Wind erosion risk assessment using time-series ground cover and climate data

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Abstract – This study explores approaches for wind erosion risk assessment utilising available time-series Moderate Resolution Imaging Spectroradiometer (MODIS) and climate products. We present a simple index and a rule-set based approach to identify wind erosion risk areas across Australian using time-series of ground cover, soil moisture and wind speed. These approaches and data sets were implemented in a geographic information system to produce wind erosion risk maps for Australia at 500 m resolution on a monthly basis for the recent eleven year period (2000-2010). These maps were compared with dust modelling (CEMSYS) and measurements from DustWatch network. Results demonstrate that time series of ground cover, soil moisture and wind speed can be jointly used to identify landscape erodibility and to map seasonal changes across Australia. The wind erosion risk maps can be used 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.

Keywords: Wind erosion, risk, ground cover, remote sensing, soil, GIS

1. INTRODUCTION

Wind erosion is an internationally recognised land degradation issue. With increasing pressure on agricultural land to produce more food and fibre for a growing population, crops will be grown on drier marginal lands more vulnerable to wind erosion. At the same time, the area affected by moderate or severe wind erosion (currently 17 per cent, nearly 130 million hectares of Australia) is likely to expand due to increased drought and climate variability associated with climate change. The frequency of major dust storms, such as those experienced in eastern Australia in September 2009 (e.g. Sydney Red Dawn on 23 September 2009), is likely to increase (http://www.nrm.gov.au/publications/factsheets/wind-erosion-factsheet.html).

Wind erosion has major impacts at the point of erosion (on-site) and beyond (off-site). On-site there is soil loss exposing unproductive saline and acid subsoils, and nutrient loss decreasing soil fertility and water storage capacity and leading to reduced food and fibre production (Leys et al 2009). Selective loss of soil organic matter by wind will release soil carbon into atmosphere, reduce soil carbon stores (Leys et al 2008) and the carbon sequestration capacity of the soil. Dust storms contain millions of dollars worth of nutrients eroded from the topsoils (Raupach et al 1994). Off-site impacts of wind erosion include reduced air quality in rural towns and cities, leading to increased health risks to asthma sufferers (Raupach et al 1994). 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 modelled (Rotstayn et al 2008).

Wind erosion is common in Australia in the summer and autumn when the soil is dry and there is little ground cover. The magnitude of any wind erosion mainly depends on wind velocity, rainfall rate, slope and soil characteristics. Though dust storms are for the most part restricted to the drier inland areas of Australia, but occasionally, during widespread drought, they can affect coastal districts. For example, the 2009 Sydney Red Dawn (23 September 2009) was reported by the Australian Broadcasting Corporation News (2009) as the worst in 70 years and led to cancelled or delayed flights, traffic problems, and health issues.

Investment in improved land management practices will minimise the impacts of wind erosion, preserve our soil asset and reduce off-site costs such as those associated with dust storms (Leys et al 2009). There is a crucial need for information on the extent and severity of the wind erosion problems so that the priority areas for reducing the risk of wind erosion can be identified at the natural resource management (NRM) region level.

In Australia, wind erosion monitoring occurs at a range of spatial scales (from national to a point) and temporal scales (1940 to current). These activities fall into the three major types: modelling, remote sensing, and observations. To date, six basic approaches have been used including Computational Environmental Management System (CEMSYS) modelling (Shao et al 1997, 2003, 2007), Dust Storm Index (DSI), Roadside Survey (RoS), dust concentration measurement at instrumented 'DustWatch' Nodes (DWN), remote sensing, and paddock scale assessment (Leys et al 2008, 2009; McTainsh et al 1989, 2005, 2008).

The remote sensing based approaches are divided into those that estimate 1) eroded ground based on the brightness of the surface (e.g. (Palmer et al. 1994); 2) dust plumes based on the temperature difference between the dust and the ground (Sokolik 2002; Bullard et al 2008; Baddock et al 2009); and 3) an aerosol index of the column of dust in the atmosphere (Torres et al 2002; Chappell et al 2003). The later two methods are concerned with estimating dust storms, while the first method seeks to map the erosion after the wind erosion event.

Globally, coarse satellite images have been used to identify dominant sources of mineral dusts, such as Total Ozone Mapping Spectrometer (TOMS) (Prospero et al 2002; Torres et al 2002; Washington et al 2003). Miller (2003) applied a normalized dust difference index (NDDI) between the red and blue channels of Wide Field-of-View Sensor (SeaWiFS), defined such that dust produces large positive differences while clouds produce relatively smaller differences.
Of particular interest in dust storm detection and wind erosion monitoring is the Moderate Resolution Imaging Spectroradiometer (MODIS) data source because of its relatively higher temporal resolutions (twice per day) compared with Landsat. MODIS has been shown to be extremely useful for visualizing dust (Ackerman 1997; Miller 2003;

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Roskovensky and Liou 2005; Baddock et al 2009), but there are significant problems with precise source identification and determination of the extent (Baddock et al 2009). Further, these satellite products have been shown to be more successful in characterizing dust transport in over-water applications (e.g. Miller 2003). But the over-water based method has its fundamental shortcoming in land areas since their spectral properties at visible wavelengths are similar to those of dust.

