Mapping wind erosion hazard in Australia using MODIS-derived ground cover, soil moisture and climate data

X Yang¹, J Leys²
¹Office of Environment and Heritage, Department of Premier and Cabinet, PO Box 3720, Parramatta, NSW 2150, Australia
²Office of Environment and Heritage, Department of Premier and Cabinet, PO Box 462, Gunnedah, NSW 2380, Australia

Abstract. This paper describes spatial modeling methods to identify wind erosion hazard (WEH) areas across Australia using the recently available time-series products of satellite-derived ground cover, soil moisture and wind speed. We implemented the approach and data sets in a geographic information system to produce WEH maps for Australia at 500 m ground resolution on a monthly basis for the recent thirteen year period (2000-2012). These maps reveal the significant wind erosion hazard areas and their dynamic tendencies at paddock and regional scales. Dust measurements from the DustWatch network were used to validate the model and interpret the dust source areas. The modeled hazard areas and changes were compared with results from a rule-set approach and the Computational Environmental Management System (CEMSYS) model. The study demonstrates that the time series products of ground cover, soil moisture and wind speed can be jointly used to identify landscape erodibility and to map seasonal changes of wind erosion hazard across Australia. The time series wind erosion hazard maps provide detailed and useful information to assist in better targeting areas for investments and continuous monitoring, evaluation and reporting that will lead to reduced wind erosion and improved soil condition.

1. Introduction

Wind erosion is widespread in Australia and many parts of the world. The magnitude of any wind erosion event depends on the interaction between the atmosphere and the landscape. Atmospheric factors include wind speed and direction while landscape factors include soil texture, soil moisture, soil surface crusts, surface roughness, slope and groundcover [1].

Wind erosion has both on-site and off-site impacts. On-site impacts include soil and nutrient losses such as soil organic matter and carbon stores [2]. Off-site impacts of wind erosion include reduced air quality, leading to increased health risk of respiratory disease [3]. In terms of climate change, dust is the only aerosol with potential to increase and decrease global air temperatures through radiative forcing, but the net effect of this remains to be measured and modeled [4].
Wind erosion hazard (WEH) is a term used to describe the susceptibility of a parcel of land to the effects of wind, and is dependent on a combination of climate, landform, soil, land use and land management factors [5]. With the increased need for food and fiber production to support a growing world population, there is a crucial need for information on the extent and severity of WEH. This information is required by national and state governments, regional natural resource management (NRM) agencies and agricultural industries so they can identify the priority areas for reducing wind erosion. Investment in improved land management practices will reduce the area of moderate to high WEH, thus minimizing the impacts of wind erosion, preserving our soil asset and reducing the off-site costs associated with dust storms [6].

In Australia, wind erosion monitoring occurs at a range of spatial scales and temporal scales. These monitoring activities fall into three major types: modeling, remote sensing, and direct observations. To date, six basic approaches have been used: 1) the Computational Environmental Management System (CEMSYS) model which is a process-based numerical modeling climate and landscape functions to calculate wind erosion metrics [7, 8, 9] and the Australian Landscape Erodibility Model (AUSLEM) which utilizes a rule-set of landscape and climatic thresholds within a Geographic Information System (GIS) modeling framework [10, 11, 12], 2) Dust Storm Index (DSI) which utilizes meteorological observations of dust phenomena to calculate the frequency and intensity of dust events [13], 3) remote sensing [14], 4) Roadside Surveys (RoS) that utilizes observations of erosion levels and land management practices in paddock, 5) DustWatch Nodes (DWN) that measures dust concentration at instrumented sites [15], and 6) paddock scale assessments that make measurements of ground cover, aggregation and erosion levels at fixed sites in paddock. Of these approaches only CEMSYS, AUSLEM and DSI have been applied nationally at coarse scales, but there is no soil erodibility term in DSI and in CEMSYS, and they require significant data inputs, computing power and scientific skill. AUSLEM soil erodibility, however, is static and defined by the particle-size distribution and the soil texture (clay, silt and sand content) respectively. An integrated approach needs to be developed to consistently and continuously monitor the dynamics of WEH, by making use of satellite, topographic, ground cover, soils and station data at adequate spatial and temporal scales.

The first attempt at an integrated approach in Australia was by Webb et al. [10] where the concept of AUSLEM was introduced. Their follow-on studies [11, 12] further demonstrate improvements and the performance and applications of AUSLEM in identification of landscape erodibility. However, their work has concentrated on using modeled inputs (e.g. grass cover and soil moisture) at a spatial resolution of 5 km or greater. Such coarse resolution is inadequate to precisely identify erodible land areas needed for land management attention.

