Quantifying Anthropogenic Dust Emissions

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Quantifying Anthropogenic Dust Emissions

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Key Points:

- Land use and land cover change impact dust emissions, but uncertainty in estimates remains large
- State-and-transition models linking ecological and aeolian processes provide a framework for accurate and management-relevant assessments
- Interdisciplinary approaches that couple dust models with land surface and agricultural models show potential for resolving the drivers

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Abstract Anthropogenic land use and land cover change, including local environmental disturbances, moderate rates of wind-driven soil erosion and dust emission. These human-dust cycle interactions impact ecosystems and agricultural production, air quality, human health, biogeochemical cycles, and climate. While the impacts of land use activities and land management on aeolian processes can be profound, the interactions are often complex and assessments of anthropogenic dust loads at all scales remain highly uncertain. Here, we critically review the drivers of anthropogenic dust emission and current evaluation approaches. We then identify and describe opportunities to: (1) develop new conceptual frameworks and interdisciplinary approaches that draw on ecological state-and-transition models to improve the accuracy and relevance of assessments of anthropogenic dust emissions; (2) improve model fidelity and capacity for change detection to quantify anthropogenic impacts on aeolian processes; and (3) enhance field research and monitoring networks to support dust model applications to evaluate the impacts of disturbance processes on local to global-scale wind erosion and dust emissions.

1. Introduction

Anthropogenic land use and land cover change (LULCC) impact rates of wind-driven soil erosion and mineral dust emission (Ravi et al., 2010). Local to regional-scale changes in dust source erodibility are occurring globally in response to the areal expansion and intensification of agriculture to meet demands for food and fiber, episodes of drought, altered hydrological regimes, and changes in land use and tenure (Zobeck et al., 2013). Dust emissions from disturbed areas impact ecosystem dynamics and agricultural production, air quality, human health, biogeochemical cycles, and climate (Field et al., 2010; Shao et al., 2011). Since the mid-Holocene, regional atmospheric dust loads have increased concurrently with the expansion of human land-use activities; for example, by up to 500% in North America (Neff et al., 2008). Elevated dust deposition rates relative to pre-European colonization have been recorded in the North Atlantic (Mulitza et al., 2010) and Australia (Marx et al., 2014). On shorter time scales, Dust Bowl conditions in the United States in the 1930s (Lee & Gill, 2015), and Australia from 1895 to 1945 (Cattle, 2016), illustrate the potentially devastating impacts of LULCC and land management-induced wind erosion for agroecological systems and the societies that depend on them (Figure 1) (ELD Initiative, 2015). However, uncertainty in the magnitude of anthropogenic dust emissions remains large. Resolving the impacts of LULCC on aeolian processes is needed to quantify anthropogenic dust loads and identify management options. These options are required now to combat land degradation and desertification, provide food security, and enable Sustainable Development Goals to be achieved (United Nations, 2015).

Global dust modeling suggests that the anthropogenic contribution to atmospheric dust loads today range between 10% and 60%, that is, between ~90 and 2000 Mt. year^{-1} (e.g., Mahowald et al., 2010; Shao et al., 2011; Tegen & Fung, 1995). Projections of future atmospheric dust loads suggest that emissions may increase (Stanelle et al., 2014), decrease below present levels (Mahowald et al., 2006; Mahowald & Luo, 2003), or remain stable (Ashkenazy et al., 2012) in response to climate change. Regional assessments are similarly uncertain. For example, Xi and Sokolik (2016) estimated an anthropogenic contribution of 18.3%–56.5% of total dust emissions from Central Asia depending on model selection and how source erodibility was represented. Regional studies have questioned the causality of observed changes in atmospheric dust loading, suggesting that changes in surface wind speeds are responsible rather than

