Indicators and benchmarks for wind erosion monitoring, assessment and management

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ABSTRACT

Wind erosion and blowing dust threaten food security, human health and ecosystem services across global drylands. Monitoring wind erosion is needed to inform management, with explicit monitoring objectives being critical for interpreting and translating monitoring information into management actions. Monitoring objectives should establish quantitative guidelines for determining the relationship of wind erosion indicators to management benchmarks that reflect tolerable erosion and dust production levels considering impacts to, for example, ecosystem processes, species, agricultural production systems and human well-being. Here we: 1) critically review indicators of wind erosion and blowing dust that are currently available to practitioners; and 2) describe approaches for establishing benchmarks to support wind erosion assessments and management. We find that while numerous indicators are available for monitoring wind erosion, only a subset have been used routinely and most monitoring efforts have focused on air quality impacts of dust. Indicators need to be related to the causal soil and vegetation controls in eroding areas to directly inform management. There is great potential to use regional standardized soil and vegetation monitoring datasets, remote sensing and models to provide new information on wind erosion across landscapes. We identify best practices for establishing benchmarks for these indicators based on experimental studies, mechanistic and empirical models, and distributions of indicator values obtained from monitoring data at historic or existing reference sites. The approaches to establishing benchmarks described here have enduring utility as monitoring technologies change and enable managers to evaluate co-benefits and potential trade-offs among ecosystem services as affected by wind erosion management.

1. Introduction

Wind erosion is a major resource concern because it affects land health, agricultural production, ecosystem function, human health and climate (UNEP, WMO, UNCCD, 2016). The negative impacts of wind erosion are generally recognized (Middleton et al., 2017; Duniway et al., 2019) and strategies to manage wind erosion are urgently needed for adapting to climate change in drylands (Webb et al., 2017a; Edwards et al., 2019; IPCC, 2019). However, limited integrated information and crude estimates have long hampered wind erosion assessments (Lal, 2001; Shao et al., 2011). These sources of uncertainty continue to affect management responses. Allocating resources to

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Goal: Reduce soil degradation around Buronga

Management Objective

Control grazing to maintain sufficient ground cover to reduce soil degradation by wind erosion around Buronga.

Maintain and Monitor
Adjust and Reassess

Decision

Monitoring Objectives

Objective 1: *Determine that 85% of grazing lands within 25 km of Buronga have >50% ground cover for December-February, with 90% confidence.*

Objective 2: *Detect reduction in PM_{10} to <60 hours with >25 $\mu g\ m^{-3}$ at Buronga with 95% confidence in 2020.*

Identify

Assess

Indicators

Fractional ground cover by type
Canopy gap size distribution
Canopy height
Dust emission flux
Dust concentration (PM_{10})

Benchmarks

Ground cover: >50% from December-February (functional threshold of erosion for cover type)
Dust concentration: >25 $\mu g\ m^{-3}$ (75th percentile of measured dust hours)

Establish

Identify

Calculate & Model

Measurements

MODIS fractional ground cover
Canopy gap intercept
Canopy height

Surface soil texture
Surface wind speeds
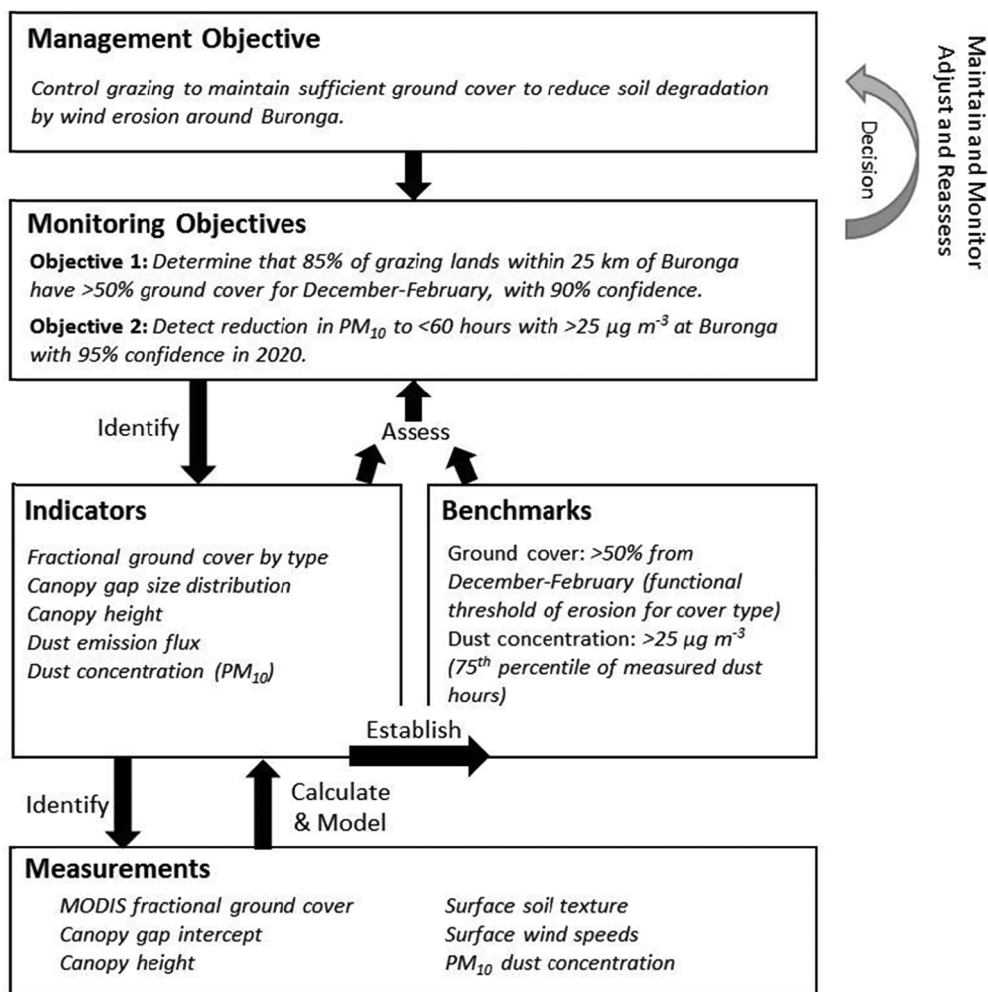*PM_{10} dust concentration*

Fig. 1. Illustration of how measurements, indicators and benchmarks are defined by monitoring and management objectives and are used to inform management decisions for a case study to reduce soil degradation around the town of Buronga, southeastern Australia. In this example, benchmarks are defined for ground cover and dust concentrations (after Leys et al., 2018) and could be expected to vary depending on management objectives and geographic location.

manage wind erosion is difficult where the problem is unrecognized, unquantified, and effects of management poorly understood (UNEP, WMO, UNCCD, 2016). Improved monitoring to quantify wind erosion would ensure that appropriate effort is directed toward its management and balanced with investment in other resource concerns (e.g., invasive species, habitat loss, biodiversity decline) that are more readily perceived and quantified (Rodríguez et al., 2006). Because wind erosion affects such a wide range of ecosystem services, reducing wind erosion can have multiple benefits. Approaches are therefore needed to guide wind erosion monitoring and inform management across agroecological systems.

