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Wind erosion and land management in Australia during 1940-1949 and 2000-2009

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ON BEHALF OF the State of the Environment 2011 Committee

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Cover image

Meringur dust storm, VIC
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Preface

This report was commissioned by the Department of Sustainability, Environment, Water, Population and Communities to help inform the Australia State of the Environment (SoE) 2011 report. As part of ensuring its scientific credibility, this report has been independently peer reviewed.

The Minister for Environment is required, under the *Environment Protection and Biodiversity Conservation Act 1999*, to table a report in Parliament every five years on the State of the Environment.

The Australia State of the Environment (SoE) 2011 report is a substantive, hardcopy report compiled by an independent committee appointed by the Minister for Environment. The report is an assessment of the current condition of the Australian environment, the pressures on it and the drivers of those pressures. It details management initiatives in place to address environmental concerns and the effectiveness of those initiatives.

The main purpose of SoE 2011 is to provide relevant and useful information on environmental issues to the public and decision-makers, in order to raise awareness and support more informed environmental management decisions that lead to more sustainable use and effective conservation of environmental assets.

The 2011 SoE report, commissioned technical reports and other supplementary products are available online at www.environment.gov.au/soe.

Wind erosion and land management in Australia during 1940-1949 and 2000-2009

1. Project Aims

The aims of this project were to:

(i) Quantify wind erosion across Australia for two periods (1940–1949 and 2000–2009)

(ii) Examine the likely impact of changes in land management on wind erosion in the two periods.

(iii) Present annual wind erosion maps across Australia for 2000-2009.

2. Background

Whilst climate is overwhelmingly the greatest driver of wind erosion, land management can either moderate or accelerate wind erosion rates. Unravelling these two influences is challenging because both vary through time, however it is necessary to maximise the sustainable management of the continent.

It has been well documented in historical accounts of land degradation in Australia that wind erosion was very active during the drought periods of the late C19 and early C20 (e.g. Ratcliffe, 1938). While these anecdotal reports present dramatic images of huge dust storms engulfing rural towns and of sand drifts burying fencelines and blocking rural roads, it has never been unequivocally established whether the “Dust Bowl” years of the 1940s were due to extreme drought and/or poor land management. The 2000s have also experienced extreme drought conditions with an increase in large dust storms and other wind erosion activity. The two extreme dust storms that hit eastern Australian cities on 23rd October, 2002 and 23rd September, 2009 have increased public awareness that wind erosion events can reach humid coastal regions and thus have off-site impacts on air quality. These events have also raised the question as to whether this recent period of wind erosion is more or less active than the 1940s, and whether changes in land management have played a role. This report presents the first quantitative measurements of wind erosion activity during the 1940s and 2000s and interprets these trends in the light of changes in land management.

3. Data and Methods

3.1 Data sources

Bureau of Meteorology (BoM) records of wind erosion event occurrence and intensity are held in the Dust Event Database at Griffith University and are used here to compare wind erosion across Australia for the 1940-49 and 2000-2009 periods. Annual maps are also provided for 2000-2009. These records derive from BoM observations made at; 36 stations for both the 1940s and 2000s (Fig. 1), whereas for the 2000-2009 period 356 stations were active.

Data processing was carried out using the Microsoft Excel 2010 software and maps were produced using the Inverse Distance Weighted interpolation method in the ArcMap (v10) component of ArcGIS (v10).

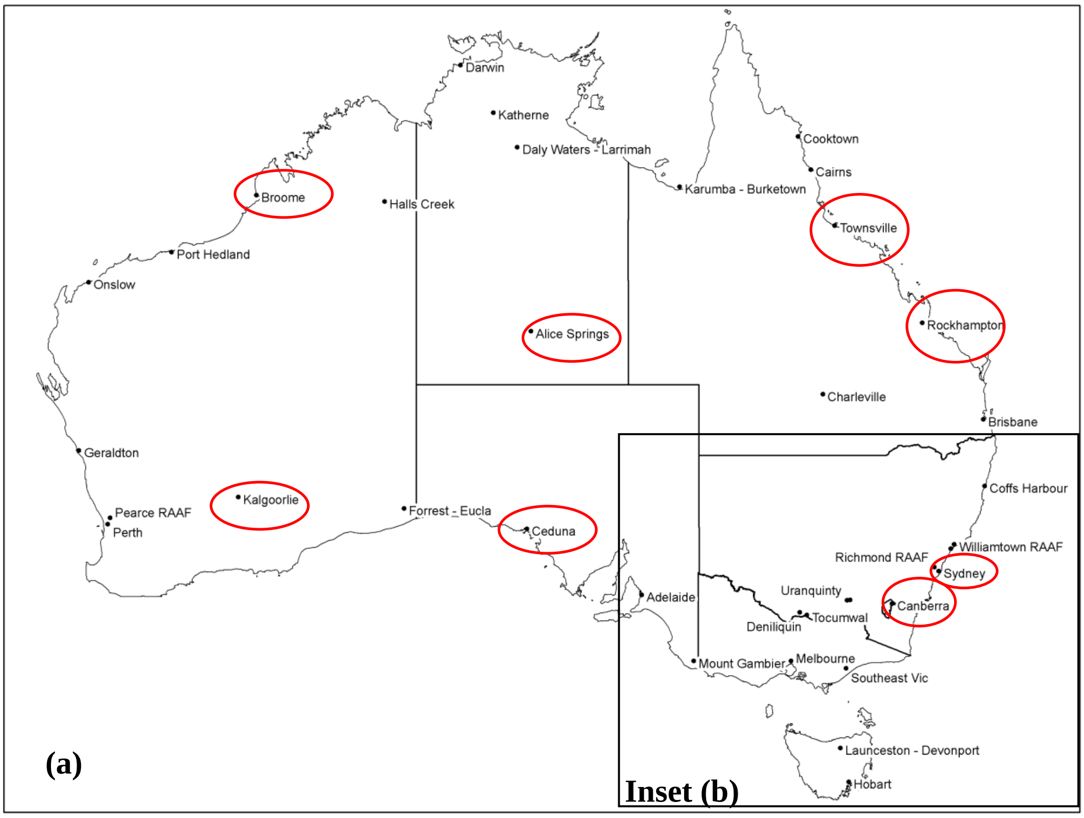


Figure 1: (a) Location of stations used to compare wind erosion in 1940-1949 and 2000-2009. Stations with complete 10-year records for both decades are circled. (b) Southeast Australia inset shows all stations in that region.

3.2 Dust Storm Index (DSI)

Meteorological data wind erosion events are used to calculate a Dust Storm Index (DSI) (McTainsh 1998, McTainsh and Tews 2007). DSI provides a measure of the frequency and intensity of wind erosion activity. DSI has been used for past State of the Environment (SoE) Reports and it is the formal measure of wind erosion activity used by the Australia and New Zealand Environment Conservation Council (ANZECC) and the National Land and Water Resources Audit (NLWRA) (McTainsh and Tews, 2007). Each of the three dust event types is given a weighting based upon measured dust concentrations in relation to visibility (McTainsh and Tews unpublished report). The DSI is calculated using the following equation,

$$\mathrm{DSI} = \sum_{i=1}^{n}\left[(5 \times \mathrm{SD}) + \mathrm{MD} + (0.05 \times \mathrm{LDE})\right]_i \qquad \text{Equation 1}$$

Where:
DSI = Dust Storm Index at n stations where i is the ith value of n stations.
SD = Severe dust storm (daily maximum weather codes: 33, 34, 35)
MD = Moderate dust storm (daily maximum weather codes: 30, 31, 32 and 98)
LDE = Local dust event (daily maximum weather codes: 07, 08 and 09*)

