change occurred among ALU sites (−9.98%) followed by ASH sites (+0.65%), and the smallest change occurred among SFU sites (+0.10%).

3.3 | Influence of drought on regional surface roughness and effects of oil/gas disturbance

Lag correlation between 1-year aggregations of the SPEI and anomalies (deviations from the 20-year normal) of August mean $\frac{u_{S*}}{U_h}$ showed a significant negative association between SPEI and $\frac{u_{S*}}{U_h}$ late in the growing season among ASH, SFU and SLU sites (Figure 5). That is, drought conditions (SPEI < 0) were correlated with reduced surface roughness (large $\frac{u_{S*}}{U_h}$) in August during the first year of drought among sites in these strata. There was no significant association between SPEI and $\frac{u_{S*}}{U_h}$ among SVS sites. We also did not see a significant association between drought and surface roughness in the years following a drought event. When the relationship between surface roughness and drought years was assessed with linear models, we found a slightly stronger response of surface roughness to same-year drought among sites without oil/gas activity but only in SFU and SLU (Tables S1 and S2). There was no difference in surface roughness response to drought between disturbed and undisturbed sites in ASH (Table S3).

4 | DISCUSSION

We found that oil/gas activity was associated with reduced surface roughness across much of the study region. For the ASH, SFU, SLU and SVS stratum (Table 1), sites where well pads, and access roads that were present generally had smaller surface roughness than undisturbed sites, resulting in greater modelled dust emissions for oil/gas developments in these climate and soil-geomorphic settings. This result indicates that oil/gas activity can reduce surface roughness and impact dust emissions at the landscape scale. However, we also