As remote sensing alone has a history of difficulty in identifying dust storms and wind erosion risk, monitoring needs to be based on using a mixture of modelling, GIS and observational methods. This will need a combination of satellite, topographic, ground cover, soils and station data at adequate spatial and temporal scales.

Recently, most of these datasets have become available in Australia through joint research programs such as AWAP (Australian Water Availability Project) and WRON (Water Resource Observation Network). These programs made available useful time series data sets such as MODIS fractional cover (Guerschman et al 2009), wind speed (McVicar et al 2008) and soil moisture (AWAP) in Australia. These datasets, though not fully validated, have application potential in wind erosion risk and dust source identification.

In this study, we will explore the use of these time series products in wind erosion risk identification. The hypothesis was that if an area of land has a silt soil texture, 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 risk and therefore likely to be a dust storm source. Our approach to identifying wind erosion risk combines modelling, in-situ data analysis, remote sensing, and validation of ground cover in the dust-laden conditions.

2. DATASETS PREPARATION

The dominant datasets used in this study include time series MODIS derived fractional cover (bare soil) and vegetation index (NDVI), as well as wind speed and soil moisture in monthly intervals from 2000 to 2010.

The time-series MODIS derived vegetation fractional cover products (2000-10), available from Water Resource Observation Network (WRON, http://www-data.wron.csiro.au/), include 8-daily fractional cover (percentage) of Photosynthetic Vegetation (PV), Non-Photosynthetic Vegetation (NPV) and Bare Soil (BS), as well as a quality indicator (FLAG). Data are unprojected, in geographic decimal degrees, referenced to WGS84 at 500 meters resolution, with extent of the entire Australia land mass (110.00, -45.00, 155.00, -10.00) (Guerschman et al 2009). We developed automated scripts in ArcGIS to process the ground cover data and produce 8-daily and monthly PV, NPV and BS products with correction using the FLAG indicators. These products were prepared at extents of nation, state and catchment management authorities (CMA).

Time-series MODIS NDVI products (MOD13Q1.005) were also obtained from WRON at 16-daily interval with 250m spatial resolution (Paget and King, 2008). The monthly NDVI data from 2000-2010 were calculated from the 16-day NDVI time-series data using the mean values. Abnormal values (e.g. null) were filled using neighbourhood values or adjacent images using GIS focal function. Any negative NDVI values were set to zero. Automated GIS programs have been developed to produce monthly NDVI products.

AWAP (Australian Water Availability Project) is operational data assimilation and modelling system that monitors the state and trend of the Australian terrestrial water (http://www.csiro.au/awap/). The project determines the past history and present state of soil moisture and all water fluxes contributing to changes in soil moisture (rainfall, transpiration, soil evaporation, surface runoff and deep drainage), across the entire Australian continent at a spatial resolution of 5 km (Raupach et al 2009). AWAP products include (1) weekly near-real-time reporting, (2) historical monthly time series (1900 to present), and (3) monthly climatologies (Raupach et al 2009).

In this project we used the monthly relative soil moisture in the upper (0.2 m) soil layers expressed as percentile ranks which are the rank of the current month in the cumulative probability distribution for that month over the climatological period 1961 to 1990.

The wind speed dataset was developed by CSIRO Land and Water in conjunction with other researchers as outlined in McVicar et al (2008). The original point data were supplied by Bureau of Meteorology. Daily wind-run (km/day) from low-set anemometers (< 3 m) were converted to daily average wind-speed (m/s) using the method reported in McVicar et al (2008). These data were then spatially interpolated using ANUSPLIN Version 4.3 (Hutchinson 1994). A transformation of distance from the coast (d) in km was applied to capture the impact of seabreezes and land-breezes on wind speed. We downloaded the Version-2 near-surface wind speed (in integer Byte format) from WRON site (1975 to 2008), and produced monthly wind speed (m/s) Arc grids at 1 km resolution for Australia. We also obtained Gridded MesoLAPS125 wind products (in NetCDF format) from Bureau of Meteorology which has 6-hourly time interval and 12.5 km spatial resolution.