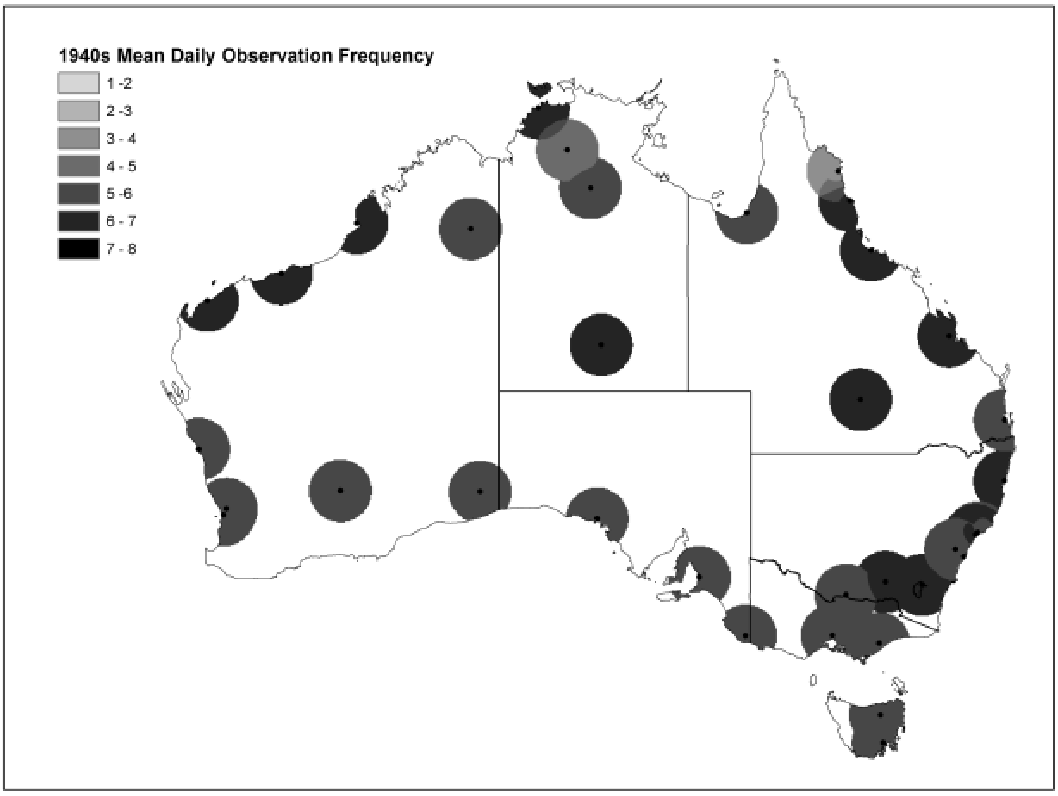
* Code 09 'Past or Distant Dust Storms' are classed as LDE in this study compared to MD for previous report. Reasons for this are provided below.

3.3 Analysis of BoM weather codes relating to wind erosion

BoM weather code records provide the only available quantitative data for measuring wind erosion in the 1940s, and as a result represent a valuable wind erosion monitoring resource. Use of these records, however presents a number of data management and analysis challenges (some of which are described by McTainsh and Tews, 2007 and O'Loingsigh et al., 2010), largely because these recording systems were not originally set up for monitoring wind erosion. These issues are examined below.

Observation Frequency

Frequency of weather observations varies between meteorological stations; from 8 observations per day at the major meteorological stations (with BoM staff), to 1-2 observations per day at the smaller stations (volunteer cooperative stations). This difference in observation frequency between stations needs to be taken into account as it may affect DSI, because an 8 observation per day station has an increased chance of recording wind erosion events compared to a 1-2 observation per day station. Figure 2 shows that the mean Observation Frequency of BoM stations in the 1940s was generally higher than in the 2000s (Fig. 2). This is because in the 1940s, all weather measurements and observations were made manually, whereas in the 2000s meteorological measurements are increasingly being used at Automatic Weather Stations (AWS). While the Observation Frequency of a station has been taken into account when interpreting DSI in the present study, in most instances the differences between the two decades are not large enough to have a significant effect upon DSI.



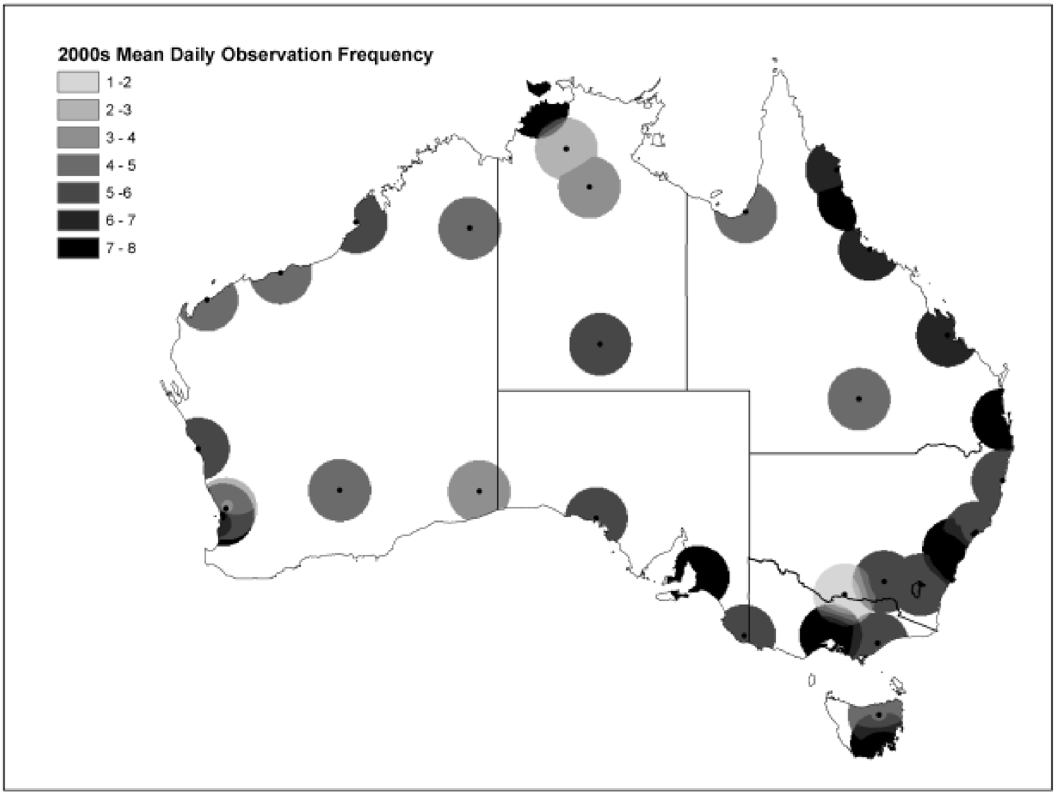


Figure 2: Decadal mean Observation Frequency in the 1940s to the 2000s.

Dust event days

The DSI value for a station is calculated from the highest dust code recorded on a day (referred to as a Dust Event Day) rather than at 3 hourly records. This has the advantage that it reduces the effect of different Observation Frequencies at stations on DSI.

Present and Past Weather codes, and code supersession

At each observation time, BoM observers record; (i) a double-digit code (from a 0-100 code chart) to describe the weather at the time of the observation (called the Present Weather [PrW] code) which has a visibility criterion, (ii) a double-digit code (from the same chart) to describe the weather *since* the last observation (called the Past Weather [PaW] code) which is *not* accompanied by visibility information. Although the Present Weather code is relatively simple to choose as it relates to the weather occurring at the time, the Past Weather code is more difficult to choose as there may have been several types of weather 'since the last observation' (which may have been 3 hours ago or up to 18 hours ago, depending upon the Observation Frequency of the BoM station). In this situation, the observer must choose the highest coded weather type from the 0-100-code chart. As seen in Equation 1, all of the dust codes used in the DSI equation (with the exception of code 98) are < 35. This means that if an observer is faced with multiple weather types, but only one recording slot, any weather code above 35 will supersede a dust code. According to the study by O'Loingsigh et al., (2010) on an 8 year sample of data from the Lake Eyre Basin, code supersession can underestimate dust event frequency (dust event days) by 7% and dust storm days by 15%. Code supersession can therefore lead to an underestimate of wind erosion event frequency.

Changes in weather code definitions

Weather observations made according to the guidelines associated with the 0-100 code chart, were not implemented at BoM stations until January 1960. Prior to this time, while “weather phenomena” including dust events were defined in Observer Manuals observers noted the occurrence of the event, rather than recording a code. These more qualitative comments from the 1930s, 1940s and 1950s were later (1960s or later) retrospectively attributed weather codes when the observer records were digitised. Therefore the presence of a ‘dust storm’ in the 1940s record was based on a qualitative definition of the event. By the 2000s a dust storm (code 30-35) was defined according to a strict visibility criterion.

The outcome of a frequency analysis of dust storm codes (30-35, 98) used in the 2000s was that all 7 codes were regularly used (although not always accurately – as discussed later). In the 1940s record there is a strong predominance of code 31 dust storms (i.e. moderate dust storm with no appreciable change), implying that when the BoM retrospectively attributed weather codes, this code was preferentially used. This has implications for the comparability of the records in the 1940s and 2000s, which will be discussed in more detail below.

Post 1960 code definitional changes

Although the recording of weather codes using the guidelines in the 0-100 code chart has significantly improved the quality of the record since 1960, in 1972 there was a definitional change to two dust codes that created a discontinuity in the record. The definitions of codes 09 (dust storm) and 07 (local dust event) were changed (Tables 1 and 2).