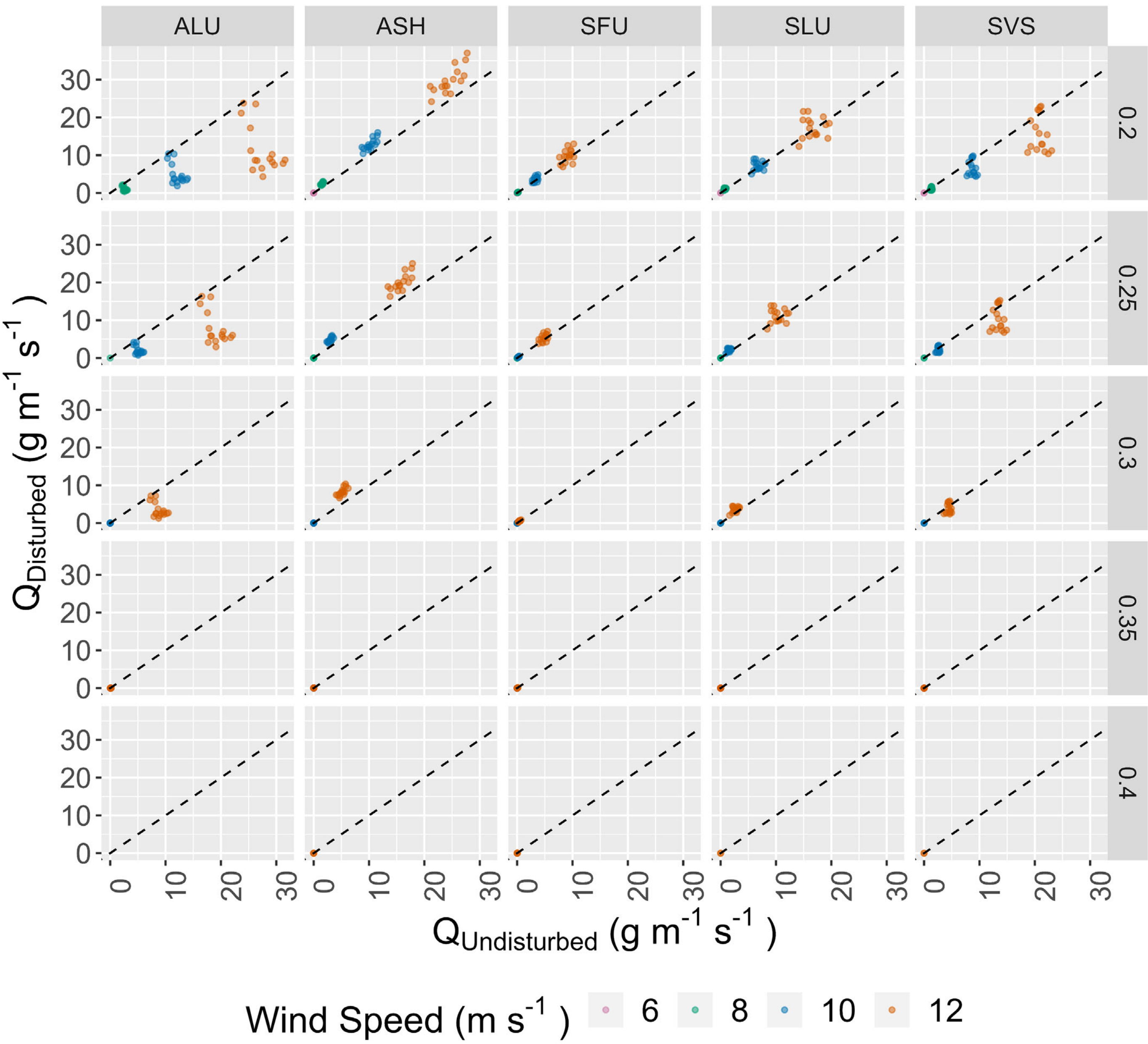

FIGURE 3 Comparison of modelled annual total sediment mass flux (Q) for disturbed and undisturbed sites from simulations using five wind speeds (U_h = 4, 6, 8, 10 and 12 m s^{-1}) and five entrainment thresholds (u_{*t} = 0.20, 0.25, 0.30, 0.35 and 0.40 m s^{-1}). ALU = Arid Loamy Uplands, ASH = Arid Saline Hills, SFU = Semiarid Finer Uplands, SLU = Semiarid Loamy Uplands and SVS = Semiarid Very Shallow (Table 1). The dashed line represents a ratio of 1:1 between $Q_{Disturbed}$ and $Q_{Undisturbed}$.

found that the effect of oil/gas development on roughness and emissions was not consistent across all land cover types in the UP Basin, with sites in the ALU that showed a 'roughening' response to oil/gas activity. In other words, disturbed sites were likely to have larger roughness than undisturbed sites, which resulted in suppression of modelled sediment fluxes. This was likely driven by ecological responses to oil/gas activity that occurred during a wetter-than-average period.

4.1 | Influence of oil/gas activity on surface roughness

These results support our hypothesis that the cumulative impact of the removal of vegetation and other non-erodible surface elements for networks of relatively small and discrete disturbances can be sufficient to reduce surface roughness at the scale of MODIS pixels (500 m). We observed a similar effect of oil/gas activity across a variety of ecosystem types, from sparsely vegetated saltbush scrublands (ASH) to grassy shrublands with nearly 50% total foliar cover (SFU). Reductions of surface roughness associated with oil/gas activity among ASH sites were somewhat stronger than those observed among SFU, SLU and SVS sites. In the case of SFU and SLU sites, this seems counterintuitive as both of these semiarid soil-geomorphic settings typically have larger 'background' surface roughness than ASH sites (Nauman et al., 2022; Table S4). The large effect of oil/gas on surface roughness among ASH sites may be due to the particularly high density of well pads at many disturbed sites in this stratum. There was also a large degree of overlap in surface roughness between disturbed and undisturbed sites in SVS, which resulted in