In addition to the main datasets mentioned above, we also prepared other relevant GIS data layers that include soil texture, digital elevation model (DEM) and rainfall erosivity. We produced a national soil texture grid layer based on available national soil clay data for of top-soil (0 - 0.20 m). The soil texture was classified into 6 classes (sands, sandy loams, loams, clay loams, light clays, clays) as described in McKenzie et al (2000). The data layer of soil texture classes is in geographical coordinates and has a grid resolution of 0.001 degrees (approximately 1.1 km). As terrain has an important influence on wind erosion, we also obtained nation-wide DEM (30m Shuttle Radar Topographic Mission (SRTM) Level 2 elevation data) and 25m DEM for selected areas. These DEMs are used in calculating slopes and landforms. The rainfall-runoff erosivity was calculated from a daily rainfall erosivity model using long-term meteorologic records (1889-2010).

3. METHODS AND PROCEDURES

As wind erosion is caused and influenced by three dominant factors (soils, climate and vegetation), our approach aims to delineate the temporal and spatial influence of these forcing variables (Brooks and Legrand 2000) on the resulting wind erosion risk by integrating them into a wind erosion risk index (WERI).

$$WERI = f(\mathrm{CSV}) \quad (1)$$

where *WERI* is the estimation of wind erosion risk, (normalized to range between 0 and 1); *f* indicates the equation includes functional relationships that are not necessarily straight-line mathematical calculations; C is the climate factor (e.g. wind speed); S is the soil factor (e.g. soil moisture); and V is the vegetative cover factor (e.g. bare soil). WERI can be regarded as an simplified version of the universal wind erosion equation (UWEE) with emphasis on estimating potential wind erosion risk, while UWEE is used to predict soil loss due to wind erosion (Van Pelt and Zobeckb, 2004).

Note that these three factors in WERI (Equation 1) can be extended to take into account of other relevant factors, such as precipitation and evapotranspiration in C factor, soil erosivity and texture in S factor, NDVI and surface roughness in V factor. In this pilot study, we only used wind speed to represent the C factor, soil moisture for the S factor, and bare soil for the V factor. Thus WERI can be simplified as

$$WERI = (wind\_speed * bare\_soil) / soil\_moisture \quad (2)$$

Note that soil moisture and bare soil 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. The data sources and overall procedures for calculating WERI are illustrated in Figure 1.

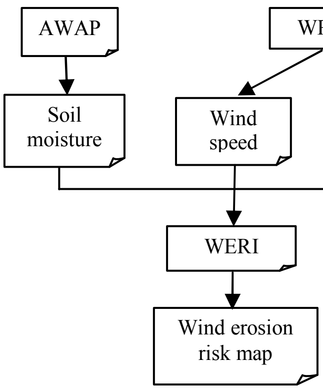

Figure 1. Procedures for calculating Wind Erosion Risk Index (WERI) from time-series Australian Water Availability Project (AWAP) and Water Resource Observation Network (WRON) products.

The resulting WERI values from Equation (2) indicate the likelihood of wind erosion risk for each period. The rescaled WERI (0-1) was in turn used to produce time-series wind erosion risk maps at monthly and yearly time steps for recent 11 years. The normalised WERI values are comparable and can be directly used to measure wind erosion risk at different times or seasons.

In addition to the WERI index (Equation 2), we also tested a rule-set based approach using the same factors. A threshold value is assigned to each factor based on relevant research describing land surface and climate conditions of erodible landscape as described in Webb et al (2006). These rule-set thresholds are set to answer for each model input: "under what conditions would a land area become susceptible to wind erosion?" (Webb et al 2006).

The wind speed threshold was set at 1.74 m/s (equivalent to 6·25 km/h) which is comparable with Gillette's (1986) minimum wind speed threshold for undisturbed dry soils with a clay content > 20%. The soil moisture threshold was set to 5%, and ground cover (or bare soil) set to 20%. That is, if the wind speed is greater than 1.74 m/s, and the soil moisture less than 5% and the ground cover less than 20% (or bare soil > 80%), then there is likely to be a risk of wind erosion for that area. For each month, if all three factors meet the thresholds, then value 1 (risk) is assigned to that month, otherwise value 0 (no risk) is assigned. The GIS conditional function is used to calculate the likely risk for each monthly such as:

$$RISK_{0912} = con(SM_{0912} < 0.05 \;\&\; BS_{0912} > 0.80 \;\&\; WS_{0912} > 1.74,\ 1,\ 0) \quad (3)$$

where SM_{0912} = monthly soil moisture (December 2009), BS_{0912} = monthly bare soil (December 2009), WS_{0912} = monthly wind speed (December 2009).