Table 1: Change in the definition of Code 09

Type of event	Where	When	Comment
> 1960: Code 09 Dust storm	AT or NEAR the station	During past hour	
> 1972: Code 09 Dust storm	AT the station	During past hour	No change
	NEAR the station	***At time of observation***	Change

Table 2: Change in the definition of Code 07

Type of event	Where	When
>1960: Code 07 Small scale dust event (not storm)	Dust raised locally (i.e: at or near the station)	At time of observation
>1972: Code 07 Small scale dust event (not storm)	***Dust raised anywhere (i.e. within, or out of, sight)***	At time of observation

The impact of tightening the 'near the station' segment of the Code 09 dust storm definition after 1972, from *'during the past hour'* to *'at the time of observation'* resulted in a large decrease in 09 codes. The loosening of the definition of Code 07 local dust events, by replacing *'dust raised locally'* with *"dust raised anywhere"* resulted in a large increase in 09 codes. This implies that after 1972 observers started using code 07 to describe dust events that they had until then coded as 09. To prevent this discontinuity in the record distorting DSI values pre and post 1972, all code 09 dust storms were converted to code 07 local dust events. This change makes the pre 1972 record (including the 1940s) (LDE) conform to the post 1972 definitions, thus standardising the 70-year wind erosion record (from 1940 to 2009).

BoM Observer code adherence

Not all BoM Observers consistently adhere to the visibility criteria when coding wind erosion events. According to the study by McTainsh and Tews (2007) using data from 1960, approximately 5% of moderate dust storms (30 to 32) and 18% of severe dust storms (codes 33 to 35) have been incorrectly coded. To reduce the effect of miscoded events upon the DSI, McTainsh and Tews (2007) proposed that event codes are checked against concurrently collected visibility records, and if there is a discrepancy the code is changed. While this approach has overcome the problem of variable code adherence, it can only be used for Present Weather Codes. Past Weather Codes (which accounted for 66% of all records in the pilot study of O'Loingsigh, et al., 2010) cannot be converted using this method because there is no independently recorded visibility at the time the past weather event occurred. As a result of this the BoM Observer coding has to date been accepted for Past Weather events in studies using post records (e.g. McTainsh and Tews, 2007). In the present study this is a minor problem for the 2000s data as code adherence error is relatively low, but it is more of a problem for the 1940s record, because code definitions were less rigorously adhered to.

The effect of variable code adherence on the DSI is compared for the 1940s and 2000s *using the Present Weather Codes only*, by showing the percentage change in the DSI based upon uncorrected codes and visibility-adjusted codes (i.e. using independent visibility data) (Appendix 3). This analysis shows that for the 2000s, 75% of the station records were unchanged as a result of code correction. Only at one station (Geraldton, WA) was there a major % difference, but as the absolute DSI values for this station are very low (DSI < 1.0) this record is not important.

In the 1940s (Appendix 3) the DSI varied much more; from being overestimated by as much as 852.4% and underestimated by as much as 400%. These extreme values are however rare and of little significance as they relate to very low absolute DSI values. Despite this, it is clear that variable code adherence is having a significant influence on DSI in the 1940s data. To compensate for this artefact, the % over and underestimates calculated using the Present Weather codes (Appendix 3) are used to correct the total record for each station. This assumes that the actual visibility-adjustment percentages from the Present Weather at a station (Appendix 3) can be applied to the Past Weather. As a result of this correction, the DSI values presented in Section 3 are shown as a range; from uncorrected to corrected DSI.

3.4 Decadal mean DSI and maximum DSI

Wind erosion activity in the two decades is compared using two DSI-based expressions. Firstly, DSI is averaged for each decade (referred to here as the decadal mean DSI), and secondly the highest DSI year for each station within each decade is presented (here termed decadal maximum DSI). While the decadal mean DSI has the advantage of averaging out the effects of climate variations within each decade, it has the disadvantage that the DSI is influenced by the number of drought and non-drought years in each decade. The decadal maximum DSI measures the maximum wind erosion activity for each decade, which is minimally affected by the mix of drought and non-drought years in each decade, and therefore provides a better measure of wind erosion for correlating with land management.

The possibility of wind speed changes with concomitant effects upon wind erosion, between the 1940s to the 2000s must also not be excluded. While published records of wind speed changes are rare, Ward and Russell (1980) suggest that the 1930s and 40s may have been a period of increased windiness in eastern Australia, and that windiness has decreased up to the mid 1970s. This lead Ward (1993) to the hypothesis that the 1940s Dust Bowl may have been, at least in part, due to increased windiness. Based upon national wind speed data from 1975 to 2006, McVicar et al., (2008) show that average wind speeds have continued to decrease; which appears to extend Ward and Russell's (1980) trends. Further studies of this kind are needed to complement the present study, to allow climate and land management drivers of wind erosion to be differentiated.

3.5 BoM station numbers

The main difficulty with comparing wind erosion in two decades 50 years apart is that there are only 8 BoM stations with continuous records (these stations are highlighted in Fig.1). As these few stations can not provide an adequate record of wind erosion across the continent, the stations with near-complete records were examined and a number of analysis techniques used to incorporate these stations.

A significant deficiency in the record is that there is no station with a continuous record in the Riverina region, which is well documented by anecdotal accounts (details in section 4.3) to have had very significant erosion in the 1940s. This problem is addressed by creating a composite record for the Riverina region by combining the records of 4 stations (Deniliquin, Tocumwal, Uranquinty and Wagga Wagga) (Appendix 1). This is achieved by choosing the highest DSI value from any available station for each calendar month, then creating a composite record.

In the Mulga region, SW Queensland and the northern WA rangelands the station records do not start until 1942 therefore the decadal mean DSI for these stations is affected. As overall 1940 and 1941 had the lowest erosion activity for the decade, the absence of data for these years is not a serious problem, because it would only raise the decadal mean DSI slightly. In addition, it would have a minimal or no effect upon the decadal maximum DSI values, as data was not used from these low DSI years. Stations for these three regions are therefore used.

In some cases stations with a record in the 1940s are no longer operating in the 2000s, therefore substitute stations have been used in the 2000s. When a station has been replaced by another close by in the 2000s (as for example in Brisbane where the Archerfield Airport station is replaced by Brisbane Airport), the near by station is used in the 2000s. In other situations, where a station in the 1940s has been closed down by 2000 and not replaced, if there is another station within an acceptable distance (i.e. < 100km) this station is used in 2000. Appendix 2 list the stations affected.

By making the above adjustments to the station records the number of stations is increased from 8 to 37 (Fig. 1a), which allows more of the main wind erosion regions to be represented. Even with this increased number of stations there remain few inland BoM stations with data available (Fig. 1a). Because of this the DSI maps produced from the 37 stations are not spatially interpolated, which leaves large areas of central and eastern Australia without DSI information. This is a significant deficiency, as there is no wind erosion data for the entire Lake Eyre Basin (LEB) and the western NSW sector of the Murray-Darling Basin (MDB) (Fig. 1b), which are the major wind erosion regions in Australia (McTainsh and Tews, 2007). To address this issue wind vectors showing the direction of eroding winds during dust storms are calculated for the moderate to high DSI stations. Using this method, it is possible to use a station record as a measure of a much larger upwind region. For example, as the eroding wind direction vectors at Charleville and the Riverina are both directed at the LEB and western MDB, these station records can be used to infer the wind erosion activity in these important regions.

The DSI maps presented in this report are based upon the decadal maximum DSI, rather than the decadal mean DSI. This has two advantages; firstly the decadal maximum DSI highlights differences in wind erosion between the decades to a greater extent than the decadal mean, and secondly it allows the use of all 37 stations instead of the 8 stations with complete records (which are essential to calculate a decadal mean). That these 37 stations do not have complete records for each decade does not affect the calculation of a decadal maximum DSI, as long as the years of most active erosion are available for the station.

4. Results and Discussion

4.1 Wind erosion during the 1940s and 2000s

Wind erosion has environmental impacts at source where soils are eroded (referred to here as on-site wind erosion), and downwind from source where air quality is reduced (referred to here as off-site wind erosion). On-site wind erosion during the 1940s and 2000s is presented in Table 1 using station records for 6 wind erosion regions: the Mulga (Qld), the Riverina (NSW/Vic), Central Australia (NT), southern SA, southern WA Rangelands and northern

WA rangelands. Decadal mean DSI and maximum DSI values are shown for the 1940s and 2000s.

Name	1940s Mean DSI	1940s Mean DSI Range	2000s Mean DSI	2000s Mean DSI Range		1940s Max	2000s Max
Mulga (Charleville, Qld)	21.3	19.0 - 23.6	0.5	0.5 - 0.6		39.0	1.7
Riverina (Wagga Wagga, NSW*****)	17.7	16.9 - 18.5	2.9	2.89 - 2.93		51.5	9.2
Central Australia (Alice Springs, NT)	13.7	11.3 - 16.2	3.5	3.4 - 3.5		37.3	15.0
Southern SA (Ceduna, SA)	6.0	5.95 - 5.98	2.5	2.3 - 2.6		17.6	7.8
The Southern WA Rangelands (Kalgoorlie, WA)	5.4	2.19 - 8.6	1.6	1.4 - 1.8		21.6	5.9
The Northern WA Rangelands (Port Hedland, WA)	4.4	3.4 - 5.5	1.3	1.1 - 1.4		20.0	7.4
Mean	**11.4**		**2.0**			**31.2**	**7.8**

Table 1: Dust Storm Index (DSI) at 6 on-site wind erosion regions for 1940s and 2000s. * Composite record of 4 stations for the Riverina (details in Section 3).