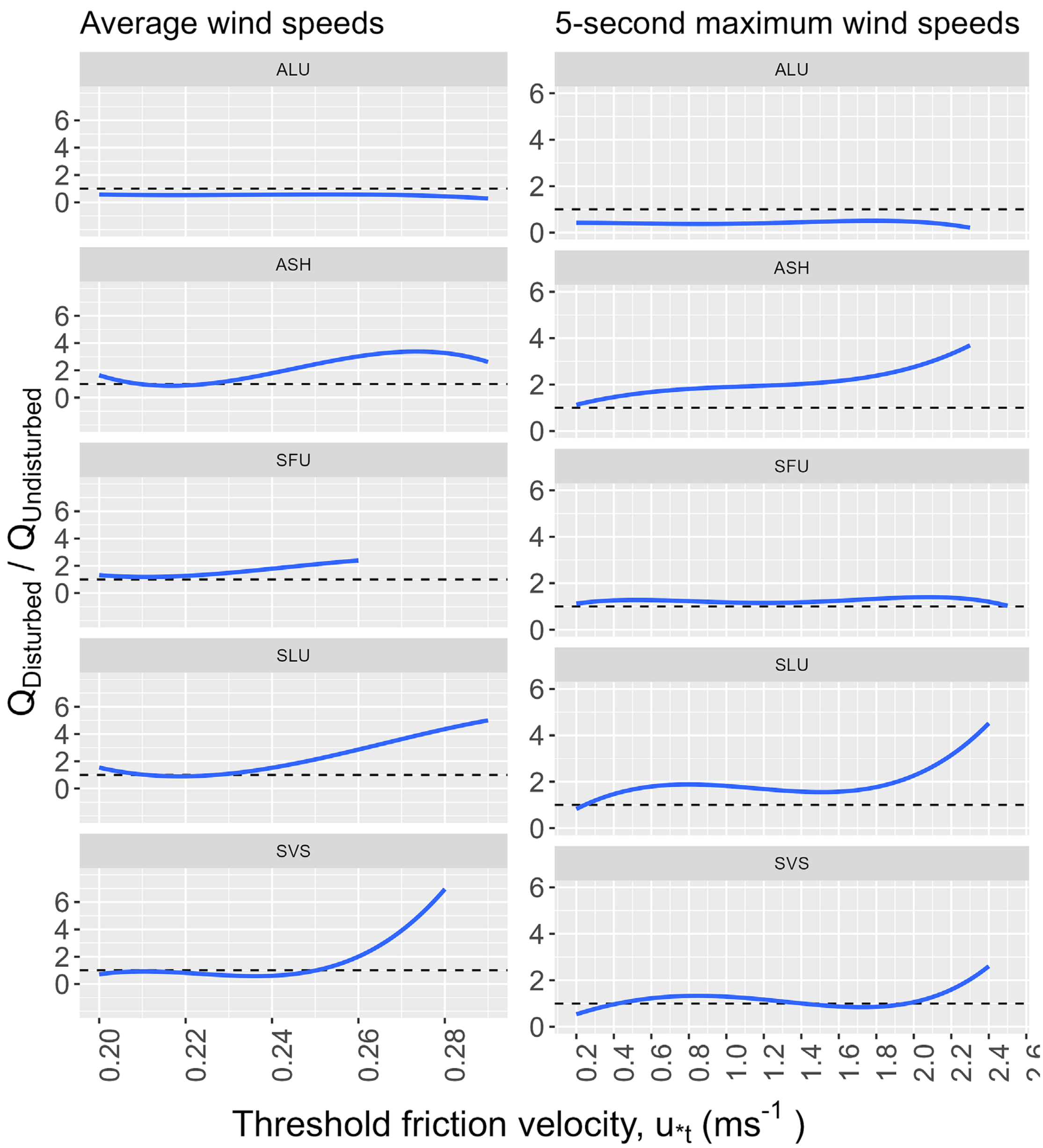

FIGURE 4 Fitted curves for ratios of modelled total annual mass flux (*Q*) for sites disturbed by oil/gas to undisturbed rangeland sites. The ratios were calculated from combined probabilities of surface wind friction velocity (u_{S*}) and daily average wind speeds and daily 5-s sustained maximum wind speeds (m s^{-1}) at 10-m height at the Vernal, UT Municipal Airport. Ratios calculated from daily average wind speeds are plotted for a range of threshold wind friction velocities (u_{*t}) from 0.20 m s^{-1} to 0.40 m s^{-1}. Ratios calculated from daily 5-s sustained maximum wind speeds are plotted for a range of u_{*t} from 0.20 to 3.0 m s^{-1}. ALU = Arid Loamy Uplands, ASH = Arid Saline Hills, SFU = Semiarid Finer Uplands, SLU = Semiarid Loamy Uplands and SVS = Semiarid Very Shallow (Table 1).

suppressed modelled sediment fluxes from disturbed SVS sites for simulations in which surface wind friction velocity was much larger than the entrainment threshold ($u_{S*} \gg u_{*t}$), particularly when u_{*t} was small (0.20 ms^{-1}).

In the ALU, sites disturbed by oil/gas activity were associated with larger surface roughness. Analysis of functional group vegetation cover shows that this unexpected effect was likely driven by colonization of disturbed areas by annual herbaceous species (Figures S4 and S5). Cover of herbaceous annuals was substantially greater at disturbed ALU sites than at undisturbed sites, and at sites in other strata, there was little difference in herbaceous annual cover between sites with and without oil/gas activity (Figure S4). This effect intensified when we compared annual herbaceous cover of disturbed ALU sites before and after development of oil/gas infrastructure (Figure S5). Non-native annual forbs and grasses frequently colonize well pads and access roads (Norton & Strom, 2013; Waller et al., 2018; Lupardus, Sengsirirak, et al., 2023a; Lupardus, Simonsen, et al., 2023b). While it is likely that construction of well pads and access roads initially reduced surface roughness and increased the likelihood of sediment transport, subsequent establishment of herbaceous