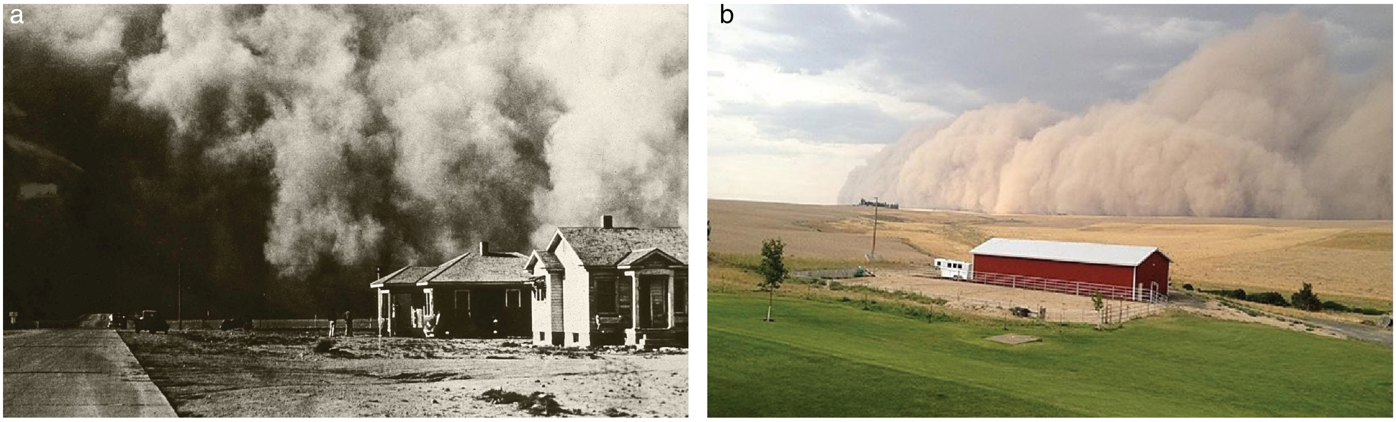

Figure 1. Wind erosion has been a key resource concern for land managers globally since the introduction of European farming practices and vast expansion of croplands. In the United States, extensive wind erosion during the 1930s Dust Bowl (a) instigated research efforts to minimize anthropogenic soil erosion and dust emissions and their environmental and human impacts. Many of these challenges remain today, for example on the Columbia Plateau, Washington (b) where dust emissions from croplands deplete soil nutrients and pose major hazards to highway safety and human health. Photo credits (a) Natural Resources Conservation Service (NRCS), (b) Associated Press.

land cover change (Ridley et al., 2014). Nevertheless, in many cases the mechanisms remain unclear as climate variability, changes in land surface roughness, and changes in erodible sediment supply may all be responsible for the observed changes in global dust emissions (Cowie et al., 2013).

Satellite remote sensing has enabled detection of dust source locations at higher spatial resolutions (e.g., Baddock et al., 2016; Bullard et al., 2011; Moulin & Chiapello, 2006; Prospero et al., 2002), and an evaluation on the basis of land use that 25% of global dust sources may be anthropogenic (Ginoux et al., 2012). However, the attribution of dust sources to anthropogenic drivers due to land use alone omits critical information about the intensity of land management and its relation to dust source erodibility. These interactions have largely been excluded from regional analyses. Extensive field and wind tunnel experimentation have provided a basis for understanding the causal mechanisms of anthropogenic wind erosion and dust emission at small spatial scales (see review by Zobeck et al., 2013). Developments in remote sensing and numerical modeling, and of indices of land use intensity (LUI), have afforded new opportunities to explore human impacts on dust source erodibility (e.g., Xi & Sokolik, 2016). Despite these advances, critical challenges remain in (1) establishing assessment frameworks that state explicitly how anthropogenic dust can be quantified, and (2) improving the sensitivity of assessment models and supporting data to reduce uncertainties and facilitate detection. Understanding how land use and land management activities impact land cover change to influence dust emission will be key to quantifying human impacts on the dust cycle.

Here, we critically review the mechanisms and evaluation approaches to quantify anthropogenic dust emissions. We then identify and describe opportunities to (1) develop new conceptual models and interdisciplinary approaches to improve the accuracy and relevance of assessments of anthropogenic dust emissions, (2) improve model fidelity and capacity for change detection to quantify anthropogenic impacts on aeolian processes, and (3) enhance field research and monitoring programs to support dust model applications to evaluate the impacts of land use, land management, and land cover change on wind erosion and dust emissions.