Overall, mean on-site wind erosion in the 1940s was almost 6 times higher (mean DSI = 11.4) than in the 2000s (mean DSI = 2) (bottom of Table 1, and locations in Fig. 1), and the mean maximum DSI for the 1940s was 4 times that of the 2000s. There are also significant regional differences (Table 1). Both decadel mean and maximum DSI results show that 1940s wind erosion was much more active in the Mulga, Riverina and Central Australia than in the SA and WA rangelands, and the decrease in wind erosion in the 2000s is much more pronounced in the east and centre of the continent. For these reasons, the main focus of the following discussion is upon the east and centre of the continent.

In the Mulga, the mean 1940s DSI is 21.3 compared with only 0.5 for the 2000s. Similarly, in the Riverina region the mean decadal DSI decreases from 17.7 to 2.9. The 1940s erosion rate in Central Australia is similarly high, however the decrease in the 2000s is less. The off-site wind erosion record at 11 coastal cities (Table 2 and locations in Fig. 1) during the 1940s demonstrates that the on-site wind erosion in inland regions had a very significant off-site impact upon the coast. This relationship is particularly apparent at the south eastern Australia coastal cities from Brisbane to Adelaide, which have much higher decadel mean and maximum DSI values during the 1940s, and a more pronounced decrease in the 2000s than in the west of the continent. Although these south east coast DSI levels in the 1940s are around 40% of those in inland regions at that time, an indication of how high these 1940s off-site DSI levels actually are, is that the mean DSI in the 2000s is < 5% of the 1940s value (Table 2).

Name	40s Mean DSI	40s Mean DSI Range	00s Mean DSI	00s Mean DSI Range		40s Max	00s Max
Cairns	2.3	1.7 - 2.9	0.0	-		7.0	0.1
Townsville	1.1	0.8 - 1.3	0.3	-		8.0	1.2
Rockhampton	3.6	-	0.2	-		21.0	0.5

Brisbane	3.8	0.7 - 6.8	0.1	0.05 - 0.15		21.0	1.2
Sydney	3.3	0.7 - 5.9	0.3	-		16.0	2.4
Canberra	7.8	-	0.1	-		15.0	0.2
Melbourne	5.0	4.3 - 5.6	0.1	-		11.0	0.4
Adelaide	8.2	7.0 - 9.4	0.6	-		29.2	5.2
Perth	1.3	-	0.0	-		4.0	0.1
Broome	0.2	-	0.3	-		1.3	0.6
Darwin	8.1	7.9 - 8.2	0.2	-		20.1	1.1
Mean	**4.1**		**0.2**			**14.0**	**1.2**

Table 2: Dust Storm Index (DSI) at 11 off-site wind erosion regions for 1940s and 2000s.

4.2 Spatial analysis of wind erosion in the 1940s and 2000s

Figure 3 provides a spatial perspective on on-site and off-site wind erosion in the 1940s (Fig. 3a) and 2000s (Fig. 3b). Areas of on-site wind erosion are dust source areas; where dust has been entrained from eroded soils, and off-site erosion is where transported dusts are observed downwind of source. The universal decrease in wind erosion activity from the 1940s to the 2000s is dramatic.

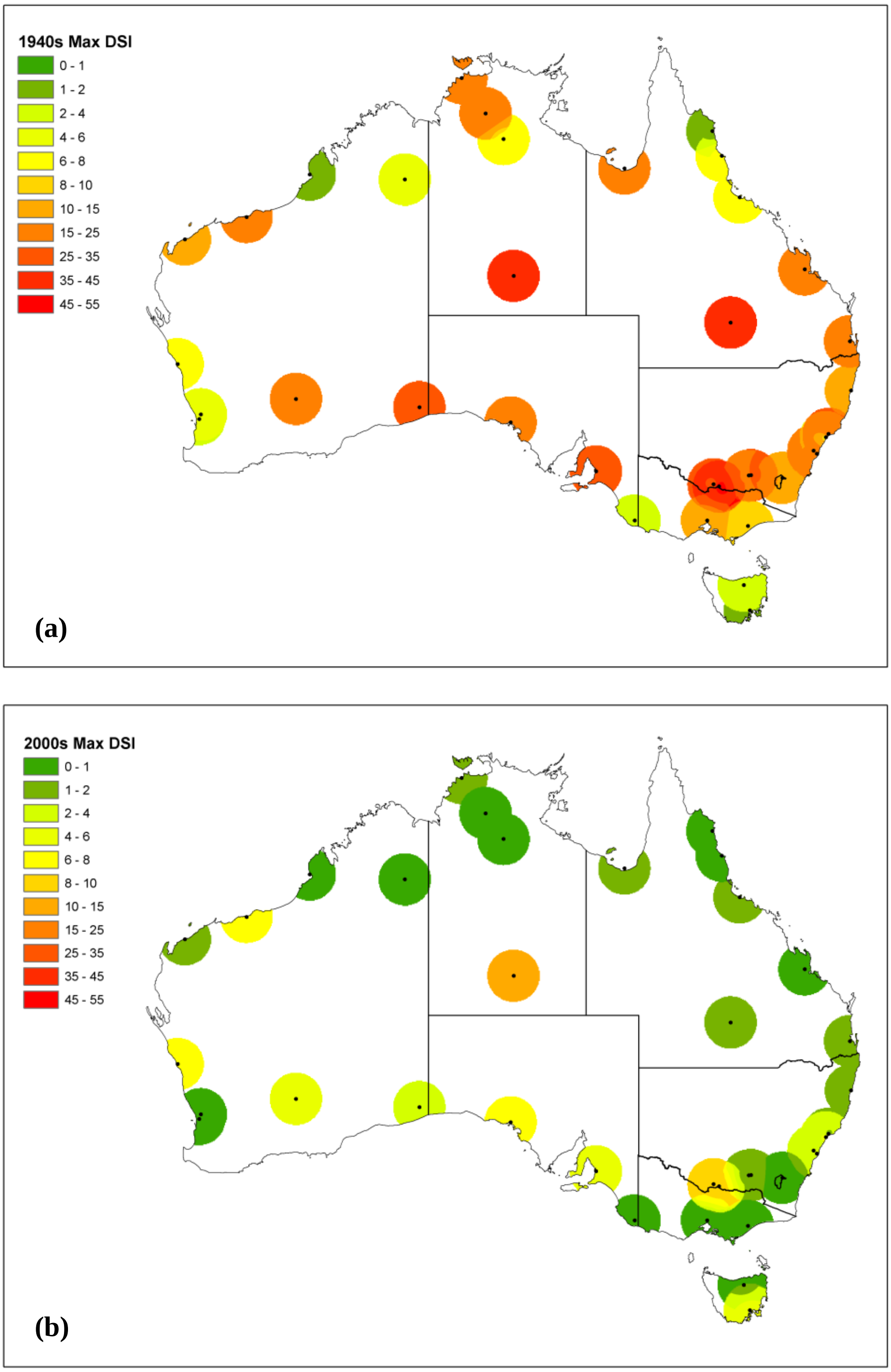


Figure 3 (a & b): Mean DSI for (a) 1940s and (b) 2000s.

As discussed in Section 3, because of the small number of BoM stations with useable records in inland Australia, the DSI values for the stations are not spatially interpolated in Figure 3. This leaves large areas of inland Australia (in particular the Lake Eyre Basin [LEB] and western Murray Darling Basin [MDB]) without records. Given that in the present day these two basins are the most actively eroding regions on the continent (McTainsh et al., 1989) this is a major issue. This data deficiency is partly overcome by using records of the direction of eroding winds during dust storms at key stations to infer erosion activity in upwind areas where there are no records (Fig. 4).

