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Remote Sensing of Environment 102 (2006) 328 – 343

Remote Sensing of Environment

www.elsevier.com/locate/rse

Using bi-directional soil spectral reflectance to model soil surface changes induced by rainfall and wind-tunnel abrasion

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Received 10 January 2006; received in revised form 21 February 2006; accepted 25 February 2006

Abstract

To improve wind erosion model calculations across several spatial and temporal scales simultaneously, there is a requirement for a non-invasive approach that can be used rapidly to assess changes in the compositional and structural nature of a soil surface in time and space. Remote sensing allows consideration of the processes controlling erodibility on the same spatial continuum to avoid time-consuming and expensive fieldwork. Multi-angular spectral reflectance appears to provide a holistic framework for the measurement and calculation of soil surface characteristics remotely using ground-based radiometers and current and future generations of angular sensors on airborne and satellite platforms. To investigate the utility of this framework, a ground-based study was performed using three soils susceptible to wind erosion that were modified using rainfall simulation and wind tunnel abrasion experiments. Measurements of those changes were made and recorded using digital images. Multi-angular spectral measurements of reflectance were also made and inverted against a bi-directional soil spectral reflectance model. Comparison of the measurements and calculations showed good agreement with small errors in accuracy. Optimised values of the model parameters produced the single scattering albedo and a description of the reflectance scattering behaviour of the soil surfaces that included an estimate of roughness. The model parameters removed the effect of illumination and viewing geometry on the spectral reflectance. The combination of single-scattering albedo spectra and model parameters for each treatment provided information about the composition and structure of the soil surface changes. The main changes detected at the soil surface included the presence of a crust produced by rain-splash, the production of loose erodible material covering a rain crust and the selective erosion of the soil surface. Redundancy analysis showed that much of the variation in the values of the soil reflectance model parameters was explained by the scattering properties and the roughness parameter of the soil surfaces. Variation in the soil surface reflectance was not explained solely by soil type. Instead, low intensity rainfall combined with short and long duration abrasion explained a significant portion. These findings provide a source of considerable variation in experimental and operational spectral reflectance measurements that has perhaps hitherto been largely ignored. The results demonstrated the readily available information on the composition and structure of the soil surface without interfering with natural processes. The directional soil reflectance methodology appears to have potential for use in improving the understanding of erodibility and ultimately for identifying and quantifying soil erosion.

Keywords: Wind erosion; Soil erodibility; Wind tunnel; Rainfall simulator; Bi-directional soil spectral reflectance model; Canonical ordination; Redundancy analysis

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1. Introduction

Wind erosion is an important problem that threatens 30 million ha of land in the United States. On cropland in the USA, about 28 million ha are eroded by wind at rates that exceed twice the tolerance level for sustainable production (USDA, 1989). Much of Australia is also affected by wind erosion and more than half of its area is in need of soil conservation treatment, and approximately one eighth is so badly damaged by agriculture that repair work is urgently needed (Beale & Fray, 1990). Cattle grazing in Queensland is very extensive but small annual rainfall and large stocking rates have removed natural vegetation cover and broken soil crusts, which protect the soil from wind erosion (McTainsh et al., 1998). From a land resource perspective and in terms of sustainable agriculture it is important to accurately determine wind erosion across several spatial scales to identify the controlling environmental processes. Thus, there is a growing

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0034-4257/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2006.02.020

need for the estimation of source areas and the intensity of dust emission at several spatial scales that can realistically only be handled by wind erosion models (Shao & Leslie, 1997).