2. Current Approaches to Evaluate Anthropogenic Dust Emissions

The connectedness of the dust cycle to human health, agricultural production and the climate system has made the need to quantify and objectively differentiate anthropogenic dust emissions from "natural" dust emissions apparent for some time (Zobeck et al., 2013). In a synthesis of the problem, Zender et al. (2004) defined two kinds of anthropogenic mineral dust emission: (1) arising from human land uses that directly emit dust to the atmosphere (e.g., cultivation) or disturb soils and/or vegetation so that the land surface is more susceptible to erosive winds; and (2) arising from human modification of the climate, which in turn modifies wind erosivity, land erodibility, and the magnitude of dust emissions. Implicit in studies framed by these definitions has been an assumption that dust emissions prior to the industrial era were natural, although land cover globally has been modified by human activities since the late Pleistocene (Kay

& Kaplan, 2015; Pongratz et al., 2008; Ruddiman, 2003). Anthropogenic dust emissions are typically assessed as the total dust emissions from land surfaces thought to be modified by humans (e.g., Ginoux et al., 2012). However, anthropogenic dust has also been quantified as the difference in emissions from a disturbed to a reference condition (e.g., Webb et al., 2014). While these definitions clearly state the potential different causes of anthropogenic dust, neither conveys the mechanisms, the complexity of the processes, or how this complexity can be resolved consistently to quantify emissions.

Figure 2 illustrates key interactions between LULCC and the dust cycle. Dust emission processes are influenced by LULCC via associated direct and indirect manipulation of soil properties that influence erodible sediment supply and vegetation properties (cover, structure, spatial arrangement) that provide resistance to the erosive forces of the wind (Gillette, 1999; Webb & Strong, 2011). Anthropogenic impacts on the wind erodibility and dust emission potential of landscapes may be extensive or intensive in terms of the area affected and the degree of land surface modification and, therefore, potentially have different levels of detectability at different spatial scales. For example, livestock grazing and trampling of rangelands can modify the foliar cover and height of vegetation (Aubault et al., 2015; Belnap et al., 2009) and break down protective soil crusts in the short term (Baddock et al., 2011; Leys & Eldridge, 1998; Munkhtsetseg et al., 2017), or act as a driver of long-term ecological (land cover) change (Bestelmeyer et al., 2015). These impacts typically occur at the landscape scale (extensive), but can also be concentrated — for example, around livestock watering points that may become locally degraded and susceptible to accelerated wind erosion (i.e., net soil loss) and dust emission (e.g., Dougill et al., 2016). Cropland management practices can create mosaic landscapes with dust emission hot spots arising in response to tillage practices and crop rotations within individual fields (Bielders et al., 2002; Houyou et al., 2016; Lee et al., 2012; Rajot, 2001; Singh et al., 2012). Similarly, intensive landscape disturbances resulting from altered hydrological regimes (e.g., river diversion), energy development, graded road networks, and off-road vehicle activity, modify land cover and potentially accelerate point-source dust emissions (Goossens & Buck, 2009; Zhao et al., 2017). Wind erosion accelerated by LULCC influences soil nutrients and biogeochemical cycles, the land surface energy budget, and climate, with feedbacks that can promote further land cover change, dryland expansion, and increased dust emissions (D'Odorico et al., 2013). For example, wind erosion of Sahelian croplands has been found to reduce soil nutrient levels by approximately the same order-of-magnitude as the uptake typically required by millet in 1 year - reducing the land potential for successful crop production (Bielders et al., 2002; Drees et al., 1993; Sterk, 2003).