annuals could have reversed this effect for disturbed sites in ALU. These data also suggest that colonization of drilled areas by herbaceous annuals might have dampened the surface roughness response to oil/gas activity among SFU and SLU sites (Figure S5), though there was no difference in annual herbaceous cover between disturbed and undisturbed sites in these strata (Figure S4).

It is likely that the strong signal of annual plants at disturbed ALU sites is driven by a general preference for these sandy loam soils

TABLE 2 Estimates of the contribution of oil/gas activity to vertical aeolian sediment flux (F) for the five climate-soil strata (Table 1) for a threshold friction velocity of $u_{*t} = 0.20\,ms^{-1}$ and a wind speed of $U_h = 12\,ms^{-1}$. Generalized clay content values for each climate-soil group were estimated from soil types described in Nauman et al. (2022). Area estimates for the extent of oil/gas activity in each climate-soil group are based on mapped data from Villarreal et al. (2023).

Stratum	Estimated percent clay of surface soil	Total area of stratum in UP (ha)	Percent area disturbed by oil/gas[a]	Total F without oil/gas activity (kg day^{-1})	Total F with oil/gas activity (kg day^{-1})	Δ Total F due to oil/gas activity (kg day^{-1})	Per cent change in total F due to oil/gas activity
ALU	15	25 600	14.75	244.03	219.67	−24.35	−9.98%
ASH	20	92 550	3.48	3736.87	3761.25	+24.38	+0.65%
SFU	20	84 325	2.49	1293.07	1294.36	+1.30	+0.10%
SLU	15	83 875	4.92	479.22	481.31	+2.10	+0.44%
SVS	15	52 075	1.73	384.04	381.92	−2.12	−0.55%
Total increase (ASH, SFU, SLU)	-	**260 750**	**10.89**	**5509.15**	**5536.93**	**+27.78**	**+0.50%**
Total offset (ALU, SVS)	-	**77 675**	**16.48**	**628.07**	**601.59**	**−26.48**	**−4.22**

Note: The total increase or decrease of dust due to oil and gas activity is emphasized in bold text.
Abbreviations: ALU, Arid Loamy Uplands; ASH, Arid Saline Hills; SFU, Semiarid Finer Uplands; SLU, Semiarid Loamy Uplands; SVS, Semiarid Very Shallow.
[a]Oil/gas activity was considered as a 25-ha site (a 500-m MODIS pixel) containing at least one active well pad and associated disturbance (e.g., access roads).