Annual risk is calculated by summing the monthly risk values such as:

$$RISK_{2009} = sum\ (RISK_{0901}, RISK_{0902}, \ldots, RISK_{0912}) \quad (4)$$

Annual risk is also calculated in financial years (as needed in management and investment) from July of one year to June next year, such as financial year 2008-09:

$$RISK_{0809f} = sum(RISK_{0807}, \ldots, RISK_{0812}, RISK_{0901}, \ldots, RISK_{0906}) \quad (5)$$

A higher risk value (annual range from 0 to 12) indicates higher likelihood of wind erosion risk. This value is also comparable among years and useful for long term monitoring and reporting the extent and severity of wind erosion risk across Australia.

An automated program in ArcGIS (Arc Macro Language, AML) was developed for the implementation of the above WERI and rule-set calculation from available time-series data as inputs so that the whole process can be automated, repeatable and fast. If any new time-series data become available, the wind erosion risk can be rapidly updated using the automated process.

4. RESULTS AND DISCUSSION

This pilot study produced monthly and yearly wind erosion risk estimation for 2000-2010 using both WERI and the rule-set approach.

WERI was based on the negative relationship between wind erosion risk and soil moisture; and positive relationship with wind speed and bare soil. Figure 2 shows such relationships between the measured dust concentration (at the DustWatch nodes) and the wind erosion factors. Among these three factors, wind speed shows repeatable seasonal distribution (high in summer, lower in winter) since it was calculated as monthly mean value. Alternatively, using number of hours greater than a wind speed threshold in a day or month might be more relavant to dust events and wind erosion risk.

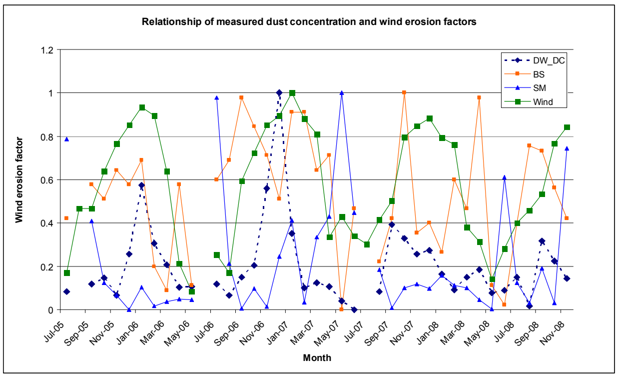

Figure 2. Relationship of measured dust concentration (at the DustWatch nodes) and the wind erosion factors.

In the rule-set based approach, a value of 1 indicates that there is likely to be a wind erosion risk as there is low ground cover and soil moisture and strong wind. The monthly time-series wind erosion risk maps show the temporal and spatial changes of the likely erodible land areas (Figure 3).