Efforts to quantify anthropogenic dust emissions have approached the problem with a focus either on plot and field-scale land management impacts on wind erosion, for example, from the early work of Chepil (1941), or on regional to global-scale dust source regions (Muhs et al., 2014). Anthropogenic dust emissions resulting from direct human modification of landscapes have been estimated from deposition records, revealing order-of-magnitude changes in dust emissions that correlate with the timing of agropastoral development and drought (Marx et al., 2014; Mulitza et al., 2010; Neff et al., 2008). Nonetheless, establishing the land use drivers from these correlations is a challenge (Cockerton et al., 2014; Waller et al., 2007). Model experiments to quantify dust emission rates have indicated the extent of land surface disturbance required to produce contemporary dust aerosol loadings (e.g., Tegen & Fung, 1995), while remaining limited by the accuracy of forcing data (Menut, 2008) and model fidelity (Raupach & Lu, 2004). Pattern analysis of remotely sensed dust optical depth has provided further insights into the distribution of source areas in relation to land use and land cover classifications, but has omitted the influence of LUI (Ginoux et al., 2012; Lee et al., 2012; Prospero et al., 2002). Research into the temporal dynamics of dust source areas has sought to explain the relative significance of regional changes in wind erosivity and vegetation for emissions (Cowie et al., 2013; Evans et al., 2016; Moulin & Chiapello, 2006; Ridley et al., 2014). Model analyses of anthropogenic dust emissions of the second kind, resulting from climate change, have shed light on potential future emissions as a function of wind erosivity and vegetation responses to warming and elevated atmospheric CO_2 concentrations (e.g., Ashkenazy et al., 2012; Mahowald & Luo, 2003; Stanelle et al., 2014).

Building on the advances cited here, many opportunities remain to improve assessment methods and models and to explore the gaps in our understanding of human-dust cycle interactions. Modeling and remote sensing analyses are yet to establish how different land uses are impacting dust emissions across land cover types, particularly at the landscape scale, and the magnitude of uncertainties in projected dust emissions due to LULCC and climate change remain largely unknown. These are nontrivial problems that require

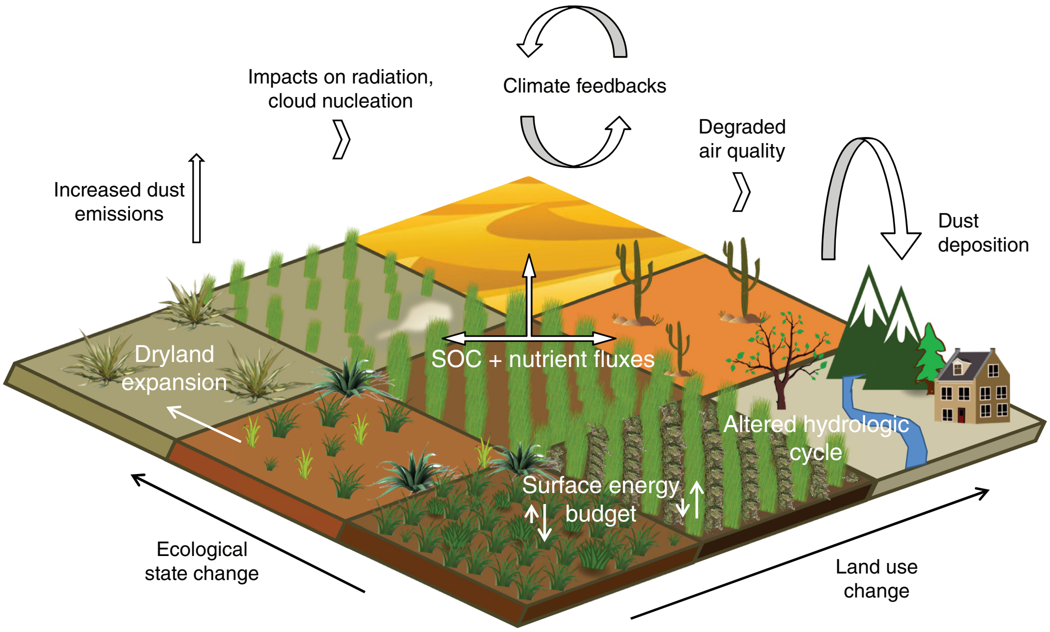

Figure 2. Illustration of interactions between anthropogenic land use and land cover change (LULCC) and the dust cycle. Human land use activities, such as agriculture and livestock grazing, potentially cause soil surface disturbance and changes in vegetation species composition, structure and spatial patterns. These land cover changes can increase the susceptibility of landscapes to wind erosion. Elevated rates of wind erosion and dust emission impact human health, soil organic carbon (SOC) and nutrient cycles, the energy budget, hydrologic cycle, and climate. Wind-driven soil loss and nutrient decline, and dust-climate feedbacks, in turn impact agricultural production and rates of ecological change and dryland expansion.

research to: better capture dust source erodibility dynamics in models, including responses to cropland and rangeland management; improve the accuracy of forcing (e.g., wind speed, land cover) data used to drive assessments and interpret dust emission patterns; and incorporate information about land management drivers of LULCC and feedback mechanisms into assessments to represent baseline and future scenarios of dust emission under climate change.