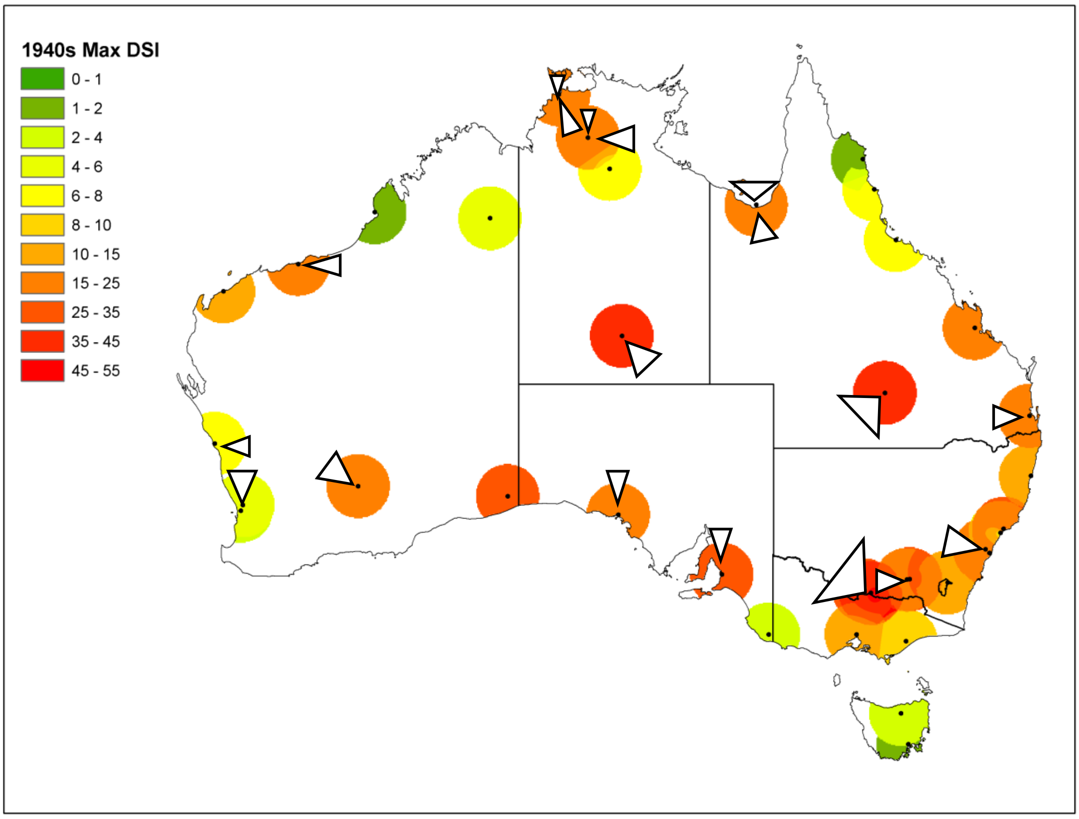


Figure 4: Direction of eroding winds at key stations in the 1940s.

Regional differences in wind erosion are examined below, starting in the north east, then the centre and the west of the continent (Fig. 4).

1. The Mulga and Riverina

The very high wind erosion activity in and around the Mulga (Charleville, Qld) and the Riverina (Deniliquin-Tocumwal-Uranquinty-Wagga Wagga, NSW) in the 1940s is the result of both local and regional factors. Local erosion in the Mulga would have been accelerated by intensive grazing by sheep during the 1940s drought, when as a result of the pasture grasses being grazed out and of the practice of "pulling" Mulga shrubs for drought stock food, soils would have been exposed to wind erosion. Local erosion would also have been increased in the immediate vicinity of Charleville, because the town was an air force base during World War 2, which would have created large areas of exposed soils (details in Section 5) (Plate 1). As Charleville was also a railhead for transporting cattle, this would have lead to increased local overgrazing and soil disturbance.

Plate 1: Charleville air force base in the 1940s. Note the areas of bare ground which would have been vulnerable to wind erosion.

The dust storms at Charleville during the 1940s came prinicipally from the south west sector (Fig. 4), driven by frontal systems passing from west to east across the continent (as described in the present day by Strong et al., 2010). South west of Charleville are the expansive rangelands of the LEB and the western MDB (Fig. 1) which were seriously overgrazed in the years leading up to, and including, the 1940s (Ratcliffe, 1936, 1937 and 1938) (details in Section 5), rendering these soils highly erodible. Figure 3a also shows high DSI values on the coast downwind of Charleville, at Rockhampton and Brisbane, which would have been produced by the eastward passage of dust storms from the Mulga, the LEB and western NSW.

The Mulga area experienced the most dramatic decrease in wind erosion on record in the 2000s (a 98% decrease - Table 1). This is probably largely a result of the improvements in land management since the 1940s. The conditions created by the World War II air force base no longer apply and rail transport of stock has largely been replaced by road trains. Arguably the most important local change from a wind erosion perspective, is the expansion of woody weeds in the Mulga during the wet years of the 1950s and 1970s (details in Section 5). While this woody weed expansion at the expense of Mulga shrubs is a degradation by-product; as a result of preferential grazing of the Mulga by sheep (because the woody weeds are unpalatable), this woody weed expansion had the advantage from a wind erosion perspective of significantly increasing ground cover. The reduction in rabbit numbers in the Mulga since the 1940s would also have significantly reduced grazing pressure on pasture grasses. The regional wind erosion in the LEB and western MDB would also have been significantly reduced by improved pastoral land management in these regions (details in Section 5). The downwind decrease in DSI at Rockhampton and Brisbane during the 2000s is also consistent with the upwind land management improvements.

The very high DSI in the Riverina region also probably reflects local and regional factors. The large dust storms which produced the very high DSI for this region in the 1940s came from the west to north west sector (Fig. 4) on, what would have been, pre-frontal winds (Strong et al., 2010). To the west is the Darling River floodplain which was severely overgrazed during the 1930s and 1940s (details in Section 5) and further upwind, the relic dunefields and floodplain areas of the Mallee area of South Australia, Victoria and New South Wales had been extensively cleared and intensively cultivated following the establishment of soldier settlement farms after World War 1 (details in Section 5). The severe wind erosion in the Mallee which led to buried fence lines and roads blocked by sand drifts is well documented (details in Section 5). Upwind of the Riverina, to the north west are the rangelands of the western MDB and LEB (Fig. 1) which were severely degraded in 1940s.

The high DSI values recorded along coastal zone of NSW in the 1940s is largely the result of the eastward passage of dust storms originating in the wind erosion regions of the LEB and western MDB, the Mallee and Riverina regions.

The significant reduction in wind erosion activity in the 2000s in the Riverina and upwind regions (Table 1 and Fig. 3b) is entirely consistent with the major improvements in pastoral and agricultural land management that have occurred in these regions since the 1940s (details in Section 5). The decrease in BoM Observation Frequency at Tocumwal (Figs. 1 and 2) in the 2000s, would artificially reduce the DSI value for that station, but as the DSI record for the Riverina is a composite of 4 stations (details in Section 5) this artefact is probably slight. That this reduction in the 2000s is less dramatic than at Charleville is probably because the Riverina area was not affected by the expansion of woody weeds, as happened in the Mulga. The reduced DSI values along the coastal zone of NSW in the 2000s, is consistent with the low Riverina DSI. That these coastal DSI values remain higher than along the Queensland coast may indicate that in general, present day land management in NSW may be accelerating wind erosion more than in Queensland.

2. Southern SA

Adelaide and Ceduna are both located on the southern coast, and as the rainfall gradient from the coast to inland SA is very steep, these BoM stations operate more like inland stations in measuring local plus regional on-site wind erosion. When compared with the Mulga, Riverina and Central Australia, the 1940s DSI values in coastal SA are moderate (although Adelaide has the highest DSI of all coastal cities) (Tables 1 and 2). The direction of eroding winds is northerly at both stations (Fig. 4). At Adelaide this possibly reflects wind erosion in the cultivated lands immediately upwind, and bounded by Goyders Line (the northern limit of cultivation designated in 1865 to reduce wind erosion further north - details in Section 5). The rangelands to the north of Ceduna were also actively eroding and some rangeland-derived dust brought from the lower LEB could also have reached these stations on pre-frontal northerly winds (Strong et al., 2010).

The reduction in DSI in the 2000s is less in Southern SA than in the eastern states because of its relatively low annual rainfall (which is similar to Charleville, Queensland, which is 800km from the coast).

3. Central Australia

The active wind erosion in Central Australia in the 1940s also reflects a combination of local and regional factors. Local erosion was very active around Alice Springs in 1940s, largely as a result of a number of local conditions. As a major rail head, Alice Springs was the focal point of regional cattle droving, and large numbers of cattle would have been held in and around the town common for rail transport (Gary Bastin pers. comm. 2011). Also, as Alice Springs was a military base during World War 2, the increased local activity would have disturbed soils and the unsealed roads would have increased dust entrainment. This active local wind erosion on the Alice Springs town common and rail head persisted into 1960s and resulted in the only attempt to rehabilitate wind eroded land in Australia (Ketch 1981, McTainsh et al., 1989). The predominant direction of dust storms reaching Alice Springs during the 1940s was from the south east (Fig. 4). These could reflect cattle grazing that was already well established in Central Australia by this time, plus long distance dust from the more “natural” dust sources in the lake beds, floodplains and dunefields of the lower LEB, which continue to be active today (Bullard et al., 2008)

In the 2000s, the DSI at Alice Springs is reduced (Table 1 and Fig. 3b), which probably reflects the removal of the local land management factors and the general improvements in pastoral land management up to this time. That the reduction in DSI in the 2000s is less than in other regions is not surprising, because the low annual rainfall in the Alice Springs area should produce higher overall wind erosion rates.