To be effective, wind erosion monitoring requires explicit articulation of objectives for which monitoring information can be interpreted and translated into management actions (Lindenmayer et al., 2013; Fischman and Ruhl, 2016). **Management objectives** should express the desired condition of resources to be achieved in a specified time frame to meet land use goals (Elzinga et al., 1998; Decker et al., 2014). **Monitoring objectives** should establish quantitative guidelines for detecting whether desired resource conditions have been achieved (Fig. 1). Monitoring objectives define desired values or trends in indicators for some proportion of an assessment area and time period that should be detected at a certain confidence level relative to a benchmark. **Indicators** are variables whose characteristics describe the state of an attribute, such as wind erosion risk or air quality (Karl et al., 2017;

Angermeier and Karr, 2019). We define **Benchmarks** here as indicator values, or ranges of values, that describe desired conditions that, when exceeded, trigger adjustments to management practices, additional data collection, or indicate management success. Identifying a core set of wind erosion indicators, approaches to establish benchmarks, and design of credible systems to detect change would enable practitioners to use monitoring data to make objective and decisive decisions about the effectiveness of wind erosion management, and when current management strategies should be reviewed, amended, or changed altogether.

The most coordinated approaches currently used to monitor indicators of wind erosion and blowing dust are meteorological and aerosol monitoring networks. Examples include the global Aerosol Robotic Network (AERONET), United States (US) Interagency Monitoring of Protected Visual Environments (IMPROVE), Campaign on Atmospheric Aerosol Research network of China (CARE-China), and Australian DustWatch program (Leys et al., 2008). Satellite observations and numerical modeling also support these monitoring efforts to provide early warning and are integral to the World Meteorological Organization's (WMO) Sand and Dust Storm Warning Advisory and Assessment System, SDS-WAS (WMO, 2015). However, with few exceptions (e.g., Leys et al., 2009; Love et al., 2019) these networks do not address which areas are eroding, and why, with enough accuracy to inform management. Recent developments in the use of remote sensing

Table 1

Summary of common indicators and measurements of wind erosion and air quality used for monitoring croplands, rangelands, and desert ecosystems by scientists and land managers. Data availability describes how accessible measurements are through established monitoring programs. Ease of interpretation describes the technical difficulty of understanding how the measurements indicate erosion risk or outcomes.

Indicator	Description	Measurement approaches	Data availability	Ease of interpretation	Example references
Soil properties					
Soil texture	Particle size distribution of soil, classified into size bins or classes	Hand texture analysis; Hydrometer; Laser diffraction	High	High	Bouyoucos (1951), Zobeck (2004)
Dry aggregate size distribution (DASD)	Size distribution of soil aggregates. The fraction < 0.84 mm is considered erodible	Rotary sieving; Hand nest sieving; Elutriation	Low	Moderate	Lyles et al. (1970), Fryrear (1985)
Wind erodibility group (WEG)	Classification of soil erodibility based on soil texture class, DASD and $CaCO_3$ content	Applied to soil texture classes	High	High	Hayes (1965, 1972)
Soil surface roughness	The physical roughness of the soil surface, including random and oriented roughness (e.g., due to tillage tools)	Pin profiler; Laser profiler; Chain set method; Remote sensing	Low	Low	Potter et al. (1990), Saleh (1993), Chappell et al. (2010)
Crust modulus of rupture	Shear stress required to fracture soil crust	Penetrometer; Torvane	Low	Low	Chepil and Woodruff (1963), Belnap and Gillette (1998)
Threshold friction velocity (u_{*t})	Wind shear (friction) velocity at which grains (aggregates) are mobilized by wind	Anemometers with saltation particle counter	Low	Low	Barchyn and Hugenholtz (2010)
Surface crust cover	Fraction of soil surface covered by physical and/or biological soil crusts	Line-point intercept; Step point transects	High	High	Herrick et al. (2018)
Loose erodible material	Fraction of loose sediment lying on the soil surface that may be mobilized by wind	Line-point intercept; Step point transects; Physical sample collection	Low	High	Herrick et al. (2018)Zobeck (1989)
Exposure to erosive winds					
Ground cover	Surface covered by rooted plant material, rock fragments, gravel (> 2 mm), embedded and loose woody and herbaceous litter	Line-point intercept; Step point; High- to moderate-resolution remote sensing	High	High	Herrick et al. (2018)Herrick et al. (2005)
Vegetation foliar cover	Fraction of surface covered by rooted woody and/or herbaceous plant material	Line-point intercept; Step point; High- to moderate-resolution remote sensing	High	High	Herrick et al. (2018)
Vegetation composition	Plant species present at a site	Line-point intercept	High	High	Herrick et al. (2018)
Vegetation height	Height of the tallest plant parts within site, provides vertical structure	Line-point intercept	High	High	Herrick et al. (2018)
Vegetation foliar density	Leaf area index (LAI); Stem area index (SAI)	Plant area meter; Calculation from stem diameter, height and population	Low	Low	Bréda (2003)
Canopy gap size distribution	Size of spaces between plant canopies, describes spatial distribution of roughness	Gap intercept; High-resolution remote sensing	High	High	Herrick et al. (2018)
Effective sheltering	Effective aerodynamic sheltering of soil surface by roughness elements	High- to moderate-resolution remote sensing	Moderate	Moderate	Marticorena et al. (2006), Chappell and Webb (2016), Potter et al. (1990)

Indicator	Description	Measurement approaches	Data availability	Ease of interpretation	Example references
Land health attributes					
Pedestals and/or terracettes	Plants or rocks appear elevated because of soil loss around them	Visual estimate	High	High	Pellant et al. (2005)

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Table 1 (*continued*)