3. Future Research Directions to Resolve Anthropogenic Dust Emissions

Perhaps the greatest research opportunities for resolving anthropogenic dust emissions will come from conceptual frameworks and interdisciplinary approaches that connect aeolian processes with the underpinning drivers of LULCC. To benefit from interdisciplinary approaches, dust model parameterization schemes and input data must better resolve dust emission responses to environmental change. These model improvements should be supported by field data across land use and land cover types that provide new insights into wind erosion sensitivities to LULCC and enable rigorous model testing. Here, we explore opportunities that support these future research directions.

3.1. Develop Interdisciplinary Approaches Supported by New Conceptual Frameworks

Connecting aeolian processes with the drivers of LULCC will be essential for resolving anthropogenic impacts on dust emissions. This requires consideration of (1) the intensity of land use and land management within land cover types, and (2) landscape-scale variability of soil and vegetation properties that control patterns of wind erosion and dust emission. These connections could be made within conceptual frameworks provided by ecosystem dynamics theory, and by integrating aeolian sediment transport processes into land surface models (LSMs) and agricultural systems models to support analyses.

Defining what constitutes anthropogenic dust with the specificity to unpack the causal mechanisms is a requisite step toward developing an assessment framework. Ecological theory describing the nonequilibrium dynamics of dryland ecosystems provides a framework in state-and-transition models (STMs)—“box-and-arrow diagrams accompanied by data-supported narratives to describe states (boxes) and the ecological processes driving change within and between states (arrows)” (Bestelmeyer et al.,