In this study, we aim to address some of the research gaps identified by Webb et al. [10]. We explore the use of recent satellite-based ground cover, wind speed and soil moisture to identify the WEH areas on a monthly basis for Australia. We test the WEH outputs against dust emission data collected from DWNs. We then produce the time series WEH maps at 500 m ground resolution across Australia. With improved model details and accuracy it is possible to interpret more precisely where are the WEH areas and where the dusts likely come from.

2. Data, methods and procedures

The dominant data sets used in this study include time series fractional cover derived from Moderate Resolution Imaging Spectroradiometer (MODIS), wind speed and soil moisture in monthly intervals from 2000 to 2012. The time-series MODIS derived fractional cover products (Version 2.2) include 8-daily fractional cover (%) of Photosynthetic Vegetation (PV), Non-Photosynthetic Vegetation (NPV) and Bare Soil (BS), as well as a quality indicator (FLAG) [16]. The Australian Water Availability Project (AWAP) made available weekly and monthly soil moisture [17] for Australia. In this project we used the monthly relative soil moisture (fraction 0 – 1) in the upper (0.2 m) soil layer. The monthly
wind speed (m/s) was calculated and spatially interpolated from point-based daily wind-run (km/day) data supplied by Bureau of Meteorology, and a transformation of distance from the coast in km was applied to capture the impact of sea breezes and land-breezes on wind speed [18]. We developed automated scripts in ArcGIS to process these time series data and produce monthly fractional cover, soil moisture and wind speed layers from 2000 to 2012. All data are in geographic decimal degrees (0.005 degree resolution) with extent of the entire Australian land mass.

The hypothesis is that if an area of land has an erodible surface (e.g. silt soil), consistently has low ground cover, low soil moisture and experiences high wind speed (all relative to known thresholds), then it is highly likely this area will have a high wind erosion hazard and therefore likely to be a dust storm source [19]. Based on this hypothesis, we developed a simple wind erosion hazard index (WEHI) taking into account these three dominant (or forcing) variables: climate ($C$), soil ($S$) and vegetation ($V$) as below:

$$\text{WEHI} = f(C, S, V)$$

(1)

where $f$ indicates the equation includes functional relationships that are not necessarily straight-line mathematical calculations. WEHI can be regarded as a simplified version of the revised wind erosion equation (RWEQ, Fryrear et al., 1998) with emphasis on estimating potential wind erosion hazard, while RWEQ is used to predict soil loss due to wind erosion [20]. If we use wind speed to represent the $C$ factor, soil moisture for the $S$ factor, and bare soil for the $V$ factor, the dynamic (monthly) components of WEHI can be simplified as:

$$\text{WEHI} = \frac{\text{wind\_speed} \times \text{bare\_soil}}{\text{soil\_moisture}}$$

(2)

where the original soil_moisture and bare_soil factors ranged between 0 and 1 (0 – 100%), while wind_speed ranged from 0 to 13.89 m/s, thus requiring re-scaling to 0-1 in order for all three factors to be equivalently dimensioned and their multiplying effect contributes linearly to WEHI. Though these factors would have exponential relationships with WEHL similar to that used in Webb et al. [11], the high-end sections are linear or near linear. In this study, only the high portion (e.g. 90th percentile) of WEHI is used to identify the wind erosion hazard areas under the assumption that the higher WEHI the more likelihood of wind erosion hazard, thus these factors in their high ends can be regarded to have linear relationships with wind erosion hazard. The data sources and overall procedures for calculating WEHI are illustrated in Figure 1.

![Figure 1](image_url)  
*Figure 1.* Procedures for calculating wind erosion hazard index (WEHI) from time-series Australian products.
Automated scripts in ArcGIS were developed for the implementation of the above WEHI calculation from the available time-series (monthly) data so that the whole process (Figure 1) can be fully automated, repeatable and fast. The above processes produced monthly and annual WEHI estimation and classes (very low, low, moderate, high and very high) for 2000-2012 period. The ‘very low’ class indicates essentially nil erosion hazard, ‘very high’ class is equivalent to the 90th percentile of WEHI indicating the worst 10% scenarios. If any new or future time-series data become available, the WEHI maps can be rapidly updated using the automated process.