Indicator	Description	Method			Reference
Wind scouring, blowouts and/or sediment deposition areas	Soil loss or gains around plants, rocks and within plant interspaces	Visual estimate	High	High	Pellant et al. (2005)
Soil surface horizon loss or degradation	Soil horizon(s) no longer present or loss of organic material from surface horizon	Visual estimate	High	Moderate	Pellant et al. (2005)
Blowing dust and air quality					
Saltation mass flux (Q)	Transport rate of sediment moving horizontally along the soil surface (g m^{-1} s^{-1})	Slot samplers Big Spring Number Eight (BSNE) Modified Wilson and Cooke (MWAC)	Low	Low	Fryrear (1986), Zobeck et al. (2003)
Dust mass flux (F)	Vertical dust emission rate (g m^{-2} s^{-1})	Derived from vertical profile of PM concentration measurements	Low	Low	Gillette et al. (1972)
Dust event frequency	Occurrence of blowing dust events, including dust storms, dust hazes, and dust devils	Visual observation for weather records	High	High	OLoingsigh et al. (2010)
Particulate matter concentration (PM)	Abundance of mineral dust particles in a volume of air (µg m^{-3})	Light scattering laser photometer Lidar	High	Moderate	Hand et al. (2016)
Aerosol optical depth (AOD)	Natural logarithm of the ratio of incident to transmitted radiance through the atmosphere	Sun photometer Moderate-resolution remote sensing	High	Low	Holben et al. (1995), Green et al. (2009)

for modelling (e.g., Chappell et al., 2019) and monitoring of global drylands – e.g., the US Bureau of Land Management's (BLM) public lands Assessment, Inventory and Monitoring (AIM) program, Natural Resources Conservation Service's (NRCS) private lands National Resources Inventory (NRI), Australian Terrestrial Ecosystem Research Network's (TERN) AusPlots, and rangeland monitoring of the Mongolian National Agency for Meteorology and Environmental Monitoring (NAMEM) – have increased the information available to identify and characterize dust source regions. However, data collected by these programs are largely yet to be utilized to inform wind erosion assessments and management (Webb et al., 2017b). This is because: 1) the data are not easily accessible from the wide range of sources; and 2) the capacity of these datasets to provide indicators, along with approaches to establish benchmarks, has not always been apparent to managers.

This paper identifies how indicators and benchmarks can be used to support wind erosion monitoring, assessment and management decisions. Our specific objectives are to: 1) review indicators of wind erosion and blowing dust that are currently available to practitioners; and 2) describe approaches and identify best practices for establishing benchmarks to support wind erosion assessments and management. We find that most monitoring efforts have focused on air quality impacts of dust. This is because health impacts of degraded air quality are generally well understood, whilst land condition impacts of wind erosion are not described well. Integration of wind erosion indicators collected in the field and through remote sensing can provide the needed information to establish monitoring benchmarks critical to formulating clear management objectives, evaluating resource condition and trend, and assessing the efficacy of management actions.

2. Available indicators of wind erosion and blowing dust

Four types of indicators have been used by practitioners to support quantitative and qualitative assessments of wind erosion and blowing dust. These indicators include: 1) soil properties; 2) exposure to potentially erosive winds; 3) land health attributes based on observations and local/expert opinion; and 4) blowing dust occurrence and air quality measures (Table 1). Direct measurements of aeolian sediment transport and more technical indicators of soil and site susceptibility to wind erosion (erodibility) have been developed for croplands and rangelands (see review by Webb and Strong, 2011). However, these require specialized instrumentation, and can be difficult to interpret, so have not been widely adopted outside the aeolian research community (Zobeck et al., 2003). Here we focus on indicators that are readily obtained from measurements collected by producers, resource managers, and agencies in the US and globally and which can be used to support model-driven assessments.

2.1. Indicators based on soil properties

Following the 1930s Dust Bowl, the USDA Soil Conservation Service (SCS) sought to identify properties of agricultural soils that describe their susceptibility to wind erosion. Extensive work by W.S. Chepil and colleagues identified soil texture (Chepil, 1953), the proportion of dry aggregates < 0.84 mm diameter at the surface soil (the "erodible fraction"; Chepil, 1951), and calcium carbonate and organic matter contents (Chepil, 1954), as indicators to classify soils into Wind Erodibility Groups (WEGs). A Wind Erodibility Index ("I" factor) was subsequently developed as an expression of dry soil aggregate stability under tillage and abrasion for the Wind Erosion Equation (WEQ), an empirical equation to estimate potential soil loss by wind (t ha^{-1} yr^{-1}) (Woodruff and Siddoway, 1965).

The WEGs and "I" factor are used by managers globally as indicators of soil erodibility (NRCS, 2018). While the classifications are often ascribed to soils based on surface texture and appear easy to apply to global texture maps (e.g., Hengl et al., 2017), the WEGs and "I" factor are broad groupings with limitations that make them inaccurate in

many soil-landscape settings, management contexts and soil conditions (Webb and Strong, 2011). The indicators describe the susceptibility of non-crusted soils to be mobilized by wind and do not necessarily represent their potential to emit fine dust. The WEGs and "I" factor therefore do not work well for non-arable soils with physical and biological soil crusts (Woodruff and Siddoway, 1965). As the classifications are static, they are also insensitive to land management activities that disturb soils (e.g., due to machinery, livestock and fire) and weathering forces (e.g., wet-dry, freeze-thaw) that change the availability of fine silt and clay particles on the soil surface that affects dust emission (Baddock et al., 2011). Because of these limitations, use of the WEGs and "I" factor on crusted soils and as indicators of wind erosion is potentially misleading. Other, more dynamic indicators of wind erosion are often more appropriate.

2.2. Indicators of exposure to erosive winds

Ground cover (vegetative and non-vegetative elements, as viewed from above) is a familiar concept to land managers and has often been used as a dynamic indicator of land susceptibility to wind erosion (e.g., Webb et al., 2009; Pierre et al., 2018). National monitoring programs and the United Nations Convention to Combat Desertification (UNCCD) have adopted metrics of ground cover to monitor risk of wind erosion and land degradation (Cowie et al., 2018). Data availability makes the indicator attractive for local to regional wind erosion assessments. However, fractional ground cover on its own is demonstrably a poor indicator of exposure to wind erosion (Chappell et al., 2018).

Wind erosion is driven primarily by lateral wind forces (Raupach et al., 1993). Wind momentum absorption and sheltering by surface roughness elements therefore have the greatest effect on reducing sediment transport (Hagen and Armbrust, 1992). These processes are moderated by the vertical structure, density and spatial distribution of roughness, which are not described by ground cover alone (Fig. 2). Vegetation shape, porosity and flexibility (including leaf and stem area) also influence momentum absorption and sheltering (Mayaud and Webb, 2017), and have been used as indicators of erosion risk in croplands (Hagen and Armbrust, 1994; Armbrust and Bilbro, 1997). However, without information on vegetation structure, as characterized by the height and distribution of ground cover, assessments may severely over- or underestimate erosion risk (Webb et al., 2014a). Alternatively, indicators of vegetation canopy height and canopy gap size distribution (measured as the spacing between plant canopies) can be collected in the field using standardized methods (e.g., Herrick et al., 2018) and can be used to explain to the first order where wind erosion may occur (Okin, 2008).