4. Northern Australia

The Katherine-Darwin region and the Gulf Country around Karumba-Burketown (Fig. 1) are both in the sub-humid tropics and therefore they would not be expected to have high wind erosion rates (McTainsh et al., 1989), although they do have a distinct dry season. During the 1940s, Darwin had the second highest DSI of coastal stations (Table 2) and Karumba had similar levels of wind erosion. Local erosion around Darwin must have been active as around 80% of the locally eroding winds were from the north (ie onshore winds). Katherine also had local erosion associated with northerly winds. As both Darwin and Katherine had considerable military activity during World War II, including the bombing of Darwin in 1942/3, it is highly likely that the local wind erosion would have been accelerated by this. A significant proportion (70%) of the dust storm winds recorded at Darwin were from the south east (towards Katherine) (Fig. 4), whereas at Katherine the dust storms mainly travelled from the east to west, therefore the Darwin dust storms must have originated from between the two towns.

At Karumba on the Gulf of Carpentaria coast, the local erosion was also active, with around 70% of winds from on-shore. As Karumba was also an air force base during World War 2 local erosion is likely to have been accelerated by military activities. The main dust storm wind directions at Karumba were southerly (Fig. 4); possibly from the Channel Country of the northern LEB, a known wind erosion region (McTainsh et al., 1999) on post-frontal southerly winds (Strong et al., 2010).

In the 2000s the wind erosion activity in all of these northern Australian regions was significantly reduced, and even though there was a reduction in Observation Frequency at Katherine (Fig. 2) which could have artificially reduced DSI further, these 2000 DSI levels are more consistent with what would be expected in sub-humid tropical regions McTainsh et al., 1989). This reduction probably principally reflects the removal of local erosion related to

World War 2, however there is also likely to have been general improvement in rangeland management in these areas.

5. Western Australia

Wind erosion activity in the southern WA rangelands around Kalgoorlie was moderate during the 1940s. This is likely to have been mainly accelerated erosion as a result of the long history of gold mining in and around the town (details in Section 5), which would have left large areas of bare ground exposed to the wind (Richmond et al., 1973, McTainsh et al., 1989). The prevailing direction of erosive winds was from the NW sector (Fig. 4). Like the semi-arid regions in Southern SA, the DSI in the 2000s did not decrease to same extent as it did further east.

The overall DSI in the Perth-Geraldton area in the 1940s was low to moderate. The majority of the dust storms reaching Perth came from the north, whereas those at Geraldton came from the east (Fig. 4). This dust source appears to be the same rangeland region that the Kalgoorlie dust storms were coming from. While there is evidence of widespread over-grazing by sheep in the semi-arid regions of the SW (as detailed in Section 5), no specific information is available from this region. In the 2000s, no dust events were reported in Perth, however in Geraldton and to a lesser extent Carnarvon, DSI levels remained moderate (compared with elsewhere on the continent at this time – Fig. 3b). It is possible that an expansion of grazing and in particular the conversion of large areas of grazing lands to cultivation since the 1940s (as detailed in Section 5) in the SW, could be a factor.

In the Onslow-Port Hedland region erosion activity in the 1940s was moderate and the erosive winds were from the east (Fig. 4). Little information is available on land management locally, or in the inland areas upwind of Onslow and Port Hedland. Given that the DSI at Port Hedland in the 2000s did not decrease as much as at Onslow it is possible that iron ore processing in the area around Port Hedland could be contributing to dust levels.

4.3 Land management influences upon wind erosion in the 1940s and 2000s

In the preceding sections changes in wind erosion rates across Australia have been examined in the 1940s and 2000s and these have been related to changes in particular regional and local land management practices. To gain a more complete understanding of how land management has changed over this period a more in depth examination is provided here.

There have been major improvements in community attitudes towards wind erosion of soils between the 1940s and 2000s, and significant advances in government policy have resulted. The following analysis will track changes in: (i) community attitudes to the environment, (ii) government policy, and (iii) land management between the two periods.

Land management in the 1940s

The Setting
In the period leading up the dust storms of the 1940s there were widespread land settlement projects (including soldier settlement schemes) and development projects (including the establishment of permanent water supplies) which increased the pressure on the land. Other impediments to good land management included limited levels of drought assistance, plus poor roads and limited trucking available to move stock out of drought areas. These resulted in increased grazing pressure on land during drought, with large numbers of stock dying on-farm. The Great Depression of the 1930s coupled with World War II meant that there was both limited funding and people available on the land to maintain infrastructure, control pests (e.g. rabbits which were in plague proportions) and protect soils. Finally, the 1937-1945 drought reduced protective vegetation cover across the continent and resulted in dramatic dust storms and widespread wind erosion of soils. Evidence is presented below to examine the extent to which this erosion was a response to poor land management.

Community awareness in the 1940s
In the period leading up to the 1940s, agricultural expansion was seen as essential for food and fibre supply to sustain an increasing population. Culturally, agricultural expansion was seen as necessary to "tame the land" (Lines 1991). This resulted from an ethos of 'hard yakka' to control nature and grow food at any environmental cost. There was also a public perception that water availability was a high priority, which resulted in irrigation schemes and settlements at Mildura and Renmark in 1886/1887 (Munns et al., 1987; Westcott, 1979), followed by another scheme in 1906 with the proclamation of the Barren Jack and Murrumbidgee Canals Construction Act 1906 (Government, 1915). Despite early evidence that these schemes may be unprofitable and could increase soil salinity (Young 1966), the Snowy Mountains Scheme was constructed, between 1949 – 1974 (ComLaw, 1949).

It soon became apparent that the original 80 acre block sizes used in soldier settlements and similar land development schemes were too small to sustain a family. This resulted in increased pressure upon land because selling up and moving further afield to find larger blocks was limited by the depressed economic conditions of the time and the poor transport infrastructure (Wadham, 1967).

The drought years of the late 1930s and 1940s provided the first stimulus to social and political awareness of land degradation. Wind and water erosion on wheat lands become severe after decades in which bare fallowing of soils was a standard practice. While the severe dust storms that engulfed Sydney and Melbourne raised the awareness of city dwellers of the wind erosion in inland regions (Reeve 1988), during the period of World War II public and media attention was inevitably focused upon the war (Young 1996). It was not until the post-war period, that the implications of the "Dust Bowl" years began to be understood. Only then did the soil degradation implications of the expansion of agriculture and pastoralism into marginal lands start to become realised (Young 1996).

Government policy in the 1940s
During the period leading up to the 1940s, government policies tended to lead community attitudes rather than reflect them. In 1938 these policies culminated in possibly the most important policy development; the formation of the first soil conservation agency in Australia, the NSW Soil Conservation Service. Then other states soon followed (except for

Queensland which followed in 1951) (Reeve et al 1989). While these agencies were too recently formed to have had a significant mitigating effect on the wind erosion in the 1940s, in the years leading up to the 1940s there were a number of policy developments which in part set the scene for what happened in the 1940s.

The table below provides a time line of the change in policies that influenced agricultural and pastoral development and land management practices.

Year	Major change/introduction
1861	NSW Land Legislation encouraged first landholders to exceed the land's capability (Roberts 1988, p4)
1865	Goyder's Line defined in SA (Young 1996 p5)
1880	NSW government continued to underwrite the cost of water supplied to rice growers (Beale & Frey 1990 p83)
1887	Queensland Dept. Agriculture established to guide agriculture production (with aims to increase yields) (Skerman et al 1988)
1900	Victorian Ministry for Public Works organised a committee to investigate serious sand drifts following indiscriminate clearing and farming in the Mallee. "No action was taken" (Roberts 1988 p70)
1901	Western Lands Act 1901 established a Western Lands Board, composed of three commissioners, to issue leases in the Western Division of NSW.
1902	Drought promoted interstate and commonwealth investigations into the Murray River irrigation (Young 1996 p10)
1910s	Soldier settlements post World War I in NSW and Victoria. Programs began in the 1890's. 40,000 returned soldiers took up land offers after WWI (www.rslnsw.org.au/commmoration/heritage/soldier-settlement) By 1924, in Victoria, soldier settlements covered 2.3 million acres, including 8,640 farms. NSW had 4,400 farms.
1915	River Murray commission established and began regulating flows (Young 1996 p10)
1923	SA Sand Drift Act, aimed principally at preventing drift of sand onto public roads from lands which were not protected from wind erosion Roberts (1988).
1933	Sand Drift Committee appointed to tackle the sand drift problem. Recommended that a board of three be created with full powers to handle the problem (recommendations were ignored) (Reeves 1988 p48)
1935	SA Director of Agriculture advocated the enforcement of Goyder's Line (Young 1996 p5)
1936	"Land degradation conference". Commonwealth asked state governments to form soil erosion committees. (Roberts 1988 p18)
1936	Soil conservation committee established to investigate extent of soil erosion in SA. Recommended a halt to clearing, revegetation, and afforestation of upland areas and contour banking to cultivated slopes, but did not make any recommendations about continuous wheat belt fallow rotation practiced in most of the states (Reeves 1988 p50)
1936	WA Soil Conservation Committee formed and erosion surveys were conducted. Farmers were aware of problems and willing to cooperate on erosion control (Reeves 1988 p50)
1938	NSW Soil Conservation Act led to the establishment of the first Soil

	Conservation Service in Australia.
1939	Committee on Soil Erosion in SA given power to enter private lands, proclaim reserves, and limit stock numbers on pastoral leases (Reeves 1988 p50)
1945	WWII War Service Land Settlement Agreements Act, 1945. Up to 1954 6,235 holdings had been allocated which were entire farms or subdivided holdings (NSW 6 million acres, WA 1 million acres, Victoria 845 acres). In NSW this was achieved by subdivision of existing land.