FIGURE 5 Results of a lagged cross-correlation function (CCF) of annual anomalies of the Standardized Precipitation-Evapotranspiration (SPEI) and anomalies of approximated surface roughness ($\frac{u_{S*}}{U_h}$) for August from 2001 to 2020 for Arid Saline Hills (ASH), Semiarid Finer Uplands (SFU) and Semiarid Loamy Uplands (SLU) (Table 1). The y-axis indicates $\frac{u_{S*}}{U_h}$ anomalies. The x-axis indicates $\frac{u_{S*}}{U_h}$ anomalies; that is, when lag (year) = 0, this shows the correlation between a drought event and surface roughness during the year the drought event occurred, lag (year) = −1 shows the correlation between a drought event and surface roughness the year following the drought event and so on. Bars greater than zero indicate positive correlations, and bars less than zero indicate negative correlations. Black dotted lines indicate upper and lower confidence intervals. Arid Loamy Uplands (ALU) not shown due to small sample of sites disturbed before August 2001 and Semiarid Very Shallow (SVS) not shown due to lack of significant effect.

(Nauman et al., 2022) and the timing of development during climatic periods favourable to annuals (Figures S6 and S7). The timing of the disturbance during favourable conditions may have created more opportunity for herbaceous annuals to establish and spread. Additionally, interim reclamation (recontouring and vegetation of parts of the initially disturbed area that are not necessary for well operation) also became more common in recent years (Di Stéfano et al., 2021), which could have influenced roughness by improving conditions for plant establishment and growth, whether they are invasive, native or seeded.

4.2 | Influence of oil/gas activity on potential dust emission

Our results indicate that removal of surface roughness by oil/gas activity could increase the potential for dust emission in some parts of the UP. Drilling activity in the ASH stratum could increase dust emissions by up to 24.38 kg day^{-1} or ~8900 kg year^{-1}. Oil/gas activity also resulted in smaller increases in modelled dust emissions from SFU (1.30 kg day^{-1} or ~475 kg year^{-1}) and SLU sites (2.10 kg day^{-1} or ~767 kg year^{-1}). However, in other parts of the UP, ecological responses to oil/gas activity reduced modelled dust emissions. Our results indicated that, following potential increases in dust emission after initial site disturbance, subsequent annual plant colonization of these sites could reduce dust production from the ALU by 24.35 kg day^{-1} (Table 2). However, because cover of herbaceous annuals is strongly related to antecedent precipitation (e.g., Williamson et al., 2020), suppression of dust from oil/gas activity by annual plants might vary widely from year to year. Site conversion to monocultures of herbaceous annuals may also result in long-term consequences for site stability and soil quality. For example, Norton et al. (2004) found that soils of sites dominated by *Bromus tectorum*, a non-native annual grass, have shallow, rapidly-cycling soil organic matter pools relative to soils of intact native *Artemisia* shrubland communities. This indicates that invasion by annual plants can lead to the loss of soil organic matter over time; intermittent erosion could be a mechanism for this loss (Shao, 2008). This supports past work that suggests dust consequences of land disturbance or degradation are greatly affected by local patterns in soil, geomorphology and vegetation (Duniway et al., 2019; Nauman et al., 2023).