Indicators of vegetation structure have been measured extensively across western US rangelands (Goebel, 1998; Toevs et al., 2011), Mongolian grasslands (Densambuu et al., 2018), and at select cropland sites (Webb et al., 2016), and could be used to assess wind erosion across plot (< 1 ha) to regional ($> 10^6$ ha) scales (e.g., NRCS, 2011). Recent remote sensing advances have enabled area-integrated measures of surface sheltering from the wind (Chappell et al., 2010; Chappell and Webb, 2016). The approach can be applied globally to estimate wind erosion, filling gaps in field monitoring (Chappell et al., 2019). As vegetation structure is extremely sensitive to land management, it is probably the best landscape scale indicator of wind erosion. One of the limitations of remote sensing is that it is difficult to know the cause of changes in an indicator. For this reason, landscape-wide monitoring with satellite remote sensing should be coupled to site-based assessments to aid interpretation.

2.3. Indicators of land health attributes including soil properties and exposure

Several global initiatives to assess land health include indicators of wind erosion (e.g., FAO and ITPS, 2010; International Resource Panel, 2016; Cowie et al., 2018). Of these, the Interpreting Indicators of Rangeland Health (IIRH) assessment protocol (Pyke et al., 2002; Pellant et al., 2005) has been applied at over 30,000 sites in the US and integrates 17 indicators of rangeland health into three attributes of soil and site stability, hydrologic function and biotic integrity (Herrick et al., 2019). Quantitative and qualitative indicators of wind erosion are incorporated into IIRH assessments, including the presence of pedestals and/or terracettes, bare ground fraction, presence of wind scouring, blowouts and/or sediment deposition areas, litter movement, and soil surface horizon loss or degradation. However, use of these indicators is not recommended for monitoring or being agglomerated to independently generate national or regional assessments (Pellant et al., 2005).

Qualitative indicators of soil and site stability and biotic integrity provide information on the status of wind erosion at a site that may not be obtained from quantitative indicators of soil erodibility and site exposure to erosive winds. Interpreting qualitative indicators like those used in IIRH requires a descriptive reference of the status of the
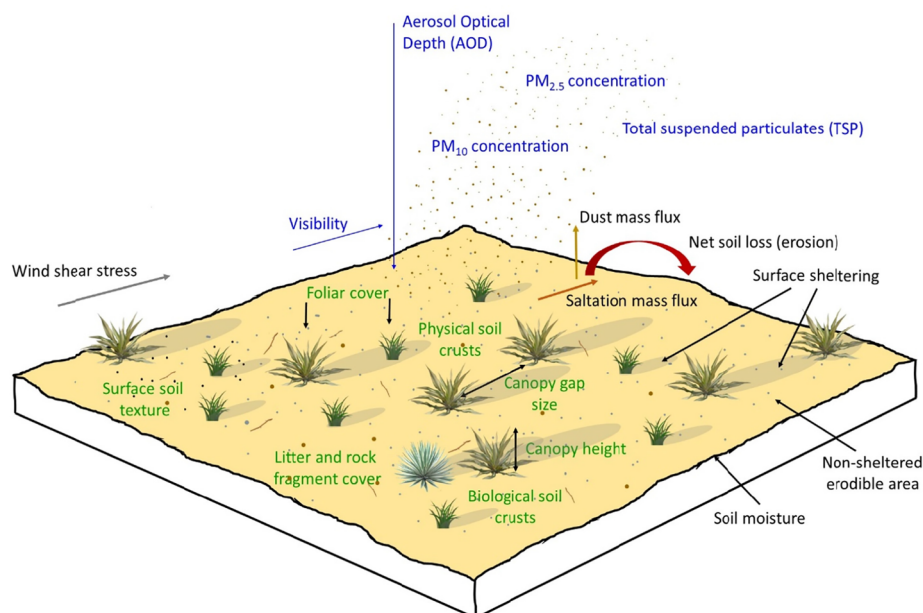
Fig. 2. Schematic illustrating main controls on the susceptibility of landscapes to wind erosion including indicators that are routinely collected by agroecological (green labels) and air quality (blue labels) monitoring programs, and which can be obtained from models (black labels) using the agroecological indicators and/or remote sensing.

indicators for a defined "healthy" site (one with a minimal departure from reference conditions), or classification for rating indicators that enables practitioners to define relative expected values for a historical reference (Herrick et al., 2019). This approach has the benefit of incorporating reference benchmarks into assessments that can help diagnose whether wind erosion is a problem, in addition to providing another line of evidence in support of more quantitative monitoring and modeling. However, wind erosion should not be assessed using land health attributes alone as they reflect current land status, influenced by past management, and not necessarily potential future erosion. Wind erosion and dust emission that functionally impact land health and degrade air quality may occur, or may have recently occurred, without visual evidence to suggest that land is departing from a reference condition. Related protocols like Landscape Function Analysis (Tongway and Hindey, 2004) and Pedoderm and Pattern Class (Burkett et al., 2013) consider similar indicators as IIRH, but use uniform criteria to describe the degree of soil erosion across all types of land rather than departure from a unique reference for each type of land (ecological site).

2.4. Indicators of atmospheric dust and air quality

Dust monitoring globally has been coordinated through meteorological observation networks and aerosol measurement networks (Goudie and Middleton, 2006). Indicators used by these networks include: dust event frequencies obtained from visual observations (e.g., McTainsh et al., 1998; Shao and Dong, 2006; O'Loingsigh et al., 2010, 2014); atmospheric particulate matter (PM) concentrations measured using high volume air samplers, lidar, and light-scattering laser photometers (e.g., Xin et al., 2015; Hand et al., 2016; Love et al., 2019); and aerosol optical depth (AOD) obtained from ground-based sun photometers and satellite observations (e.g., Holben et al., 1995; Prospero et al., 2002; Ginoux et al., 2012). While these indicators directly relate to climate, visibility and human health impacts of dust, attributing transported dust loads to specific upwind source areas and land uses with enough accuracy to inform management is very challenging (McTainsh et al., 1998; Webb and Pierre, 2018). Additionally, dust aerosol data are generally collected and interpreted by agencies, or divisions of agencies, that have interests in air quality (e.g., environmental protection agencies) and dust forecasting (e.g., WMO SDS-WAS) but may have little or no formal connection to programs responsible for monitoring and managing source area soils and vegetation. Such connections are being addressed by the USDA-NRCS National Air Quality Initiative, and New South Wales Office of Environment and Heritage that collects and publishes hourly aerosol data on the Rural Air Quality Network. These air quality data are then interpreted in conjunction with remotely sensed ground cover, rainfall and fire data to report on causes of wind erosion in south-eastern Australia via the Community DustWatch project (Leys et al., 2008).