Land management practices in the 1940s

Agricultural practices

In the 1940s cropping systems were based upon mixed farming techniques, inherited from England. Farm technology levels were generally low, until the introduction of tractors in the mid 1940's, however the expansion of cropping land before World War II was aided by a large rural labour force. On the other hand in the wake of the Great Depression of the 1930s there was a strong demand for food which led to the use of continuous cropping. Also, land clearing was encouraged by land tenure policies requiring that land be cleared before it could be occupied in some regions. (Harris 1990).

The English mixed farming approach was a fallow-wheat rotation involving long fallowing with multiple cultivations. This approach did not adequately control annual weeds, and the removal of stubble between crops exposed soils to erosion. It also meant that part of a farm was out of production for one year, therefore more land was required for a farm to remain viable (Wadham, 1967). From a soil erosion point of view, long fallowing resulted in large parts of the landscape being left devoid of cover, nutrient levels being reduced and the surface soil loose and broken down into a fine seedbed; all perfect conditions for wind erosion. As a result of this practice around 75% of SA cropping lands were fallowed in the 1940s (Woodroffe 1950). In WA, cropping remained limited due to drought, and in the early 1940s the "light soils" between Perth and Geraldton were abandoned. Wind erosion was widespread at this time, and it was not until the introduction of fertilisers to improve soil fertility and the establishment of a railway network to move grain to port that WA crop areas increased and erosion began to be controlled (Russell and Isbell, 1986)

Pastoral practices

In the 1940s large pastoral properties were subdivided after World War I to provide land for soldier settlement schemes. This often resulted in small financially unsustainable family owned properties where overgrazing was accepted.

In assessing grazing practices perhaps the most critical aspect is their effects during drought. Due to limited financial resources land owners were seldom able to move stock to better areas during drought, thus increasing grazing pressure on the land. Also, as stock transport was by droving, if there was no feed or water on stock routes, stock movements were restricted and overgrazing resulted. Mulga and Mallee scrub was often pulled as a feed source during droughts thus accelerating the removal of vegetation cover. In South Australia, stock losses of 75% were common in the 1940s. In the western Division of NSW 50% stock losses were common, and by 1944 up to 70% stock had been lost (ie over 1 million sheep) in the western Riverina (McKeon et al 2004). Overstocking of sheep stations was also reported in WA in the mid 1930s to 1940s (Pearson and Lennon, 2010).

Although the installation of fencing and wind mills were considered property improvements (Ratcliffe, 1938), they also allowed stock to stay longer on country when feed had run out, thus increasing pressure on the land (Russell and Isbell, 1986). Stock numbers were the highest on record before the 1940s drought (approx 120 million sheep and 14 million cattle – Australian Agricultural Assessment) which resulted in overstocking as the drought developed (Ratcliffe, 1938, McKeon 2004).

Other developments that accelerated wind erosion

Rabbits

In 1859 twenty four rabbits were released outside of Melbourne and rapidly spread across the continent at about 130 km per year. As early as 1881 farms were being abandoned because of de-vegetation by rabbits, and in 1887 10 million rabbits were killed (McTainsh and Boughton, 1993). By the 1900s there was an estimated one billion rabbits in Australia and by 1926 this number had exploded to 10 billion (Williams et al., 1995). Chemical rabbit control programs using strychnine, phosphorus, arsenic, calcium cyanide and sulphur dioxide had little effect upon the increasing numbers.

Woody weeds

Woody weeds can both increase and decrease wind erosion, depending on their density. At high densities they protect soils within shrubland, but at low densities they cause wind funnelling between bushes increasing wind erosion. Erosion is also increased on the margins of high density shrublands, where woody weeds compete for soil moisture leaving these areas as bare scalds (McTainsh and Leys, 1993). The first wave of woody weed encroachment was noted as a problem in 1860-1890s, however there were few attempts to control it as burning could threaten stock and remove valuable pasture (McKeon et al., 2004).

Rail heads

In the early days stock transport was mainly by droving and rail. Many towns (including Alice Springs, Charleville and Kalgoorlie) had rail yards that were used to hold stock prior to transport out of the region (Pearson and Lennon 1910). Stock were droved to the stock yards and grazed on what local pasture was available until they were loaded on the trains. These high concentrations of stock around railheads inevitably de-vegetated these areas and they became major sources of local dust.

Town commons

Town commons were used by town's people to run goats, and cattle for milk and meat, as well as being overflow areas to temporarily store cattle that had been droved to a railhead (Walker, (1976). These town commons (such as at Broken Hill, Cobar and Alice Springs), became severely degraded and were local sources of dust.

Military airfields

A large number airfields were established in rural towns throughout Australia for military use, or to support army bases (serviced by planes) during World War II. Aircraft in the 1940's had relatively short ranges, therefore transporting planes from for example Brisbane to Darwin would require fuel stops at Charleville and Karumba (on the Gulf of Carpentaria). Many runways were unsealed or gravel and vehicle traffic around airport facilities and temporary accommodation areas, would all have reduced grass cover and exposed local soils to the wind.

Land management in the 2000s

The Setting
Community attitudes towards the environment, and land management in particular, have improved dramatically since the 1940s, and a number of progressive government programs to support better land management have been implemented since the 1940s. Pastoral companies and other agri-businesses have been consolidated to form larger and public and private funded enterprises.

There are now numerous government programs which actively support sustainable land management. The major ones are the National Landcare Program, the Natural Heritage Trust, and most recently the Caring for our Country Program. State-based Natural Resource Management agencies provide a range of regionally targeted sustainable land management incentives. Nationally, better targeted drought subsidies, better rural roads and more efficient stock transport systems all help to reduce the impact of drought upon the land. Rabbits are now at very low levels due to effective pest control programs. The knowledge-base that landholders can access is now vastly greater, with industry and government promoting science and technology findings to landholders. The national economy is strong compared with the post-Depression years of the 1940s and rural commodity prices are holding up well. On the negative side, the severe drought of the 2000s that began in 2001 was also the hottest on record (since 1910), compounding the impact of the low rainfall on protective vegetation. Like the 1940s, this drought has resulted in dramatic dust storms and widespread wind erosion of soils, however the question remains whether improvements in land management have reduced the wind erosion response.

Community attitudes
Post WWII agricultural mechanisation, introduction of new legumes and rotational cropping, and improved pastures were evidence of a new optimism towards farming and grazing (Young 1996). By the 1970's the mood had changed, as pessimism overtook the agricultural and pastoral sectors with the realisation that natural resources are finite. During the 1980's this mood changed to a sense of 'get big or get out', and a rural-urban drift of young people had set in. Urban communities began to have an increasing influential voice on issues that affect rural communities. Parts of both communities (but mainly urban communities) became aware of overseas trends towards increased environmental awareness, and as a result the 'ecological significance' of some agricultural practices came under scrutiny (e.g. the application of chemicals on farms was seriously questioned) (Young 1996). This new environmental awareness is perhaps best exemplified by the 'No Dams' campaign that had began with the flooding of Tasmania's Lake Pedder and extended to the Gordon River Scheme. Sufficient public pressure was exerted in these campaigns for the Federal Government to intervene and enforce the 1983 World Heritage Properties Conservation Act to prevent the Gordon River dam being built and override Tasmanian state decisions. Over the subsequent 30 years there was a dramatic increase in environmental activism, and with this an appreciation of the ecological services that native vegetation and the soils provide.

The concept of sustainable development defined by the Brundtland Commission (1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", has now become accepted as the baseline to approach agriculture. Interestingly, this concept is similar to an earlier slogan of the NSW Soil Conservation Service that; "soils should be used to their potential, but protected according to their needs". Ultimately, these changes in community attitudes have lead to increased investment in soil and water conservation.