The ALU strata has the highest intensity of oil/gas activity (14.75% disturbed; Table 1), but it also encompassed the smallest total area of the study region (Table 2). This indicates that on a regional scale, increased dust production after development of well pads and access roads in ASH, SFU and SLU could have a more far-reaching effect than potential dust reductions in ALU and SVS. Together, ASH, SFU and SLU sites comprise nearly 3.4 times the area of ALU and SVS sites (260 750 ha vs 77 675 ha), and by per cent area, there is considerably more opportunity for oil/gas development in ASH, SFU and SLU than there is in ALU. The difference in modelled dust emission between the study strata highlights how future oil/gas development could influence dust emissions and adds to a growing body of work on the importance of climate and soil-geomorphic setting on impacts of oil/gas development (Lupardus, Sengsirirak, et al., 2023a; Nauman et al., 2017).

Our simulation results suggest that oil/gas activity has the greatest potential to increase dust emissions relative to undisturbed during frequent, lowest-intensity wind events at which sediment flux occurred (Figure 4) or when u_{S*} was close to u_{*t}. As surface wind friction velocity increased relative to the entrainment threshold with increasing wind speed (i.e., $u_{S*} >> u_{*t}$), we see a decline in the magnitude of the difference in modelled Q between disturbed and undisturbed sites. This is because the arrangement of roughness elements on a surface has the most influence on the magnitude and distribution of shear stress on that surface when u_{S*} is close to u_{*t} (Webb, Okin, & Brown, 2014). In other words, if u_{S*} is much larger than the entrainment threshold for a site, then the entire site—undisturbed vegetated patches and disturbed bare patches—can be expected to experience sediment transport. This is not to say, however, that oil/gas disturbance would not influence aeolian sediment flux during high-intensity wind events. Our simulations using measured 5-s maximum wind speeds (Figure 5) indicate that even for stronger, less frequent wind events (up to $80\,m\,s^{-1}$; Figure S1), horizontal sediment fluxes from areas disturbed by oil/gas activity were usually ≥50% larger than fluxes from undisturbed areas.

It is important to recognize limitations in our approach pertaining to conditions or management of oil/gas disturbances that affect soil erodibility (u_{*t}) and emissivity. Uncertainty in our estimates is introduced by (1) our use of a fixed range of threshold wind friction velocities (u_{*t}) for a region with large heterogeneity of soils and thus sediment entrainment thresholds and (2) likely differences in u_{*t} between well pads and roads and off-pad rangeland and (3) our use of generalized values of clay content in our calculation of dust emission flux. Sediment entrainment thresholds of undisturbed desert surfaces could be >$0.40\,m\,s^{-1}$ (our maximum u_{*t} for our simulations) due to surface crusting and protection by rock fragments and may have limited loose erodible material (Marticorena et al., 1997). Additionally, because the top layers of soil are removed from well pads upon construction, the characteristics of deeper soil horizons likely play a larger role in determining well pad erodibility than the soil surface characteristics of the surrounding undeveloped landscape. There is also the possibility of the application of gravel or another surface amendment to the pad by operators for the purpose of dust mitigation (Lupardus, Simonsen, et al., 2023b). There is an opportunity for future work that measures erodibility and emissivity from active well pads and roads and the degree to which different surface treatments mitigate dust.

Another limitation of our approach is that we could not account for the influence of vehicle traffic in our dust emission estimates or previous oil/gas developments that were not mapped. Vehicular travel is necessary to establish and maintain well pads and transport extracted materials. Vehicles can greatly reduce u_{*t} and increase the supply of erodible sediment by disrupting the top few centimetres of soil on trafficked surfaces (Le Vern et al., 2020). Dust emissions from unpaved roads increase linearly with vehicle mass and speed (Dyck & Stukel, 1976; Gillies et al., 2005), which suggests that the heavy equipment and semitrucks that frequent access roads likely produce large emissions. For example, a 2018 sediment sampler study found that mean predicted sediment flux from unpaved roads was $\sim 39\,g\,m^{-2}\,day^{-1}$ or ~7 times the mean sediment flux predicted for rangelands, and the maximum flux measured on roads, $128\,g\,m^{-2}\,day^{-1}$, was from an active well access road (Nauman et al., 2018).