3. Indicators for multiple management objectives

Management decisions about wind erosion are rarely made in isolation from other conservation and production objectives. To reduce the need for costly dedicated monitoring, wind erosion indicators can be selected that are used to assess the status, condition, and trend of other ecosystem services of management interest; that is, are multi-use and available from or have value to existing monitoring programs (Probst and Stelzenmüller, 2015; Karl et al., 2017). Examples include vegetation foliar cover, canopy gap size distribution and vegetation height that are widely used to monitor land health, invasive species and habitat quality (e.g., Goebel, 1998; Toevs et al., 2011) in addition to wind erosion (Webb et al., 2016). Selection of multi-use indicators should consider whether sampling used for their monitoring adequately captures the spatiotemporal variability of wind erosion to confidently detect its change.

Wind erosion and dust emission models can be used to integrate soil and vegetation indicators to support assessments at the farm scale (e.g., Pierre et al., 2018; Tatarko et al., 2019), at plot-to-regional scales using plot monitoring data (e.g., Munson et al., 2011) and at landscape-to-global scales using remote sensing (e.g., Chappell et al., 2019). By combining effects of different indicators, models can enable more robust assessments of wind erosion than when indicators are used independently. However, available models can be difficult to parameterize without expert knowledge. Available models also provide metrics that remain generally unfamiliar to practitioners as they are difficult to interpret without a defined reference. These estimates include soil loss (t ha^{-1} yr^{-1}), sediment transport rates (g m^{-1} s^{-1}) and dust emission (g m^{-2} s^{-1}). Establishing benchmarks related to commonly measured soil and vegetation indicators is necessary for land managers to understand how the indicators relate to sediment transport and erosion rates across scales, and to assess whether sites have an acceptable, or unacceptable, risk of erosion and act accordingly (Pretorius and Cooks, 1989).

4. Establishing benchmarks for monitoring objectives

Benchmarks are needed to determine if observed indicator values at assessed locations are within the range of desired conditions to meet management objectives. If monitoring information shows that an insufficient amount of a management area has met a benchmark, then changes in management can be triggered (Lindenmayer et al., 2013). Conversely, failure to set benchmarks can make it difficult to interpret monitoring data because there are no decision criteria for how to use observed values to evaluate management objectives (Elzinga et al., 1998; Fischman and Ruhl, 2016). Critical for establishing wind erosion benchmarks is an understanding of how aeolian processes respond to natural environmental gradients through space and time, management actions, and environmental change such as land cover change.

Wind erosion and dust emission are controlled by climate, soil and vegetation properties that also determine site potential and the ecological state of a site (Webb and Pierre, 2018). Site potential determines the capacity of a site to produce certain kinds, amounts and proportions of vegetation, and its responses to disturbances and management (USDA, 2013). Vegetation dynamics determine the ecological states of a site as plant communities and soil properties respond to endogenous (e.g., competition, facilitation) and exogenous (e.g., disturbance) processes (Bestelmeyer et al., 2003). Ecological states can be described by vegetation structural features (e.g., ground cover/bare soil, canopy gap size distributions and canopy height) associated with different plant communities. Persistent state changes may occur when structural thresholds are crossed that trigger shifts in feedbacks reinforcing new structures (e.g., grassland to shrubland transitions; Fig. 3a,b,c). The vegetation structure of states also impacts the function of aeolian processes, with functional thresholds determining how aeolian processes respond to changes in vegetation structure; e.g., the cover of canopy gaps at which a non-linear increase in erosion occurs (Fig. 3d), and how sites are impacted by erosion (Okin et al., 2006; Sasaki et al., 2018). Models can be used to identify functional thresholds for wind erosion based on inputs of vegetation structure (Fig. 3e). Structural and functional thresholds are related (e.g., through ecological feedbacks) and so provide a biophysical basis for defining benchmarks for different indicator types relative to ecosystem dynamics (e.g., state changes), the mechanics of aeolian processes, and erosion and dust impacts (Bestelmeyer, 2006). Differences in site potential can be accommodated in benchmarks by grouping sites based on land classification systems, like 'ecological sites' with associated state-and-transition models (STMs) to identify structural thresholds of concern (USDA, 2013; Bestelmeyer et al., 2015).

Within this context, approaches to establish benchmarks may draw on: 1) experimental studies reported in peer-reviewed literature; 2) mechanistic and empirical models; and 3) distributions of indicator
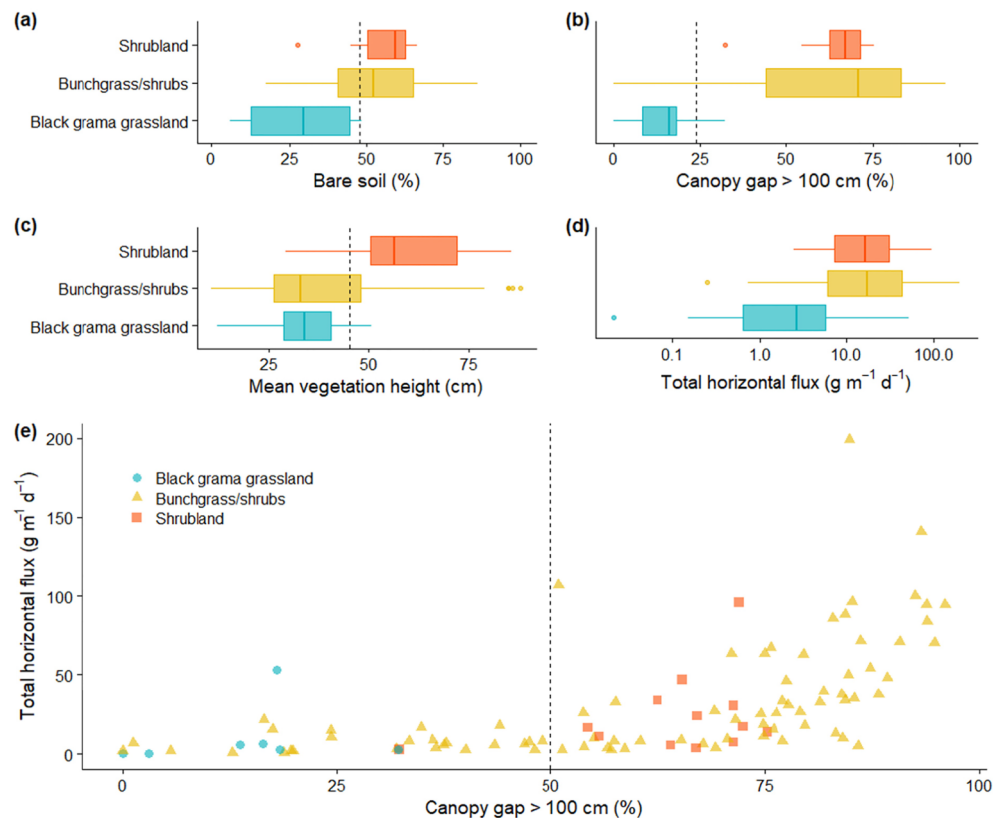
Fig. 3. Illustration of wind erosion indicator values for (a) bare soil (%), (b) percentage of canopy gaps > 100 cm, (c) mean vegetation height (cm), and (d) total horizontal sediment mass flux on log axis (g m^{-1} d^{-1}) resulting from vegetation state change (grassland to shrubland transition) in the sandy ecological site group in Major Land Resource Area 42 in New Mexico, USA. Indicator distributions were obtained from 166 BLM AIM and NRCS NRI monitoring plots and the wind erosion model of Okin (2008) applied to the plot data following Webb et al. (2014). Vegetation structural thresholds defining ecological states were selected as benchmarks from the 90th percentile of indicator values for the reference black grama grassland. Benchmarks are shown as dashed lines for bare soil (a), canopy gaps (b) and mean vegetation height (c), and their relation to state-specific distributions and functional threshold for aeolian sediment transport (e).