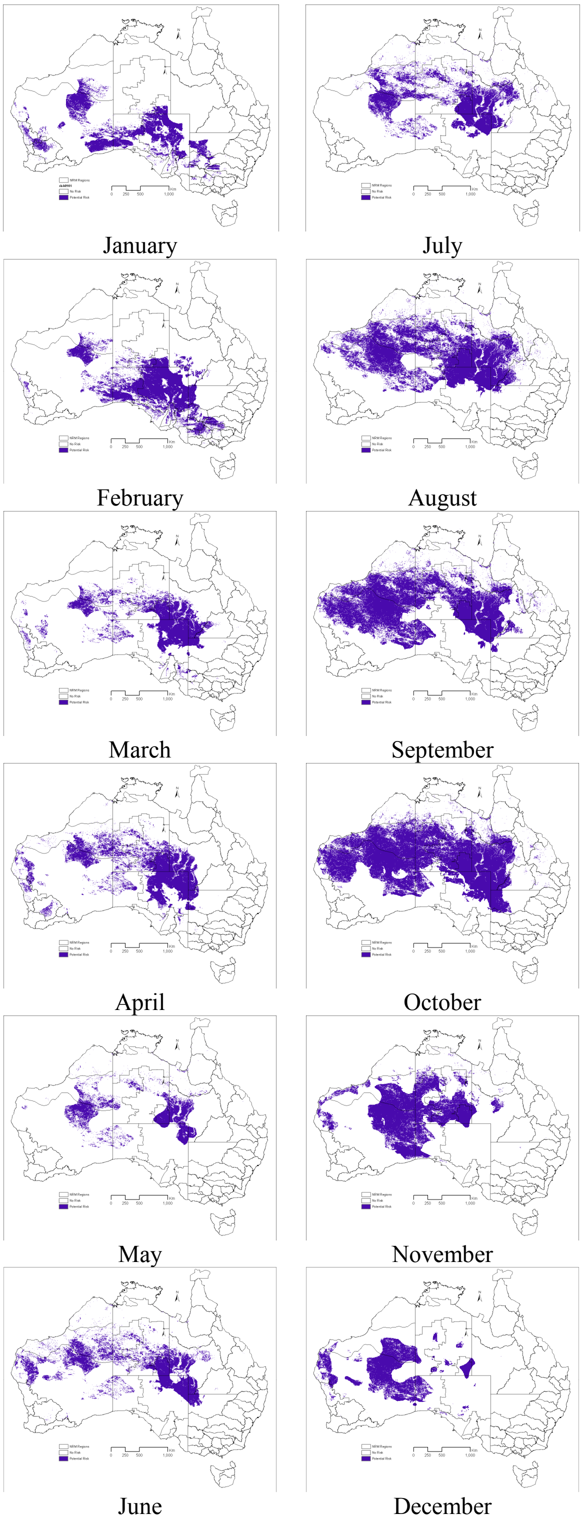

Figure 3. Monthly wind erosion risk areas in 2009 based on the rule-set approach.

If an area consistently has value 1 for an extended period (e.g. over a year), then this area can be regarded as highly erodible; an example is the area intersected by the state borders of land area such as the intersection area of Queensland, Northern Territory and New South Wales. Figure 4 presents the accumulated frequency of wind erosion risk over 10 year period (2000-2010) for each month which might be more useful in comparing the overall seasonal changes over a certain period (e.g. 10 years).

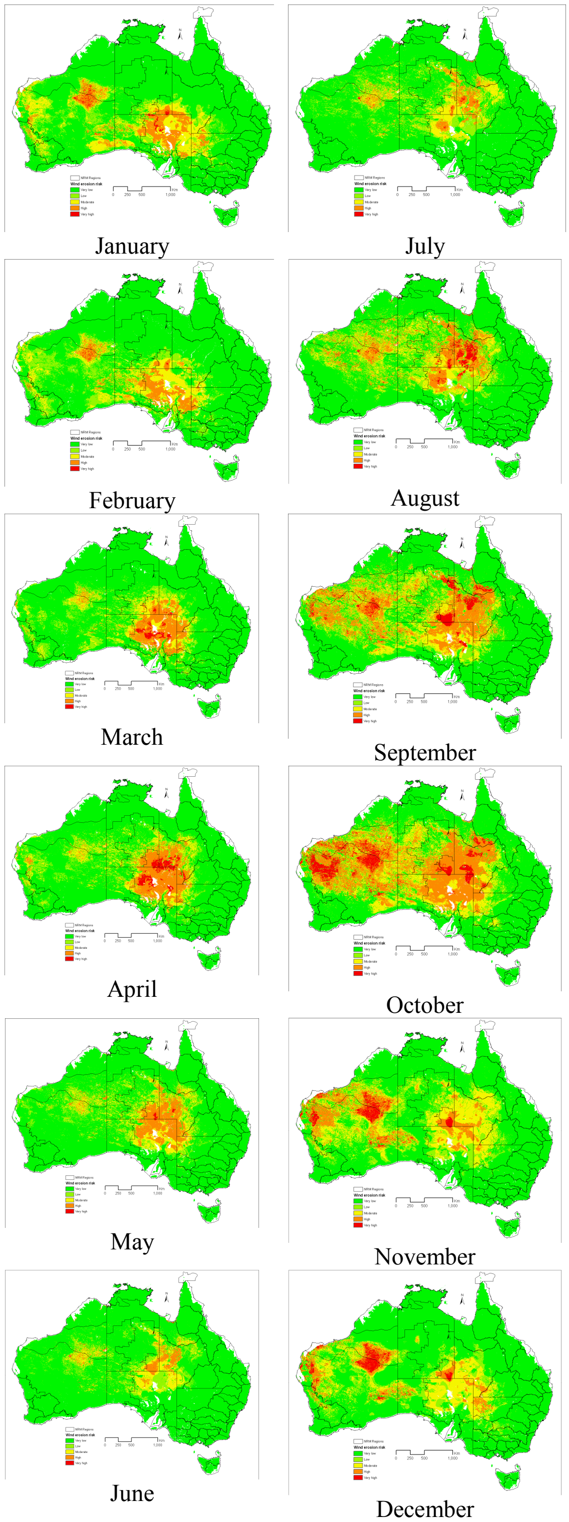

Figure 4. Accumulated wind erosion risk frequency for each month in eleven year period (2000–2010) presented in 5 classes from very low (green) to very high (red) (rule-set approach).

These highly erodible land areas and the monthly trends (e.g.

increased wind erosion risk in spring and early summer) are generally in agreement with the results from Computational Environmental Management System (CEMSYS) model in the same period, for example 2009 as shown in Figure 5.