3. Results and discussion

The monthly time-series wind erosion hazard maps show similar temporal and spatial trends compared with results from Computational Environmental Management System (CEMSYS) model [6]. For example, both methods show trends of increased wind erosion hazard in spring and early summer (August to November) but decreased in Autumn and winter months (April to July).

Figure 2 shows the examples of annual WEHI, CEMSYS and DSI maps. They reveal general patterns of high hazard area (such as central Australia) and the regions consistently erodible (such as the Eyre Peninsula, southwest Queensland) which agree with the AUSLEM model output [10]. With these maps we can locate those natural resource management (NRM) regions with consistently high erosion hazard, thus high priority for investment and control.

![Figure 2](image)

*Figure 2. Comparison of modeled wind erosion hazard (Left) with CEMSYS modeled dust concentration (Middle) and DSI (Right) for 2002-2008 (green = low, red = high). The background boundaries are natural resource management (NRM) regions.*

Though the outcomes agree in general with other modeled products, there are noticeable discrepancies among them as the model inputs, methodology and spatio-temporal resolutions are very different. For example, the WEHI approach identified a high wind erosion hazard region in central Western Australia (middle-left in the left map of Figure 2), but such pattern did not appear in other two model outputs (middle and right maps of Figure 2). This was because that this region has consistently low soil moisture and low ground cover, thus a potential area of wind erosion hazard or dust source areas based on WEHI. While other models (CEMSYS and DSI) focus more on actual dust concentration or frequency, rather than the erodibility.

DustWatch observations in NSW compliment the measurements of dust concentrations (ug/m$^3$) taken by instruments at 26 sites every 15 minutes throughout NSW since July 2005 [15]. These measurements, though not directly comparable, are valuable (the only available dust concentration measurements) to test our wind erosion hazard model. Figure 3 compares the correlation between modeled wind erosion hazard and dust concentration measurements between July 2005 and December 2008. In the figure, WEHI is an estimation of likelihood of wind erosion hazard and DW is the actual measurements of dust concentration. Conceptually, they are not directly comparable, but there exists some positive correlation (Figure 3) which suggests that wind erosion hazard areas or potential dust sources are contributing to the measured dust concentration at the DustWatch nodes.
4. Conclusion and further studies

This pilot study has demonstrated the use of three forcing factors to identify wind erosion hazard from readily available time-series products. Time-series wind erosion hazard maps at monthly and annual time steps have been produced and used to understand the spatial-temporal dynamics of landscape erodibility in Australia. The estimated wind erosion hazard (extent and trend) is in general consistent with previously documented research outcomes, independent dust event maps and satellite imagery revealing major Australian dust source areas. Using these monthly time series maps we can identify the frequency and extent of potential wind erosion hazard where ground cover is bare or low, soil is dry and wind is strong.

The spatial resolution (500m) of the outputs is so far the most detailed in Australia which is high enough to reveal relationship between erodible land areas and geographic landscape features land management activities in paddock scale. However, they are insufficient (without validation and correction) to demonstrate exactness in erosion hazard or location at times when these land areas are known to be erodible.

The study has also demonstrated that even simple approach, along with consistent long time-series data, is useful for the identification of land areas susceptible to wind erosion, interpretation of the physical nature of erodible landscapes and their dynamics in space and time. The approach has potential to be applied elsewhere at regional or global scale as these time-series data sets are widely available worldwide. The model output enabled a preliminary analysis of landscape erodibility in Australia to be made, demonstrating that consistently erodible land areas in Australia can be successfully mapped. The modeled time-series outputs can be used to understand relationships between landscape erodibility, arid/semi-arid landscape features, and climate variability.

The simple approach developed under this project may be of interest to State and local government as well as to the large scientific community involved in remote sensing of dust source identification. Our wind erosion hazard model using readily available national data may be incorporated into the routine dust monitoring system in NSW Government. Results of our work will help to improve the wind erosion monitoring, evaluation and reporting (MER) capacity. The method and associated data sets can be readily implemented in a GIS using automated scripts and applicable to paddock and regional scales.
In our further studies, we will test the 6-hourly wind data (or hourly in some areas recently become available) to model strong wind “gusts” which cause wind erosion. Using hourly data, we will be able to count hours in a day when wind speed is greater than threshold. We will also utilize a new soil texture map and introduce a dynamic soil erodibility term that accounts for changing levels of loose erodible material caused by changing soil aggregation and crust levels in response to rainfall (e.g. three-monthly above average rainfall deciles). We will re-run the WEHI and AUSLUM models using the improved data set and make further comparisons and improvements.

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