values obtained from reference site monitoring data. Following these approaches, benchmarks can also be defined by non-ecological thresholds, including human goals relating to health and social impacts of blowing dust. For example, benchmarks can be set for levels of sediment production that have significant impacts on respiratory health, degradation of viewsheds, or around the cost to replace or maintain structures and equipment compromised by the erosive forces of blowing dust. All of the approaches to establish benchmarks vary in their potential for bias (and our ability to quantify that bias), ease of communication, applicability to management questions and policy mandates, and availability in the geographic region of interest (Wiersma, 2005). The most suitable approach may depend on the particular policy or management objective(s) a benchmark is trying to address.

4.1. Benchmarks from scientific literature

Monitoring benchmarks should be established based on the best available science and data, and whenever possible be supported by published experimental studies. Field and laboratory wind tunnel studies addressing effects of soil properties (e.g., Chepil, 1944; Fryrear, 1985; Gillette et al., 1980) and ground cover levels (e.g., Wasson and Nanninga, 1986; Leys, 1991) on functional thresholds for wind erosion have been conducted to inform management. Results from field and laboratory experiments can be used to validate benchmarks derived from monitoring data (Section 4.3) by informing how wind erosion responds functionally to changes in its controlling factors, and how agricultural, ecological and human systems respond to different intensities of wind erosion (e.g., Okin et al., 2006). Care should be taken to ensure that literature used to inform benchmarks is rigorous and relevant to the soils and potential vegetation at the geographic location of interest (i.e., site potential). Available studies that could inform benchmarks are largely limited to croplands and discipline-specific journals. New research and a synthesis of soil and vegetation thresholds for wind erosion across agroecological systems are therefore needed to

enable managers to access this information to develop benchmarks.

4.2. Model-informed benchmarks

Mechanistic and empirical models can be used in multiple ways to support benchmark establishment. Mechanistic models can be used to evaluate how much wind erosion could occur at a site, and identify functional thresholds of concern for ecological sites and states. For example, Webb et al., (2014) used the aeolian transport model of Okin (2008) to identify erosion thresholds of ground cover and vegetation canopy gap sizes across Chihuahuan Desert ecosystems. A current limitation of mechanistic wind erosion models is that they have been parameterized at small (plot) scales for few land cover types and, with exception of the Wind Erosion Prediction System (WEPS, Tatarko et al., 2019), they currently do not account for dynamic soil surface properties like crusting and aggregation (Webb and Strong, 2011). Where important, other indicators of these properties should be considered alongside model estimates to enable a more complete assessment of whether management objectives are being met.

Empirical models can be used to support benchmark establishment by identifying areas of similar ecological potential (e.g., Nauman and Duniway, 2016; Nauman et al., 2017) and how indicator values measured at 'reference' sites vary across landscapes in response to natural environmental gradients (e.g., Hawkins et al., 2010). This can be particularly useful for predicting the conditions of sites where historical conditions are unknown, and predicting conditions that should occur in the absence of anthropogenic impacts. Predicted 'reference' indicator values can then be compared with observed values to assess the degree of departure from the reference state.

Empirical models of the relationships among indicators (e.g., ground cover and dust concentrations) can also be used to support benchmark establishment. For example, Leys et al (2018) showed how empirical relationships based on monitoring data can be used to establish benchmarks to support the management objective of reducing
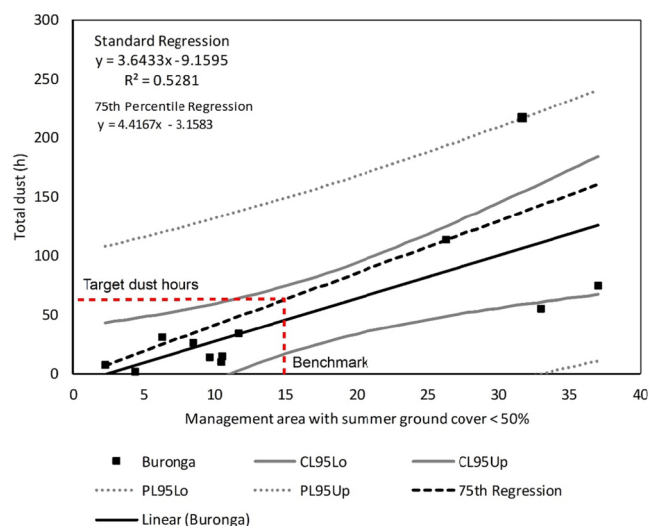
Fig. 4. Relationship between percentage area of summer (December, January and February) ground cover in management area within 25 km radius from Buronga, Australia, and total hours of dust ($PM_{10} > 25\,\mu g\,m^{-3}$) per year (July to June). Standard linear regression (linear Buronga), confidence limit 95% upper (CL95Up) and lower (CL95Lo), prediction limit 95% upper (PL95Up) and lower (PL95Lo), and 75th percentile regression line (75th regression) are shown. A benchmark can be set for ground cover in the management area based on the 75th percentile regression to meet the target of 60 h of dust.

soil degradation by wind erosion (Fig. 4). They used dust activity (hours with $PM_{10} > 25\,\mu g\,m^{-3}$) and rainfall data to build a regression model of how dust activity increased with decreasing rainfall in a dust storm year. A target number of dust hours (60 h) in the management area was identified by the 75th percentile regression; where values > 60 h suggested wind erosion exceeded that expected for the annual rainfall in the management area. The dust activity target was then related to fractional ground cover derived from 500 m MODIS data (Guerschman and Hill, 2018). Benchmarks were then identified from a regression between dust activity and the proportion of the management area with ground cover < 50% (Fig. 4).

