ARTICLE IN PRESS

Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Improving ground cover monitoring for wind erosion assessment using MODIS BRDF parameters

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ARTICLE INFO

Keywords:
Ground cover
Lateral cover
Wind erosion
Albedo
MODIS
BRDF
Australia
USA

ABSTRACT

Measuring and monitoring controls on wind erosion can facilitate detection and prediction of soil degradation important for food security. Ground cover is widely recognised as an important factor for controlling soil erosion by wind and water. Consequently, maintaining ground cover (e.g., vegetation, crop canopy, crop residue) is a recommended management practice which is widely adopted by farmers and land owners. Wind erosion is a lateral or horizontal process and the amount of ground cover needed to maintain lateral cover ($L_c = nbh/S$ where n roughness elements occupy ground area S and have b and h mean breadth and height, respectively) is not well-established. Soil may be removed from beneath or between crop and natural vegetation canopies depending on the width, height and distribution of cover types relative to wind direction and strength. Monitoring by repeated measurement or estimation of ground cover provides information to develop an understanding of its spatial and temporal variation. Fractional cover (f_c) retrieved from optical satellite remote sensing (e.g., Moderate Resolution Imaging Spectroradiometer; MODIS) provides a consistent and repeatable measure of ground cover when viewed from above. Therefore, f_c provides an areal assessment of components of ground cover. Fractional cover is consequently not the most appropriate approximation of the protection of the soil from wind erosion. Extant wind erosion model parameterisations of L_c already benefit from the use of satellite-derived cover data (L_{fc}). However, the parameterisations are not well developed. Here, we address the need for a dynamic (multi-temporal), moderate resolution and global metric for wind erosion assessment and modelling. We demonstrate the benefits of using L_c within the context of monitoring ground cover for the assessment of wind erosion and review the basis for estimating ground cover using L_c. We describe a new method for an albedo-based approximation of aerodynamic sheltering (L_ω). We use ray-casting of rough surfaces from an existing wind tunnel study to establish a relation between measured L_c and directional hemispherical reflectance $\omega_{dir}(0^\circ,\lambda)$, the so-called 'black-sky albedo' and its inverse to estimate shadow. The relation is confirmed to be dependent on the solar zenith angle (θ) and spectral (λ) confounding factors (e.g., soil moisture, soil mineralogy). We reduced the λ dependency of $\omega_{dir}(0^\circ,\lambda)$ by normalising with the MODIS (MCD43A1) BRDF parameter f_{iso} to estimate albedo-based lateral cover (L_ω) globally over space (500 m pixels) and time (every 8 days). We compared L_ω with f_c and L_{fc} over time for selected locations in Australia and examined L_ω across Australia and the USA using national biogeographic regions. Consistent with current approaches to estimating L_c, our results were not field validated due to the dearth of ground-based measurements. However, our results demonstrate that L_ω will improve wind erosion models particularly over large areas and L_ω is likely to be a valuable source of decision-support information to guide policy makers and land managers on where, when and how to reduce wind erosion.

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http://dx.doi.org/10.1016/j.rse.2017.09.026
Received 20 September 2016; Received in revised form 11 September 2017; Accepted 20 September 2017

1. Introduction

Wind erosion is a major driver of soil degradation particularly in the world's drylands (Lal, 2001; Ravi et al., 2010). Wind erosion and dust emission promote the loss of soil organic carbon and soil nutrient decline (e.g., Li et al., 2008; Chappell et al., 2013; Webb et al., 2012), impact land productivity (Lal, 1998; den Biggelaar et al., 2003a, 2003b; Sterk et al., 1996) and influence global terrestrial and marine biogeochemical cycles and climate (Calvo et al., 2004; Jickells et al., 2005; Shao et al., 2011). By the end of this century, drylands are expected to increase to cover half of the Earth's land surface (Huang et al., 2016). Increased aridity enhanced by warming and a rapidly growing human population are expected to increase land degradation and decrease food security particularly in the drylands of developing countries (Huang et al., 2016). Measuring and monitoring controls on wind erosion can facilitate detection and prediction of soil degradation, providing a basis for improved land management and understanding dust impacts downwind (McTainsh et al., 1990; Koch et al., 2015). Detection and prediction remain challenging prospects for broad scale (regional to national) monitoring and assessment (McTainsh et al., 1990; Webb et al., 2009). Remote sensing has been key to improving wind erosion and dust emission model capabilities for some time (Shao et al., 1996), and have been used to inform management and policy (State of the Environment 2011 Committee, 2011; US Department of Agriculture, 2015). These models require information on structural characteristics of soil and vegetation that attenuate the aerodynamics of the land surface and the soil susceptibility to erosion (Chappell et al., 2006, 2007). The most successful models have exploited multi-temporal remote sensing data to represent dynamic land surface conditions that control the location and timing of wind erosion and dust emission (Shao, 2000; Marticorena and Bergametti, 1995). Further integrating remote sensing products into wind erosion models is expected to improve model fidelity and substantially reduce the uncertainty in predictions (Chappell et al., 2010).