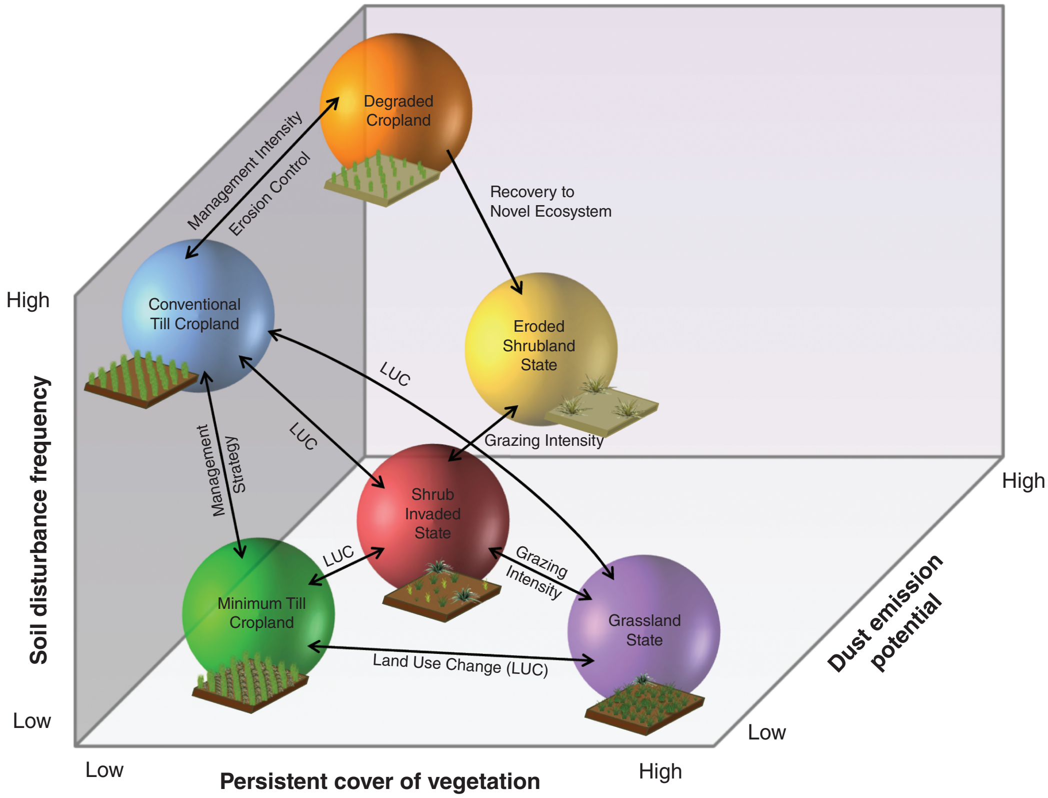

Figure 3. Conceptual state-and-transition model (STM) illustrating ecological states (spheres) and potential state-changes and land use change (arrows) with their management drivers and dust emission responses. For a given ecological site, each ecological state (e.g., grassland, shrub-invaded grassland or shrubland) will have some range of potential wind erodibility based on the ground cover dynamics and soil disturbance frequency. These characteristics are moderated by land use intensity and management practices, which may also be drivers of state change. Anthropogenic dust emissions may result from a management-induced state change, or change in ground cover within an ecological or land use state.

2015)—within which we can define two levels of human-dust cycle interaction. Anthropogenic dust emissions may be considered: (1) a departure of the magnitude of dust emissions from the established "normal" range for a land cover type associated with a gradual or abrupt transition (regime shift) from one ecological state and land use to another (e.g., grassland to shrubland, or grassland to cropland), where the transition can be attributed to human activities, and (2) a departure of the magnitude of dust emissions within an ecological state and land use (e.g., grassland) that is outside the natural variability for that state and where the within-state ground cover change (e.g., reduction in foliar cover or protective soil crusts) can be attributed to human activities (e.g., Webb et al., 2014). The STM framework makes explicit the fact that each soil-vegetation complex within a landscape has potentially a unique ecological response to land use, land management and climate (Figure 3) (Bestelmeyer et al., 2010). The framework also highlights the challenge of establishing an anthropogenic dust signal, as human factors often cannot be identified with confidence as being the sole driver of land cover change (D'Odorico et al., 2013). For example, it can be difficult to isolate the role of livestock grazing as a driver of land cover change in drylands typified by stochastic precipitation, nonequilibrium plant communities, and multiple feedbacks between biotic and abiotic processes (Sayre, 2017). The period over which an assessment is being made will be critical to determining whether anthropogenic dust can be attributed to an ecological state change, as states can persist for decades and changes may have occurred decades ago (Peters et al., 2015). Due to this complexity, in many cases quantifying the anthropogenic dust contribution may not be straightforward or even possible.

Implementing an STM framework to assess anthropogenic dust emissions requires an ecological land classification that defines kinds of land that respond similarly to management actions and natural disturbances. These have been defined in the United States as "ecological sites" (United States Department of Agriculture

[USDA], 2013), although the classification is applicable globally. LUI is represented in STMs to describe ecological site responses to, for example, livestock grazing, cropland management, and disturbances like fire and vegetation clearing (Bestelmeyer et al., 2010). Ecosystem dynamics models (e.g., BIOME3 (Mahowald & Luo, 2003), DAYCENT (Parton et al., 1998), and ViSTA (Mayaud et al., 2016)) could be used to evaluate dust emission responses to ecosystem state changes at different spatial and temporal scales. For example, Aubault et al. (2015) applied the GRASs Production (GRASP) model to evaluate wind erodibility responses to different grazing strategies and land condition. Hyper-temporal remote sensing approaches to mapping ecological sites (Maynard & Karl, 2017) offer potential for assessing dust emission responses to LULCC and breaks in seasonal dust trends that may be attributed to natural or anthropogenic drivers. These approaches suggest that resolving anthropogenic impacts on wind erosion and dust emission may be most effective at the landscape scale, at which land management-land cover interactions take place.