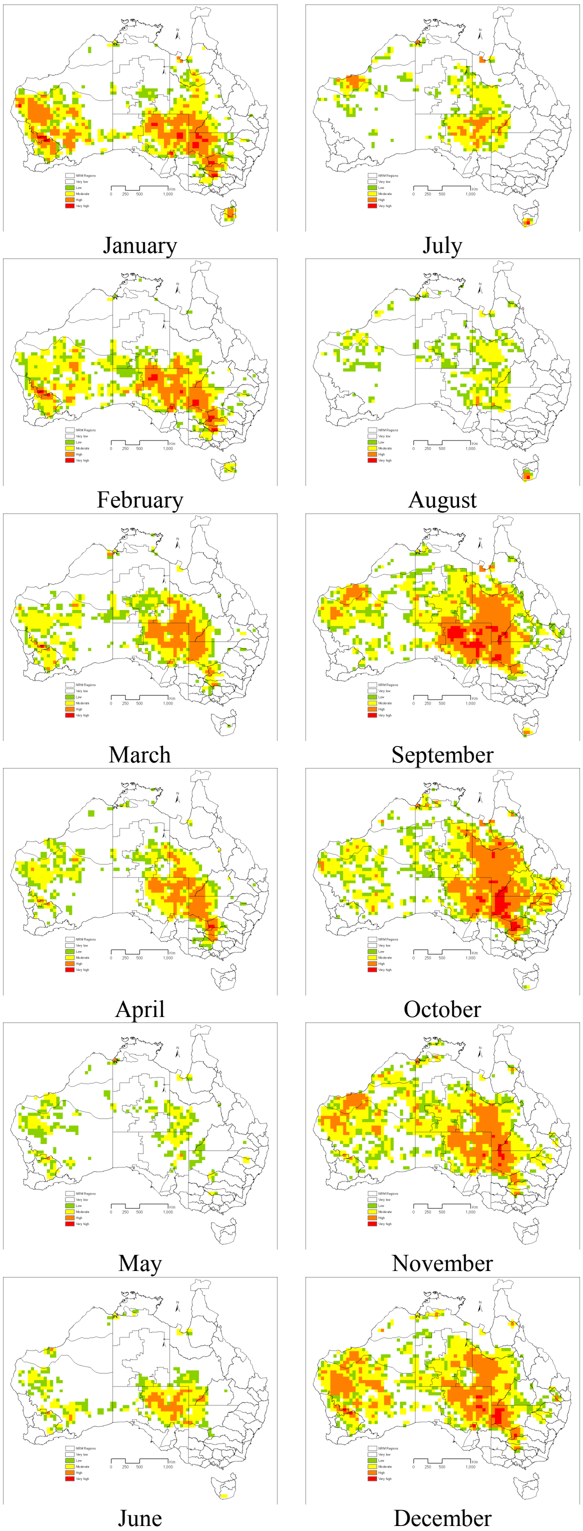

Figure 5. Monthly dust concentration modelled from CEMSYS for 2009.

In addition to monthly outputs (refer Figures 3-5), annual wind erosion risk (or frequency within a year) was also calculated using both WERI and rule-set methods (Figure 6). The annual maps show more general patterns and trends over time. The extent and severity classes are also comparable among years.

