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Exploring dust emission responses to land cover change using an ecological land classification

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A B S T R A C T

Despite efforts to quantify the impacts of land cover change on wind erosion, assessment uncertainty remains large. We address this uncertainty by evaluating the application of ecological site concepts and state-and-transition models (STMs) for detecting and quantitatively describing the impacts of land cover change on wind erosion. We apply a dust emission model over a rangeland study area in the northern Chihuahuan Desert, New Mexico, USA, and evaluate spatiotemporal patterns of modelled horizontal sediment mass flux and dust emission in the context of ecological sites and their vegetation states; representing a diversity of land cover types. Our results demonstrate how the impacts of land cover change on dust emission can be quantified, compared across land cover classes, and interpreted in the context of an ecological model that encapsulates land management intensity and change. Results also reveal the importance of established weaknesses in the dust model soil characterisation and drag partition scheme, which appeared generally insensitive to the impacts of land cover change. New models that address these weaknesses, coupled with ecological site concepts and field measurements across land cover types, could significantly reduce assessment uncertainties and provide opportunities for identifying land management options.

1. Introduction

Wind erosion of dryland soils is a global problem exacerbated by land cover change (Lal, 2001). The impacts of land cover change on wind erosion have been evaluated at regional and global scales using integrated land surface-atmosphere-dust modelling, which suggests that human modification of landscapes may contribute < 10–60% of global wind erosion (e.g., Tegen et al., 2004; Mahowald et al., 2004; Mahowald et al., 2010). Remote sensing studies appear to support the case that anthropogenic land cover change (e.g., cropland expansion into rangelands) accounts for around 25% of wind eroding areas globally (Prospero et al., 2002; Ginoux et al., 2012). At the field scale, research targeting the impacts of land use and land management practices on land cover change has revealed more about the nature of wind erosion responses to cropland and rangeland management (e.g., Webb et al., 2009; Aubault et al., 2015; Pierre et al., 2015, Pierre et al., 2017) and the impacts of landscape-scale ecological change (Floyd and Gill, 2011; Webb et al., 2014a). However, our ability to assess the impacts of land cover change on wind erosion remains limited by the capabilities of assessment models (Raupach and Lu, 2004; Li et al., 2014) and by the precision of land cover classifications used to evaluate change at broad spatial scales. Identifying land management strategies to mitigate soil degradation and build resilient agricultural systems requires that the impacts of land cover change on wind erosion can be accurately resolved (Zobeck et al., 2013; Webb et al., 2017). To improve assessment capabilities, research is needed to investigate the utility of different land classification systems and models for detecting dust emission responses to land cover change.

Land cover is defined as the (bio)physical cover of the Earth's surface (Di Gregorio and Jansen, 2005). Land cover classifications have provided a means for delineating areas, for example grasslands and shrublands, that have different surface roughness/aerodynamic characteristics and therefore susceptibilities to wind erosion (Cowie et al., 2013). Land cover has been used synonymously with land use, which describes the arrangement of human activities at the Earth's surface, and to assess anthropogenic influences on wind erosion (Ginoux et al., 2012). However, neither land use or land cover classifications used at regional and global scales (e.g., Friedl et al., 2010) contain sufficient information to identify how and why the wind erodibility of landscapes has changed. Increasing the level of detail in information used to

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interpret dust emission dynamics, and identifying models with sufficient precision to represent these dynamics, will be critical for understanding the relationship between land cover change and wind erosion and for finding management options.

Ecological models of landscape change have potential to increase the precision of dust emission assessments across land cover types and the evaluation of accelerated and anthropogenic wind erosion (Webb and Pierre, 2018). In the United States, ecological sites have been adopted by resource management agencies including the Bureau of Land Management (BLM) and the Natural Resources Conservation Service (NRCS) to provide a framework for classifying landscapes and landscape responses to natural (e.g., climate variability) and anthropogenic (e.g., management) drivers of change. Ecological sites are defined as "distinctive kinds of land with specific soil and physical characteristics that differ from other kinds of land in their ability to produce distinctive kinds and amounts of vegetation and their ability to respond similarly to management actions and natural disturbances" (USDA, 2013). State-and-transition models (STM) are used to depict and organise information about the ecological dynamics of ecological sites (e.g., Bestelmeyer et al., 2009). STMs enable integration of quantitative and qualitative information about the causes and nature of land cover change (Fig. 1), including the biophysical and biogeochemical interactions between drivers and responses, such as wind erosion (Okin et al., 2006). Connections between ecological sites, their ecological dynamics and wind erosion have previously been explored at the plot scale (e.g., Bergametti and Gillette, 2010; Webb et al., 2014a). Recent research has incorporated hydrologic data and estimates of water erosion into STMs to inform rangeland management (Polyakov et al., 2016; Williams et al., 2016). Integrating landscape-scale aeolian process responses into STMs is now required to examine the applicability of the ecological framework, coupled with the assessment power of available dust emission models, to improve understanding of the impacts of land cover change on wind erosion and identify management-relevant knowledge gaps.