Within assessment frameworks, analyses of anthropogenic dust emissions would also benefit from the integration of dust models with LSMs and agricultural systems models that enable human-dust cycle interactions to be quantified. Building dust emission, transport and deposition processes into LSMs (e.g., the Joint UK Land Environment Simulator [JULES], ORganizing Carbon and Hydrology in Dynamic EcosystEms [ORCHIDEE], and Noah models) and agricultural systems models (e.g., the Agricultural Policy/Environmental eXtender [APEX], the Agricultural Production Systems sIMulator [APSIM], and Decision Support System for Agrotechnology Transfer [DSSAT]) would enable more advanced scenario development to test the effects of LULCC and land management change on the dust cycle than have previously been achieved at the field scale or globally (Evans et al., 2016; Pierre et al., 2015, 2017). Research seeking to establish climate change impacts on dust emission could incorporate agricultural adaptation scenarios to represent management change, as well as considering the uncertainty in climate projections (Pelletier et al., 2015). Ensemble dust modeling through the Agricultural Model Intercomparison and Improvement Project, AgMIP (Rosenzweig et al., 2013) could provide additional insights into climate change-land management-wind erosion relations, and their feedbacks to terrestrial ecosystems and food security.

3.2. Improve Dust Model Fidelity and Capacity for Change Detection

Improved dust model parameterization schemes and model input data are needed to resolve dust emission responses to LULCC and the intensity of land management. Recent advances in our understanding of dust source emission processes are helping to constrain model uncertainties (Bryant, 2013). However, dust model limitations that have persisted over the last few decades (Raupach & Lu, 2004) continue to restrict anthropogenic dust assessments because (1) drag partition schemes to represent surface roughness effects on sediment transport have been insensitive to spatial patterning of vegetation, and (2) soil erodibility temporal dynamics, surface disturbance, and dynamic vegetation conditions are often inadequately represented at broad spatial scales (Webb & McGowan, 2009).

Land cover change is often characterized by one or more changes to vegetation foliar cover, canopy height, and canopy spatial configuration, which influence dust emission. Drag partition schemes based on approximations of the land surface aerodynamic roughness (z_0) and lateral cover (λ) can be difficult to parameterize (Pierre et al., 2014) and are insensitive to roughness distribution (see review by Shao et al., 2015). As a result, they inadequately represent the heterogeneous distribution of wind momentum at the soil surface that is responsible for driving dust emissions (Webb et al., 2014). This has resulted in a need to retain rudimentary dust source masks in models that restrict emissions to regions with arbitrarily small vegetation cover. Model insensitivity to vegetation spatial patterns limits the ability of assessments to detect the impacts of land cover change (Shao et al., 2015). New remote sensing approaches to estimate land surface aerodynamic properties look to overcome this limitation of drag partition schemes, and how models account for vegetation (Chappell & Webb, 2016). Ultimately, resolving anthropogenic dust emissions may require a conscious shift away from bulk drag partition schemes based on z_0 and λ toward schemes that are sensitive to roughness configuration dynamics that moderate patterns of dust emission (Okin, 2008).

Solutions to representing soil erodibility dynamics beyond the effects of soil moisture have remained limited to cropland wind erosion models, although remote sensing may also be key to describing soil surface change at broad spatial scales (Chappell et al., 2007; Marticorena et al., 2006). Short of a generalizable dynamic soil erodibility model, significant improvements could be made now to dust model sensitivity to LULCC by representing the land cover dynamics (Ito & Kok, 2017). Computing power and the availability of surface roughness data, including global photosynthetic and nonphotosynthetic vegetation cover fractions (Guerschman et al., 2009) and lateral cover (Chappell et al., 2017), should encourage dust modeling to move beyond use of the normalized difference vegetation index (NDVI) and leaf area index (LAI) vegetation indices that can misrepresent plant phenological effects (Lu et al., 2003). Refinement of remote sensing approaches to estimate the land surface aerodynamic roughness and entrainment threshold (e.g., Chappell & Webb, 2016) should overcome limitations of static dust source erodibility characterizations that are insensitive to land cover change (Parajuli & Zender, 2017). Linking dust models to LSMs and agricultural systems models will arguably encourage greater consideration of how land surface properties that respond to anthropogenic LULCC and land management can be incorporated into dust modeling (Pelletier et al., 2015).