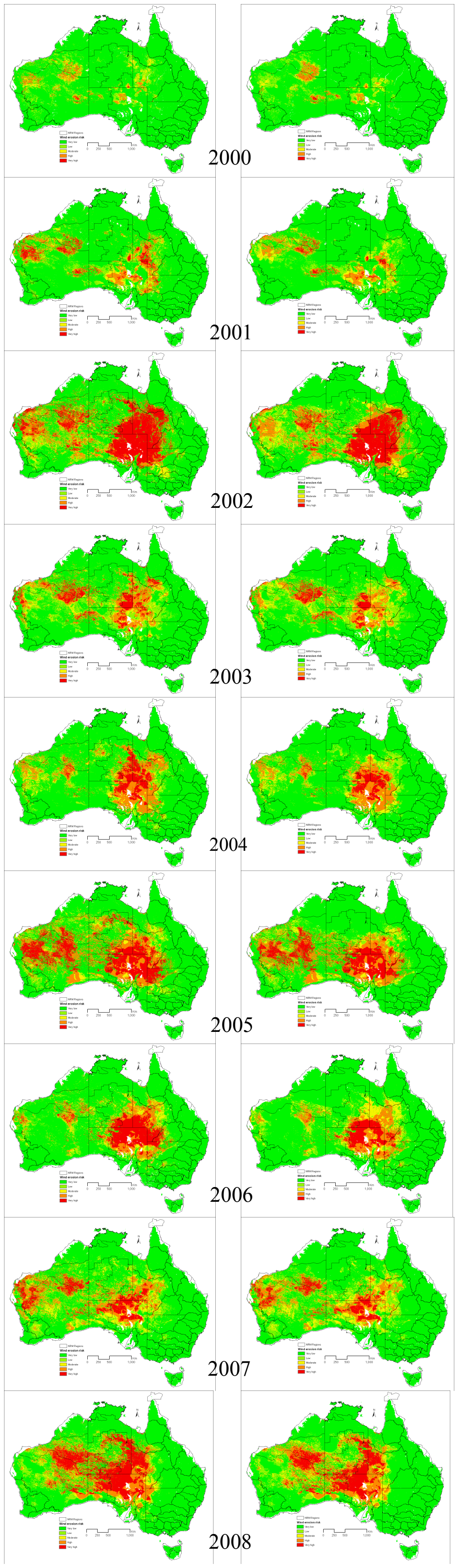

Figure 6. Yearly wind erosion risk (2000-2008) based on the rule-set approach (left) and WERI (right).

Both WERI and the rule-set approach reveal similar patterns of modelled wind erosion risk areas (Figure 5). From these maps we can see that regions consistently erodible include: the Eyre Peninsula, southwest Queensland, the Channel Country, Great Victoria Desert and Gibson Desert which agree with the AUSLEM model output (Webb et al 2006). With these maps we can locate those natural resource management (NRM) regions with high erosion risk, thus priority for investment and control.

Further, we compared the modelled wind erosion risk with other modelled outputs (such as CEMSYS and dust storm frequency) which use different data sources and methods (Butler et al 1996, 2001). Such a comparison for financial year 2007-08 is presented in Figure 7.

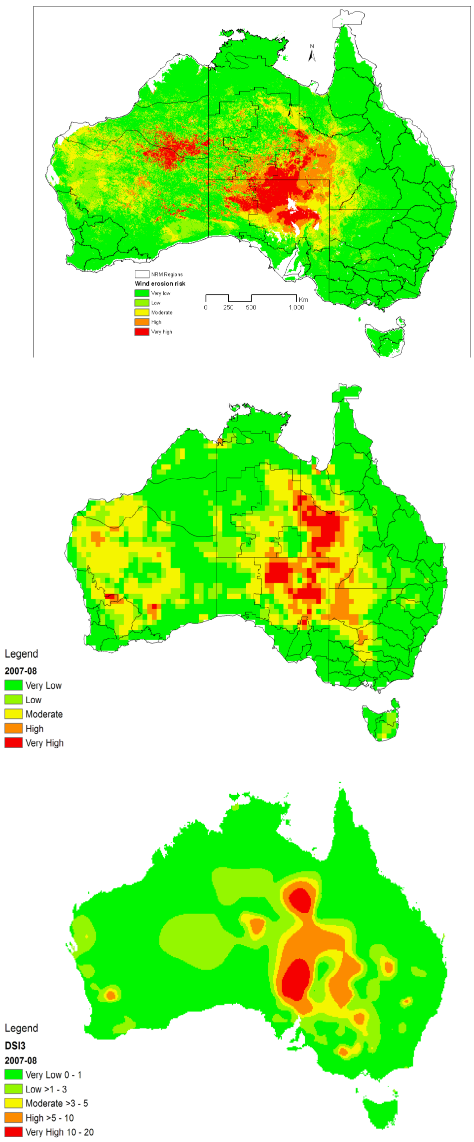

Figure 7. Comparison of modelled wind erosion risk with CEMSYS and dust storm frequency in 2007-08. Top: wind erosion risk estimated using the rule-set approach (this study); Middle: CEMSYS modelled dust concentration; Bottom: Estimated frequency of dust-storms over Australia (Middleton, 1984)

The above visual examination and comparison demonstrate that the extent and severity of wind erosion risk at monthly and annual steps in Australia can be modelled using available time-series products, and the outcomes are generally in agreement with other modelled products. 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. This relationship is demonstrated by comparison of the monthly time series outputs. 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.

Quantitative measures of wind erosion hazard are not available for much of Australia. Verification of the model output is therefore limited to qualitative comparisons (Figures 3-7) with modelled and documented observations of landscape–erodibility and dust concentration

DustWatch observations in NSW compliment the measurements of dust concentrations taken by instruments at 26 sites every 15 minutes throughout NSW since July 2005 (Leys et al 2008). These measurements are valuable to validate our wind erosion risk model. Figures 8-10 present and compare the correlation between modelled wind erosion risk and dust concentration between July 2005 to December 2008. In these figures, WERI or RISK is an estimation of potential risk; DW is the actual measurements of dust concentration. Conceptually, they are not directly comparable, but there exists some correlation (Figures 7-9).