Recent developments in wind erosion models (e.g., Böhner et al., 2003; Fryrear et al., 1998; Shao & Leslie, 1997) and models of dust emission (e.g., Marticorena & Bergametti, 1995; Sokolik & Toon, 1996; Zender et al., 2003) have also highlighted the need for information on the spatial and temporal variation of composition, aggregation and roughness because these soil surface conditions control the surface susceptibility to wind erosion (erodibility) and hence the emission of dust (Zobeck, 1991b). Shao et al. (1996) suggested that the main limitation of wind erosion models is their inability to incorporate the evolution of surface soil conditions. The SOIL sub-model in the USDA-Agricultural Research Service, Wind Erosion Prediction System (WEPS) model was developed in recognition that the soil's aggregation and surface state can dramatically affect erodibility (Hagen et al., 1995). Thus, changes in soil and surface temporal properties are simulated daily by the model. Soil layer properties such as bulk density, aggregate size distribution and dry aggregate density are maintained on a daily basis. Surface properties such as random and oriented roughness, crust generation, coverage fraction, density, stability and thickness and loose erodible material on crusted surfaces are also taken into account (Wagner, 1995). Collection of these data, even in the USA, is often limited to individual agricultural fields or administrative regions because in situ measurements are labour-intensive and very time-consuming and experiments to understand the variation of erodibility over several spatial and temporal scales are prohibitively expensive. Arguably, these field-based approaches are even inadequate at the field scale where soil surface conditions vary considerably and evolve simultaneously in space and time. Shao et al. (1996) provided one of the first physically based wind erosion models to operate across spatial scales from the field to the continent (Australia). One of the main reasons for its success was its inclusion of remote sensing data. However, Shao and Leslie (1997) suggested that the Shao et al. (1996) model required more detailed estimation of erodibility, in particular the estimation of surface roughness elements, soil water content and surface crusting. They suggested that the dynamic effect of surface roughness elements is difficult to describe because surfaces are often composed of standing roughness elements, flat surface covers, tillage ridges and various levels of random roughness elements (Potter et al., 1990).

To improve wind erosion model calculations across several spatial and temporal scales simultaneously requires a non-invasive approach that can be used to rapidly assess changes in the compositional and structural nature of a soil surface in time and space. Furthermore, the approach is required to provide a holistic framework so that the factors controlling the processes of erodibility may be considered on the same continuum (Geeves et al., 2000). One approach to providing this information is to use remote sensing to measure soil surface reflectance frequently and at many locations across relatively large areas simultaneously. Measurements of the intrinsic optical properties of the soil surface produce wavelength-specific absorption of electromagnetic radiation, yielding diagnostic reflectance spectra for the properties under investigation. Observed spectral variations will provide information on the chemical composition of the soils involved, whilst directional variations will elucidate the structure of the materials under investigation. The main controls on soil surface reflectance variation; organic matter, soil water, mineralogy, particle size and surface roughness (Huete & Escadafal, 1991;

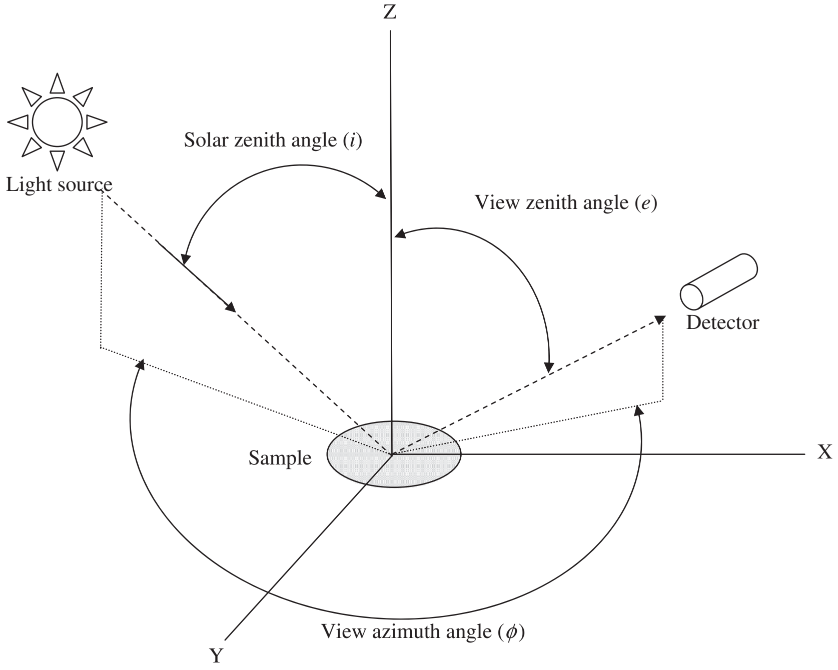

Fig. 1. Illumination and viewing angles used in the soil bi-directional spectral reflectance model of Jacquemoud et al. (1992).