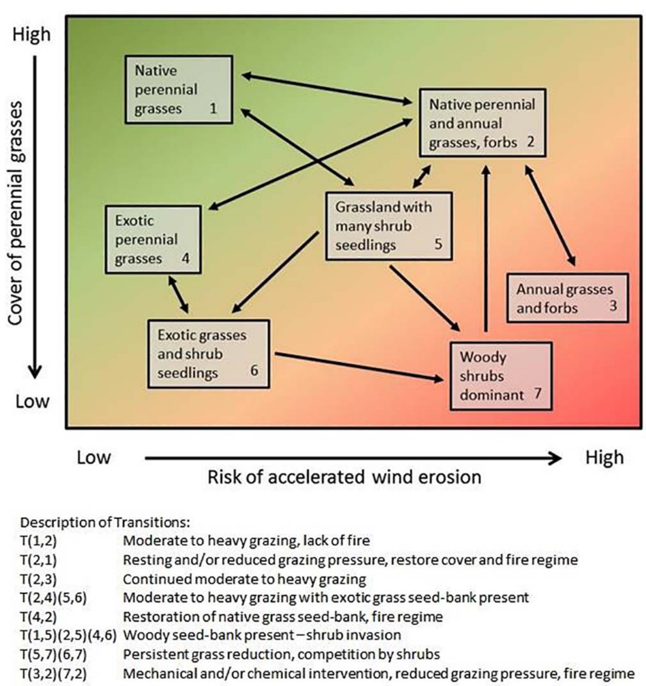

Fig. 1. Generalized state-and-transition model (STM) for an ecological site illustrating relationship of land cover change between vegetation states (1–7) with management intensity, and risk of accelerated wind erosion (modified after Ash et al., 1994). Transitions between vegetation states, for example from native perennial and annual grasses (State 2) to a shrub-invaded state (State 5) or shrub-dominated state (State 7), often entail changes in ground cover, distribution of exposed soil surfaces, and the aerodynamic roughness of a site. These changes can result in increased wind friction velocities at the soil surface, increased sediment transport rates, and the local redistribution and off-site transport of soil and nutrients. Positive biogeochemical and hydrological feedbacks between aeolian and fluvial processes may further enhance ecological change (Ravi et al., 2010).

The objective of this research was to evaluate the application of ecological site concepts and a spatial dust emission model to detect and describe the impacts of land cover change on wind erosion. We conducted the research by applying a state-of-the-art dust model (Shao, 2004), run offline with the Weather Research and Forecasting (WRF) model, with a land surface database representing soil properties and ecological sites across the southern Jornada Basin in the Chihuahuan Desert, New Mexico, USA. We evaluated model estimates of horizontal sediment mass flux and dust emission (2012–2015) in the context of historical field measurements across five ecological sites and their vegetation states (plant communities and soil surface conditions that control feedback mechanisms and ecological processes (Bestelmeyer et al., 2010)) to identify the magnitude of dust emission responses to land cover change, and how both the assessment framework and models can be improved to better assess land cover change impacts on wind erosion.

2. Materials and methods

2.1. Study area

The study area encompasses the Jornada Experimental Range, a 78,413 ha US Department of Agriculture (USDA) Agricultural Research Service (ARS) research station in the Chihuahuan Desert of southern New Mexico, USA, and additional field plots located in the adjacent Chihuahuan Desert Rangeland Research Center that is managed by New Mexico State University. The study area has a history of long-term research into the biophysical, management and climatic drivers of ecological (including land cover) change and its feedbacks with wind erosion (Havstad et al., 2006). Land cover change within the Jornada Basin has been extensive since the 1880s, following a pattern of shrub encroachment and grassland-shrubland conversion typical of the northern Chihuahuan Desert (Peters et al., 2006). The area has a history of livestock grazing, predominantly by cattle, which has been identified with drought as a driver of regional land cover change (Bestelmeyer et al., 2013). The basin therefore provides an ideal setting for evaluating the impacts of land cover change on wind erosion at scales bridging the gap between field measurements (e.g., Webb et al., 2014a) and regional modelling studies (e.g., Mahowald et al., 2010). The study area is dominated by six ecological sites: Loamy, Clayey, Gravelly, Sandy, Shallow Sandy, and Deep Sand, with the sandy sites differentiated by soil depth to a petrocalcic horizon (Shallow Sandy at 20–50 cm) and/or textural change (Sandy at 50–75 cm; Deep Sand at > 50 cm). Table 1 reports the total area covered by each ecological site within the study area and defines their vegetation states. Fig. 2 illustrates the spatial distribution of the ecological sites and modelling domain within the Jornada Experimental Range. The study area has an arid to semi-arid climate, with long-term (90-year) mean annual temperature of 15 °C (Wainwright, 2006). Mean annual precipitation (1915–2014) for the study area was 250 mm (coefficient of variation 35%), with 60% falling in the summer months from June through September.

2.2. Model description

2.2.1. Dust model

Wind erosion and dust emission were estimated using the Shao (2004) dust model run offline using atmospheric and land surface (i.e., soil moisture) data from the Weather Research and Forecasting (WRF) model, and a GIS database representing static soil properties and ecological sites. Similar and online applications of the dust model are reported by Shao et al. (2007), while Darmenova et al. (2009) provide a