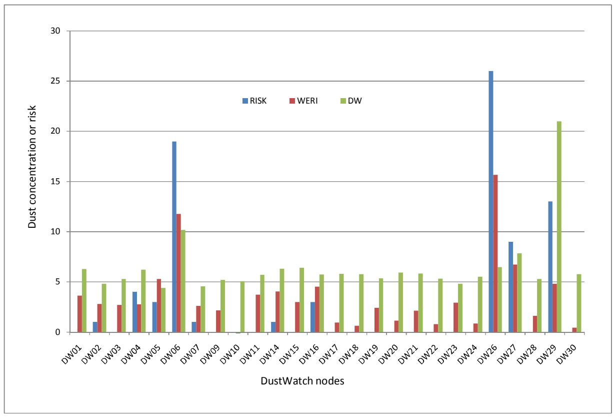

Figure 8. Modelled wind erosion risk and dust concentration at NSW DustWatch nodes (RISK = the rule-set derived risk, WERI = WERI derived risk, DW = dust concentration measured at DustWatch nodes).

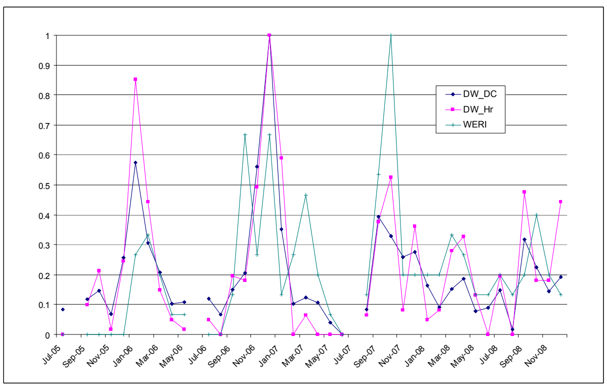

Figure 9. Modelled wind erosion risk (WERI) and measured dust concentration (DW_DC) and hours (DW_Hr) from

DustWatch Node 6 (DW06) at Tibooburra between July 2005 to December 2008.

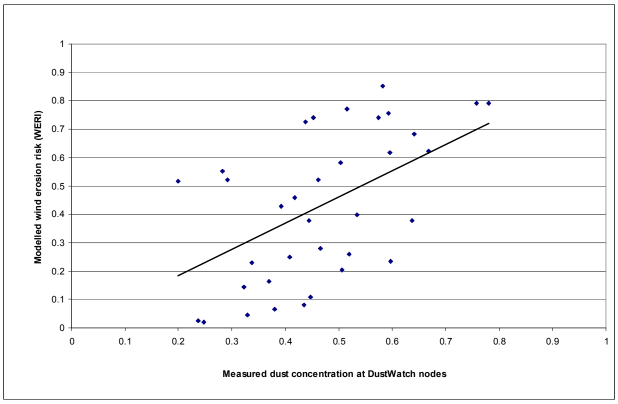

Figure 10. Relationship and trendline between modelled wind erosion risk (WERI) and measured dust concentration from DustWatch nodes. Values are rescaled to the same range (0-1) and extreme values at both ends were removed.

5. CONCLUSION AND FURTHER DIRECTIONS

This pilot study has demonstrated the use of three principal factors to identify wind erosion risk from readily available time-series products. Time-series wind erosion risk maps at monthly and yearly time steps have been produced and used to understand the spatial-temporal dynamics of landscape erodibility in Australia. Using these monthly time series we can identify the frequency and extent of potential wind erosion risk where ground cover is bare or low, soil is dry and wind is strong.

The relationships between the modelled erosion risk areas and measured dust concentration during 2005–2010 are examined which show positive correlations. The estimated wind erosion risk (extent and trend) is in general agreed with CEMSYS modelled results.

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 modelled time-series outputs can be used to understand relationships between landscape erodibility, arid/semi-arid landscape features, and climate variability. Comparisons with other models and measurements; output is consistent with previously documented research outcomes, independent dust event maps and satellite imagery revealing some of Australia's dust source areas.

The simple approach developed under this project may be of interest to CMAs as well as to the large scientific community involved in remote sensing of dust source identification. Our wind erosion risk 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.

In our immediate further studies, we will replace monthly wind data with 6-hourly or hourly data to model strong “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 use more relevant datasets (soil, terrain, climate), once available and validated, in the wind erosion risk model to improve accuracy.

Other future research aims include: 1) link wind erosion risk with natural resource management practices; 2) refine the model thresholds using ground truth data measured at known erodible locations; 3) develop methods for calibration via point data by establishing instruments and network; 4) link to policy development through targeting areas for investment using integrated assessment and decision support tools.

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