4.3 | Influence of drought on surface roughness response to oil/gas activity

Strong associations between drought events and concurrent $\frac{u_{S*}}{U_h}$ reflect the strong effect of precipitation on plant recruitment and herbaceous cover in drylands. We found a pronounced difference in roughness between wet and dry periods across disturbance levels, but the response of surface roughness to oil/gas did not vary between wet and dry periods in most cases, suggesting that the regional drought signal overwhelms the more localized signal of oil/gas. Several studies have found a strong correlation between fine dust (particulate matter size 2.5) and large-scale climate patterns, that is, Pacific-Decadal Oscillation and El Nino-Southern Oscillation (Achakulwisut, Shen, & Mickley, 2017; Hand et al., 2016; Pu & Ginoux, 2016). These climate patterns exert a large influence on soil moisture, temperature and precipitation in the western United States (Kim et al., 2006; Tobin et al., 2020), which, in turn, influence surface roughness and dust emission potential (Edwards et al., 2019). These modelling studies suggest that climate is the primary driver of dust emissions, and, considering only surface roughness effects, our lag correlation results appear to agree. However, a sediment sampler study evaluating interactive effects of drought and land uses has found that, across soil types, sites with minimal surface disturbance experience minimal change in sediment fluxes due to drought (Nauman et al., 2023). This indicates that drivers of dust emissions are more complex than large-scale modelling studies suggest.

4.4 | Influence of other land uses on surface roughness

The Colorado Plateau supports numerous land uses in addition to oil/gas activity, and many of these, most notably livestock grazing, are widespread and understood to impact dust emissions from drylands (Copeland et al., 2017; Eldridge et al., 2017; Nauman et al., 2018, 2023). Livestock grazing can reduce surface roughness via direct reduction of herbaceous vegetation (Cagney et al., 2010) or by facilitating shifts in plant community composition (Archer et al., 2017; Reisner et al., 2013) and may substantially increase aeolian sediment fluxes (Aubault et al., 2015; Belnap et al., 2007; Duniway et al., 2019; Nauman et al., 2018, 2023). It is notable that even for our simulations of landscapes with small u_{*t}, like those that have experienced continuous, low-level surface disturbance such as livestock grazing, the presence of well pads and access roads still increased modelled *Q*. Several other land uses in the study area likely contribute to regional dust (e.g., off-highway vehicles, cultivated agriculture and open-pit mining), though they are less spatially extensive than oil/gas or livestock activity in the study area (Copeland et al., 2017).

4.5 | Regional context of oil/gas effects on wind erosion within the UP and the Colorado Plateau

The results of this study show that oil/gas activity decreases surface roughness and could increase aeolian sediment fluxes in landscapes with large amounts of oil and natural gas development. However, it is important to consider the regional context of drilled areas across the UCRB. In the densely drilled UP, oil/gas infrastructure is present on ∼16% of the landscape, and on the Colorado Plateau as a whole, it is present on only ∼5% (Villarreal et al., 2023). The limited spatial footprint regionally of oil/gas activity suggests that oil/gas likely contributes much less to regional dust emissions than broader-scale land uses like livestock grazing (Nauman et al., 2018). However, dust emissions from well pads and access roads could still have large impacts, particularly for health and well-being of local communities (Achakulwisut et al., 2019; Achakulwisut, Mickley, & Anenberg, 2018; Goudie, 2014; Vowles et al., 2020). For example, in the Uinta Basin floor (Omernick Ecoregion 20f; Woods et al., 2001), where the town of Vernal, UT is located, drilling disturbance is particularly dense (∼32% of land area affected by oil/gas activity). Air quality of the Vernal area is impacted by high levels of volatile organic compounds (VOCs) and ozone, of which oil/gas activity is a suspected source (Prenni et al., 2022). Although health impacts of VOCs and winter ozone in the Uinta Basin remain uncertain (Edwards et al., 2014; Mansfield & Lyman, 2020), winter ozone related to oil/gas activity has been correlated with respiratory illness in other western US drilling basins (Pride et al., 2015). Elevated dust emissions due to oil/gas disturbance could place additional health burdens on this community.