Wind erosion and dust emission occur when there is a coincidence of sufficiently strong winds (wind erosivity) and a soil surface which may be eroded (soil erodibility). Soil erodibility is controlled by soil grain size and cohesion, which vary considerably in space and time in response to soil moisture, physical and biological crusting and disturbance (Webb and Strong, 2011). Wind erosivity is moderated by roughness features that control the land surface aerodynamics (Raupach et al., 1993). In agricultural regions, roughness is dominated by crops, pastures and oriented soil ridges with various heights, widths and spacing. In rangelands, roughness is characterised by the heterogeneous and anisotropic (i.e., clumped) distribution of vegetation with different growth forms and the varied phenology of vegetation growth and responses to management (Gillette et al., 2006). Perhaps the greatest challenge for wind erosion monitoring and prediction is to characterise and represent these land surface controls on the erosion process across the continuum of land surface roughness from homogenous to heterogeneous and from static to dynamically changing. While advances have been made in capturing surface roughness effects on wind erosion through remote sensing, substantial limitations remain with the approach and the parameterisation.

Ground cover is a proxy for roughness in wind erosion models (Shao, 2000) and is used to monitor the susceptibility of the land surface to wind erosion. Ground cover is defined here as vegetation (living and dead), biological crusts and stone that is in contact with the soil surface (Muir et al., 2011; Herrick et al., 2017). Maintaining ground cover to protect soil from erosion is a recommended management practice which has been adopted by farmers and land users (Leys, 1991; Li et al., 2007). Felton et al. (1987) suggest that prevention of wind erosion requires 70% ground cover of cereal residue fixed to the soil. The maintenance of adequate ground cover of at least 50% on average across a field is recommended to protect soil against wind erosion (Leys et al., 2009). However, this threshold is a general rule used for agricultural extension purposes. It does not account for different wind speeds, roughness configurations and structures, or for different wind directions and seasons.

Considerable effort has recently been devoted to deriving products representing the fractional ground cover (f_c) of photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV) and bare soil (BS, including stones and rock) using hyperspectral and multispectral sensors (e.g., Guerschman et al., 2015 their Table 1). The availability of fractional cover products in Australia at moderate spatial (e.g., 500 m) and temporal (8–16 day) resolutions, provide the means of accounting for horizontal (planform) cover, thus enabling ground cover monitoring and the effects of climate variability and land management on wind erosion to be assessed (Stewart et al., 2011). However, soil erosion is a primarily lateral process and wind erosion in particular may occur beneath tall vegetation and crop canopies and between some types of ground cover (Bergametti and Gillette, 2010). Fractional cover f_c does not capture the effects of cover (roughness) structures projected into the airstream, or its interactive effects due to its 3-dimensional spatial distribution. These factors substantially affect land surface aerodynamics and rates of wind erosion. For example, the 'green' (PV) f_c has been used with vegetation height classifications to approximate the frontal area of vegetation as input to drag partition schemes that represent the aerodynamic effect of vegetation on wind momentum (Shao et al., 1996). We contend that, because of the reliance on f_c, current approximations of land surface aerodynamics generate large uncertainties in wind erosion assessments. New metrics that account for the vertical structure and distribution of surface roughness are urgently needed to improve the accuracy of wind erosion monitoring and prediction (Webb et al., 2014).

This paper addresses the need for a dynamic (multi-temporal), moderate resolution (500 m) and broad-scale (national) metric for representing the aerodynamic roughness of the land surface for wind erosion monitoring and models. The aim of the research is to develop estimates of lateral cover (L_c), a horizontal projection of the lateral density of roughness across the land surface, using the Moderate Resolution Imaging Spectroradiometer (MODIS). We begin by defining L_c and its use in existing wind erosion models. We establish an empirical relation between L_c and the albedo of rough surfaces, normalised to remove spectral influences, and demonstrate how the relation is general and universal for surfaces comprised of mixed spectral signatures from plants and soil. We then show how MODIS data can be used to estimate lateral cover and thereby satisfy the requirement for large area assessment of vertically- and horizontally-projected land surface aerodynamic roughness. We apply the new approach to a MODIS time series for selected land cover types in Australia, then map MODIS global L_c and explore how the new data can be used to improve ground cover monitoring and modelling of wind erosion.

2. Background to methodology

2.1. Aerodynamic roughness and lateral cover

Surface roughness includes erodible and non-erodible features of the land surface, such as living or dead vegetation and rocks. It also includes erodible features such as soil aggregates and ridges that change in size, shape and distribution in response to weather and land management. Surface roughness influences wind erosion by: (a) directly sheltering the soil surface from erosive winds; and (b) absorbing a portion of the wind momentum flux, thus reducing the wind erosivity (shear stress) at the soil surface (Marshall, 1971; Raupach et al., 1993). The direct sheltering effect of vegetation is captured in part by the area of ground covered by vegetation, but this measure does not account for the additional sheltering that occurs in the lee of standing roughness or the absorption of wind momentum. This sheltering constitutes areas of flow separation downwind of roughness elements (Arya, 1975) and may incorporate other roughness elements depending on the wind direction