A benefit of both mechanistic and empirical modeling is that the approaches can provide quantitative error/uncertainty estimates that can be considered in management decision making (Olson and Hawkins, 2013). Accuracy and precision vary widely among available wind erosion models (Shao et al., 2011), and these should be considered in model selection relative to the desired accuracy and precision of benchmarks. As relationships among indicators within models will be a product of model formulation, it should be recognized that benchmarks will also be influenced by model fidelity to aeolian processes. Model sensitivity analyses and reviews can help users consider trade-offs in fidelity, accuracy and precision in model selection and select appropriate benchmarks informed by model uncertainty (e.g., Darmenova et al., 2009; Webb and McGowan, 2009).

4.3. Benchmarks based on desired or reference conditions

In rangelands, 'reference conditions' are illustrated by areas where structural and functional indicators are within historical (e.g., pre-agricultural) or desired value ranges and/or anthropogenic disturbances are below thresholds thought to impact structure and function. Reference sites have been defined as locations in a 'historical condition', 'minimally-disturbed condition', 'least-disturbed condition', 'best available condition' and 'best attainable condition' (Stoddard et al., 2006). These diverse definitions have arisen from the difficulty of identifying reference sites in rangelands due to their long land use histories. For croplands and other intensively managed sites, reference sites can be identified by other functional indicators of soil and plant

processes (as inferred from soil health; e.g., soil organic carbon, electrical conductivity, microbial biomass). As criteria used to identify reference sites can vary, the use of reference sites to define benchmark conditions can be highly subjective and difficult to gain agreement on among stakeholders. The end goal of management may not be to attain reference condition, but to assess the degree of departure from the reference state and decide whether such departures are desirable given management objectives or if a new 'improved' condition should be the target (Monaco et al., 2012).

Once reference sites have been identified, percentiles of reference indicator values for an ecoregion could be used as benchmarks to classify the condition of a monitoring site as having "major", "moderate", or "minimal" departure from reference conditions, respectively (Hughes et al., 1994; Stoddard et al., 2006). When possible, indicator percentiles used to define benchmarks should be guided by the best available knowledge of the structure and function of the system and of the consequences of departure (e.g., Simon and Klimetz, 2008). Managers may aim to keep anthropogenic disturbances below thresholds thought to accelerate erosion and negatively impact agroecosystem function. Using this approach without accounting for natural environmental gradients within physiographic boundaries can lead to over- or under-protection of sites due to natural environmental gradients in indicator values. The amount of uncertainty is also strongly dependent on sample size for which the indicators were measured (Webb et al., 2019), and especially the criteria used to select the 'reference' population. Managers should consider the benefits and limitations of approaches to defining reference sites as they impact benchmarks before deciding on an approach.

4.3.1. Use of historical reference site networks

When historical reference sites can be identified, data collected at networks of reference sites can be used to develop frequency distributions of reference site indicator values and identify structural thresholds of concern (e.g., Herrick et al., 2006; Pollock et al., 2012). The distributions of indicator values are a characterization of the 'historical' range of variability expected to occur in a region in the absence of certain anthropogenic impacts. Percentiles of the resulting distributions can then be used to set benchmarks (e.g., for reference ecological states) against which monitoring data can be compared and deviations from reference conditions identified (Stoddard et al., 2006). Reference site networks are typically grouped by, or modeled continuously within, categorical variables such as physiographic boundaries (e.g., ecoregions) to account for differences in reference site potential and subsequent variability resulting from factors such as climate and topography (White and Walker, 1997). Difficulty identifying sites that have not been influenced by land use and management can make 'historical' reference sites less practical to use and reference sites may instead be defined for desired conditions.

4.3.2. Desired conditions from other monitoring data

When historical reference sites cannot be clearly identified, existing monitoring data could be used to develop benchmarks based on sites in an identified desired condition. First, monitoring sites could be screened using land use and disturbance criteria, or specific attributes related to the desired conditions (e.g., Stoddard et al., 2006; Ode et al., 2016). Screening attributes should ideally be related to erosion potential, such as conditions defining classification to ecological states. There should be sound reasoning to expect that sites represent the desired condition. Benchmarks will correspond with percentiles of indicator values for the selected sites in the desired condition.

When sites in a desired condition cannot be identified, sites in a 'least disturbed', 'best available' or 'best attainable' condition could be used. However, setting 'least disturbed', 'best available' or 'best attainable' conditions as the standard for management can have very significant policy implications, particularly if current technology and economic constraints (e.g., 'best attainable') define the reference. The

condition of 'reference sites' defined in any of these ways can vary across space and through time as human impacts are disproportionately distributed, change through time, and can have differing impacts under certain physiographic conditions (e.g., Pickup et al 1998; Vanacker et al., 2007; Bastin et al., 2012). An assumption in defining benchmarks from current conditions is that these conditions are good enough. This may be appropriate for meeting management objectives if the 'best available' current condition matches the desired condition or ecological state. However, management objectives may aspire to smaller wind erosion and dust emission rates than are occurring today. Accepting a baseline that represents, or is shifting towards, an alternative state or degraded condition, or including too many degraded sites in the reference, can reduce benchmarks, potentially under-protect assessed sites and perpetuate soil degradation (Wiersma, 2005; Soga and Gaston, 2018). It is also conceivable that some 'least disturbed' sites may have larger erosion rates than disturbed locations (e.g., with invasive grasses that provide surface sheltering), and this should be considered against other management objectives. To avoid unintended consequences, selecting sites with specific attributes defined by ecological states should be used to identify the 'least erodible conditions'. Monitoring sites used to establish benchmarks should be independent of those being assessed to avoid introduction of circular reasoning into management decisions.