The dust emissions for the climate-soil groups for which we estimate a net increase (ASH, SFU and SLU; increase in 27.78 kg day^{-1} or ∼10 139 kg year^{-1}) are small compared with annual dust production estimated for the Colorado Plateau ecoregion (1.45 Tg year^{-1}; Hennen et al., 2022) or dust concentrations measured during single dust events (Tong et al., 2012). However, an increase of 10 139 kg year^{-1} could have regional consequences if that dust is transported to alpine and subalpine areas in nearby mountain ranges when snow is present, impacting radiative forcing of mountain snowpack (Skiles et al., 2012), and impacting surface water availability in the Colorado River Basin (e.g., Painter et al., 2010).

4.6 | Dust mitigation strategies for well operators and land managers

Well operators can greatly reduce the risk of wind erosion with surface amendments such as gravel cover on vehicle access areas of well pads, drill seeding, hummocking or application of dust suppressants like MgCl (Duniway et al., 2019; Di Stéfano et al., 2021; Lupardus, Simonsen, et al., 2023b). Wetting of pads and access roads is a commonly used method of dust mitigation of unpaved roads (USDOT, 2013). However, this method requires frequent reapplication and raises concerns about environmental and human health risks, especially when wastewater from drilling operations is used as the surfactant (Tasker et al., 2018). The U.S. Bureau of Land Management also recommends reduced speeds on access roads and minimization of traffic on well roads for dust mitigation from vehicle traffic (BLM, 2018; Lupardus, Simonsen, et al., 2023b). Deployment of sediment and particulate matter samplers near drilled areas, particularly in downwind residential areas, can help identify areas where more intensive dust mitigation is needed (Prayascitra, Prabowo, & Asmoro, 2019).

5 | CONCLUSION

In this research, we provide a first of its kind estimation of the relative contribution of oil/gas activity to regional dust emissions. Our results indicate that development of well pads and access roads can reduce landscape surface roughness and increase the risk of dust emission, but dust responses to oil/gas activity vary across soil types and climate zones. Annual plants colonizing these disturbances have the potential to increase surface roughness and reduce wind erosion and dust emission risk relative to undeveloped rangeland, at least ephemerally. While drought reduced surface roughness across landscapes, we found little indication that drought conditions significantly altered the effect of oil/gas on surface roughness. Net modelled aeolian sediment flux and dust emission increased for both disturbed and undisturbed landscapes during drought periods, and generally modelled sediment fluxes were larger for disturbed sites regardless of drought.

While this work focused on the UCRB in the western United States, it provides a methodology that can be applied to other dryland regions where oil/gas drilling takes place. Our results also provide an estimate of the dust contribution of oil/gas activity in the UCRB that researchers and land managers can use as a baseline in future studies. Such work can guide mitigation efforts aimed at limiting anthropogenic dust emissions and associated impacts on the UCRB.

AUTHOR CONTRIBUTIONS

Gayle Tyree: conceptualization, methodology, investigation, writing/editing. **Adrian Chappell:** resources, reviewing/editing. **Miguel L. Villarreal:** resources, reviewing/editing. **Saroj Dhital:** resources, reviewing/editing. **Michael C. Duniway:** resources, supervision, reviewing/editing. **Brandon L. Edwards:** conceptualization, supervision, reviewing/editing. **Akasha M. Faist:** conceptualization, supervision, reviewing/editing. **Travis W. Nauman:** resources, reviewing/editing. **Nicholas P. Webb:** conceptualization, methodology, supervision, reviewing/editing.

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CONFLICT OF INTEREST STATEMENT

No potential conflict of interest was reported by any of the authors of this work.

DATA AVAILABILITY STATEMENT

Data generated during this study are available from the USGS ScienceBase catalog (Tyree et al., 2024).

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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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