3.3. Enhance Field Measurements and Observation Networks

Field measurements of aeolian sediment transport responses to land management and land cover change remain critical to resolving anthropogenic dust emissions. Field data are needed to improve understanding of aeolian process responses to LULCC and to support development and testing of dust models to quantify their uncertainties. Some disconnect has emerged, through methodological differences, between research at small spatial scales to resolve land management impacts on wind erosion and broad-scale (regional to global) studies of anthropogenic impacts on the dust cycle (Webb & McGowan, 2009). New opportunities to connect the research domains and our understanding may be found in measuring and monitoring landscape-scale processes and LULCC-land management-wind erosion interactions.

Networked and geographically diverse dust monitoring programs are supporting linkages between small-scale aeolian process research and regional dust modeling that could promote advancements in anthropogenic dust assessment (UNEP et al., 2017). The long-term Australian DustWatch program (Leys et al., 2008), Sahelian Dust Transect (Marticorena et al., 2010), and US National Wind Erosion Research Network (Webb et al., 2016) are connecting research across sites and scales to address critical challenges in modeling dust emission responses to LULCC and land management. Standardized and networked measurements of sediment transport rates across land cover types enable more rigorous model testing than has been possible at the site scale and are required to assess dust impacts of LULCC and land management. Model assimilation of aerosol monitoring data (e.g., the Aerosol Robotic Network, AERONET) will continue to be important for testing regional dust estimates (Pope et al., 2016) and could benefit from incorporation of networked surface measurements of aeolian sediment transport rates and their land surface and meteorological controls (Webb et al., 2017). However, the success of networked monitoring programs and field experiments to support dust modeling and analyses will be strongly influenced by their measurement uncertainties. To date, wind erosion sampling designs that have relied on measurements at one or a few locations in space have limited the capacity of networks to measure statistically significant change among sites (Chappell et al., 2003). Current and future efforts must consider the sampling power and uncertainty of field and landscape-scale wind erosion monitoring. To achieve this, monitoring programs must employ sampling designs with a sufficient sediment number of samplers to capture the large spatial variability in sediment transport, in addition to the temporal variability, and are appropriate to establish at a relevant confidence level the minimum detectable change. Maintaining funding for long-term monitoring networks will ensure that quality standardized data are available to support analyses and dust modeling efforts to understand the drivers and effects of anthropogenic dust emission.

4. Conclusions

Anthropogenic LULCC has potentially massive impacts on rates of wind-driven soil erosion and dust emission, but the magnitude of these impacts remains highly uncertain. Societies, supported by sustainable agroecological systems, need accurate information about how land uses and land management impact aeolian processes and their feedbacks to biogeochemical cycles, ecological processes, and the climate system. While significant progress has been made to understand and quantify human-dust cycle interactions at small and large spatial scales, numerous opportunities remain to reduce the uncertainty of assessments and produce information that can better inform land management and policy options. Here, we have explored future research directions that could generate new lines of enquiry and insights into the causes, magnitude, and effects of global anthropogenic dust emissions.

We propose that the development of interdisciplinary approaches that integrate conceptual models of ecological state change-land use change with aeolian processes will be key to assessing where, when, and how LULCC and land management influence dust source erodibility and emissions. The STM framework underpinning current research on dryland ecological systems provides context for developing new definitions of anthropogenic dust that make explicit the nature of LULCC-land management-wind erosion interactions that has been missing from previous assessments. The STM framework also highlights the complexity of quantifying anthropogenic dust, and potential benefits that may be derived from more integrative research coupling dust models with LSMs, ecosystem dynamics models, and agricultural systems modeling. In support of these efforts, the sensitivity of dust models to soil and vegetation dynamics must be improved. New remote sensing approaches show promise for capturing land surface aerodynamic responses to land cover change, and reducing model uncertainty. Long-term wind erosion and aerosol monitoring programs will continue to play a crucial role in support of model development and applications to assess anthropogenic dust and its impacts.

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