5. Establishing benchmarks for policy and regulation

Most monitoring benchmarks relating to wind erosion have been set for policy and environmental regulations for air quality. The US Clean Air Act of 1970 and Environmental Protection Agency's (EPA) 1999 Regional Haze Rule are examples of regulatory actions to manage air quality and visibility impairment, including impacts of mineral dust. Similar regulations are in place at national, state and county levels globally. The regulations typically stipulate concentrations limits (e.g., for wilderness areas and around cities and towns) as functional thresholds for particulate matter with aerodynamic diameter $< 10\,\mu m$ (PM_{10}) and $< 2.5\,\mu m$ ($PM_{2.5}$) that may be suspended in the atmosphere for long periods (e.g., hours to weeks) and impact human health. For example, the US National Ambient Air Quality Standards (NAAQS) state the 24-hour average PM_{10} concentration must not exceed $150\,\mu g\,m^{-3}$ more than once per year on average over three years to meet the NAAQS (EPA, 1997).

Policy and regulations may stipulate benchmarks, and so should be referenced by managers, but they are not the mechanism used to develop a given benchmark. Benchmarks adopted as policy should be developed based upon scientific understanding and identified from one or more information sources (e.g., scientific literature, models, monitoring data) on the impacts of indicator conditions on the environment and human health and safety. Science-policy briefs may outline principles and approaches for establishing benchmarks. For example, the UNCCD developed 'Target-Setting Building Blocks' to provide guidance for identifying indicators, setting benchmarks, and assessing progress toward Land Degradation Neutrality that are relevant to managing wind erosion and other sustainability challenges (UNCCD, 2016).

To provide managers with flexibility in meeting targets and avoiding unintended consequences, policy should encourage use of indicators of outcomes (e.g., dust concentrations) over factors that determine these outcomes. However, unless policy is made relevant to managers and land management agencies, the existing disconnect between dust monitoring and land management (Section 2.4) is likely to remain. Policy should therefore provide a clear path for agencies and managers to link wind erosion and air quality outcomes to management actions. This could be achieved, for example, by requiring natural resource management plans of land management agencies to address air quality policy set out by environmental protection agencies. Establishing such links would also require models and analysis tools that enable managers to connect indicators of controlling factors of wind erosion to air quality impacts of dust. This would enable managers to

adopt locally relevant mitigation strategies (e.g., increase area sheltered from wind erosion) and understand how effective management strategies are (and why) in meeting broader policy objectives. Where indicators of outcomes are too expensive to measure, management flexibility may be promoted by identifying alternative indicators (e.g., vegetation cover and structure) that may be used to predict achievement of outcome-based targets, provided that the outcome remains the overall objective. This both helps promote innovation as managers focus on the desired result, rather than the regulation, and allows for the introduction of new less expensive measurement technologies in the future.

6. Best practices for establishing monitoring benchmarks

In the absence of existing benchmarks for wind erosion, managers are faced with the need to use best professional judgement to develop benchmarks from available information sources. In all cases, best professional judgement should be based on relevant science and data (Gordon et al., 2016). The approaches described above for establishing benchmarks are not mutually exclusive in principle or practice. Using a combination of approaches is therefore recommended. Multiple lines of evidence should be provided for different monitoring indicators. Benchmarks should reflect aeolian process mechanics whilst being relevant to broader land management objectives at relevant scales of management. Air quality benchmarks may reflect blowing dust impacts but should be related to the causal soil and vegetation controls in eroding landscapes to directly inform management. A basic set of principles for developing monitoring benchmarks should therefore be followed.

Benchmarks should account for differences in site potential across landscapes and thresholds of structural and/or functional concern. This can be achieved by establishing benchmarks for areas defined by climoedaphic groups (e.g., ecological sites; USDA, 2013) using information that is relevant to the geographic area of interest. Linking wind erosion indicators to ecological sites through applications like the Ecosystem Dynamics Interpretive Tool (Bestelmeyer et al., 2016) would improve our ability to set benchmarks, assess whether sites meet (or fail to meet) monitoring objectives, and enable wind erosion to be considered alongside other ecosystem processes and services (e.g., Galloza et al., 2017).

The amount and quality of information and compatibility of data collection methods used to group sites and establish benchmarks should be described. This includes policy documents, regulations and scientific literature, which should be cited with a rationale for including (and excluding) different information sources or studies. It is important to understand the geographic location and sample size of data used to establish benchmarks and how reference conditions were defined and used to develop indicator distributions and models. Understanding how model uncertainties and the shape and bias of indicator distributions can affect benchmarks is important to determine whether model-informed benchmarks will result in more or less protection of resources than other data-driven approaches. All approaches for setting benchmarks have their own limitations and are subject to error. Benchmarks should be periodically reviewed and updated as new information becomes available. Benchmarks should also be updated to account for shifting baselines in resource condition and ecological state transitions, including emergence of 'novel states', in response to land use and climate change (Soga and Gaston, 2018). Overall, robust benchmarks should enable managers to: (1) assess the degree or risk of departure of sites from desired conditions; and (2) make objective decisions to maintain agroecosystem structure and function and air quality.

7. Conclusions

Identifying indicators and establishing benchmarks for monitoring wind erosion and blowing dust are required to quantitatively assess

management outcomes and whether management objectives have been met (UNEP, WMO, UNCCD, 2016). Numerous indicators of wind erosion are routinely collected by coordinated monitoring programs, including indicators based on soil properties and vegetation characteristics, indicators of land health attributes, and indicators of air quality. Some of these (e.g., air quality indicators) are widely used among practitioners interested in the impacts of blowing dust, while available soil and vegetation datasets are generally underutilized to inform wind erosion assessments and management.

Using monitoring data to inform wind erosion assessments and management requires indicator benchmarks that describe desired conditions and can trigger adjustments to management practices, additional data collection, or indicate management success. Wind erosion and air quality benchmarks have been established by policy and environmental regulations from peer-reviewed literature, but approaches that use readily available soil and vegetation indicators are needed to provide clearer links between land management and wind erosion outcomes. However, care should be taken to account for shifting baselines and potential under-protection of resources when using existing monitoring data to establish benchmarks. Few scientific studies have quantified functional thresholds for wind erosion and research and syntheses are needed, particularly for rangelands, to enable land managers to access this information to establish benchmarks. The best approach to establishing benchmarks is one that is based on rigorous science and/or monitoring data and documents the rationale for selecting indicator values or ranges based on their environmental and human impacts. By promoting links between land management and indicators of outcomes (e.g., through resource management plans), policy can promote management flexibility for meeting benchmarks to avoid trade-offs and unintended consequences. The approaches to establishing benchmarks described here have broad utility for managing agroecological systems, as monitoring technologies change, and for considering co-benefits of resource management among multiple ecosystem services.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105881.

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