Government policy

The repeated economic hardship and land degradation that accompanied the droughts of: the 1890s, 1901-1903, 1920s, 1930s and 1940s stimulated State Governments to establish soil conservation agencies. These agencies and their States have since cooperated with Federal Governments to; restructure the rural economy, support landholders in times of drought, reduce or halt clearing of native vegetation and to improve the overall level of agronomic, animal husbandry and environmental knowledge to land holders. In the 1980s in particular, there was an increase in "environmental" policies, as understanding improved of how exploitative or inappropriate land use and management can increase land degradation.

The table below provides a time line of the change in policies that influenced agricultural and pastoral development, and land management practices in the period since the 1940s.

1946	National Standing Committee on Soil Conservation formed to; coordinate policies and programs on soil conservation, arrange training of appropriate personnel, and to facilitate exchange of information and other forms of mutual assistance between the governments within Australia
1951	Soil Conservation Act was passed in Qld to estimate the amount of erosion. Trials were run and information was given to help land owners (Skerman et al 1988)
1960s	The practice of acquiring remnant vegetation patches for conservation purposes began to spread nationally (Beale & Frey 1990 p25)
1962	The Brigalow Land Development Scheme, Qld encouraged clearing large area to secure ownership (Boulter et al 2000 p42) (Dover 1994, Chap 10)
1975	First National Assessment of Land Degradation "The Collaborative Study" Commonwealth & State Survey (Roberts 1988 p14)
1980	ACT Nature Conservation Act 1980 became the primary legislation for the protection of native plants and animals in the ACT and for the management of the conservation reserve network.
1983	The National Soil Conservation Programme (NSCP) (1983 to 1992), was the vehicle for the Commonwealth's soil conservation funding up to 1990, and Landcare funding to 1992. The NSCP objectives were to complement the existing activities of other bodies, catalyse the involvement of additional resources and raise the public profile for soil conservation.
1983	Tax concessions for clearing land removed (Conacher & Conacher 1996 p121)
1985	Australian Soil Conservation Council formed.
1985	The Rural Land Protection Act, Qld encompassed the development of strategies for managing weeds, pest animals and the state's 72,000 kilometre network of Stock Routes. (Rangeland Tracking changes 2001 p 137)
1985	The Soil Conservation (Financial Assistance) Act, 1985 was used by the Commonwealth Government to set up a National Soil Conservation Program Fund.
1986	The WA Environmental Protection Act 1986 formed the Environmental Protection Authority. It also provided for the prevention, control and

	abatement of pollution and environmental harm and for the conservation, preservation, protection, enhancement and management of the environment.
1987	The Victoria Planning and Environment Act 1987 set up a system of planning schemes to regulate the use and development of land.
1987	Ecological sustainable development, adopted after the UN Bruntland Commission (Boulter et al 2000 p23)
1988	Fertiliser subsidies removed because they were not promoting good land management. (Conacher & Conacher 1996, p121)
1988	The Victoria Flora and Fauna Guarantee Act 1988 was the key piece of Victorian legislation for the conservation of threatened species and communities and for the management of potentially threatening processes.
1989	Soil Conservation and Land Care Act - South Australia (Rangeland Tracking Changes 2001 p144)
1989	Pastoral Land Management and Conservation Act - South Australia (Rangelands Tracking changes 2001 p 145)
1991	The Native Vegetation Act 1991 was a progressive piece of legislation designed to prevent the broad scale clearance of native vegetation for agriculture and urban development in South Australia. The Act covers both private and public land.
1992	The National Landcare Program (1992 – 2008) funded 4,500 community groups with about $1 billion, with the goal of developing and implementing resource management practices to enhance Australia's soil, water and biological resources.
1992	The Pastoral Land Act - Northern Territories allowed for the protection and conservation of wildlife on private land. (Rangeland Tracking Changes 2001 p148)
1994	Victoria Catchment and Land Protection Act 1994 (CLP Act)
1994	Land Act - Qld (Rangeland Tracking Changes 2001 p 137)
1997	Land Administration Act - Western Australia (Rangelands Tracking Changes, 2001)
1997	Natural Heritage Trust (1997-2008) set up by the Commonwealth Government to help restore and conserve Australia's environment and natural resources.
1999	Queensland Vegetation Management Act 1999
1999	The Our Country Our Future program attempted to establish a coordinated national approach to water conservation and develop an integrated program of soil, water and forest research through a new body, Natural Resources Research and Development Corporation (Beale & Frey 1990, p50)
1999	The Hawke Government made its “One Billion Trees Program” the centrepiece of its environment statement (Beale & Frey 1990, p37).
2003	The NSW Native Vegetation Act 2003 was introduced to end broadscale land clearing. The Department of Environment and Climate Change is the government agency charged with ensuring that native vegetation is protected for future generations.
2004	The Queensland Vegetation Management and Other Legislation Amendment Act, 2004 changed Queensland’s tree clearing laws

	incorporating the tree clearing provisions of the Land Act 1994 and the Vegetation Management Act 1999 into a single piece of legislation for both leasehold and freehold land.
2007	The Queensland Delbessie Agreement (also known as the State Rural Leasehold Land Strategy) is a framework of policies and guidelines aimed to achieve sustainable land management, and for assessing rural leasehold land condition.
2008	The Commonwealth Government, Caring for Our Country Program, 2008 was established to fund environmental management of our natural resources [http://www.nrm.gov.au]
2009	The Queensland Vegetation Management (Regrowth Clearing Moratorium) Act aims to regulate the clearing of vegetation in a way that conserves regional ecosystems, conserves vegetation in declared areas, ensures clearing does not cause land degradation, and prevents the loss of biodiversity.

Land management practices

Agricultural practices

In the 2000s cropping systems have the dual objectives of: profitability of agricultural production and sustainability of the land resource. These objectives have been achieved by: (i) a change in the ethos of land ownership, (ii) an increased demand from markets for more sustainably-derived products, and (iii) better farming technology and agronomics, based on scientific research and trials (Australian Government Assessment, 2001).

The key features of these better farming systems are:

- Maintenance of adequate plant residue cover for soil erosion protection through the adoption of stubble retention systems.
- The adoption of minimum/zero tillage systems that have the dual aims of erosion protection and soil structure maintenance/improvement.
- Avoidance of cultivation in high erosion risk periods.
- Reduction in burning stubbles.
- Use of chemical fallowing rather than tillage.
- Integrated feral fauna and flora control programs, including biological controls.
- Fencing to land class through a developed farm plan.
- Retention of boundary tall perennial vegetation.
- Avoiding grazing erosion-prone areas by fencing these areas.
- Intensive strip grazing/ cropping.
- Land reclamation of degraded areas for both production and conservation uses.
- Involvement of agricultural commodity industries in promotion of better land management practices, (e.g. Grains research and Development Corporation – Grain and Graze, Mallee Sustainable Farmers).

While the above list is indicative of "better" farming practices, not all land holders have adopted these management practices, and it is for this reason that accelerated wind erosion still occurs. Even if all these management practices were adopted, extreme climate and weather events will continue to test these farming systems to the point that they may fail to control erosion.

Pastoral practices
In the 2000s grazing systems have also progressed. A feature of these systems is the use of technology to manage stock health, stock movements and the environment, through forecasting of climate and pasture growth. Markets, government policy and community attitudes all now play a significant role in the daily management of increasingly large pastoral 'corporations' (Annett 2003).

The key features of the 2000s grazing systems are:

- Stock transport is readily available (Pearson and Lennon, 2010).
- Government drought relief programs to encourage early destocking and "drought proofing".
- Animal attributes have been improved to achieve better disease resistance and better capacity to survive flood and drought conditions, leading to higher productivity (McKeon et al 2004).
- Animal husbandry, grazing system knowledge, education level of landholders have all improved. (McKeon et al 2004). This is supported by legislation (at least in NSW) which makes it illegal to let animals starve or leave animals in distress as a result of drought conditions (McKeon et al 2004).
- Better control of total grazing pressure (native, feral and domestic stock, e.g. kangaroo culling, goat trapping and camel shooting).
- Sustainable grazing systems promoted by industry for the higher rainfall zones (>600mm) of southern Australia.

Other developments that accelerate wind erosion
Rabbits
The introduction of Myxomatosis in 1952-1954 killed an estimated 99.8% of the rabbit population in Australia, but by 1990 the rabbit population was estimated to be back at about 600 million. In 1996-1998 the Rabbit Calicivirus Disease (RCD) and integrated rabbit control used in large-scale group campaigns has seen some regions aiming to become rabbit free, but in other arid areas rabbit populations are still estimated to be at 50% of the 1990 numbers. The devastating effects that rabbits have on vegetation cover and soil surface stability, remain a crucial land management issue if land degradation is to be minimised.

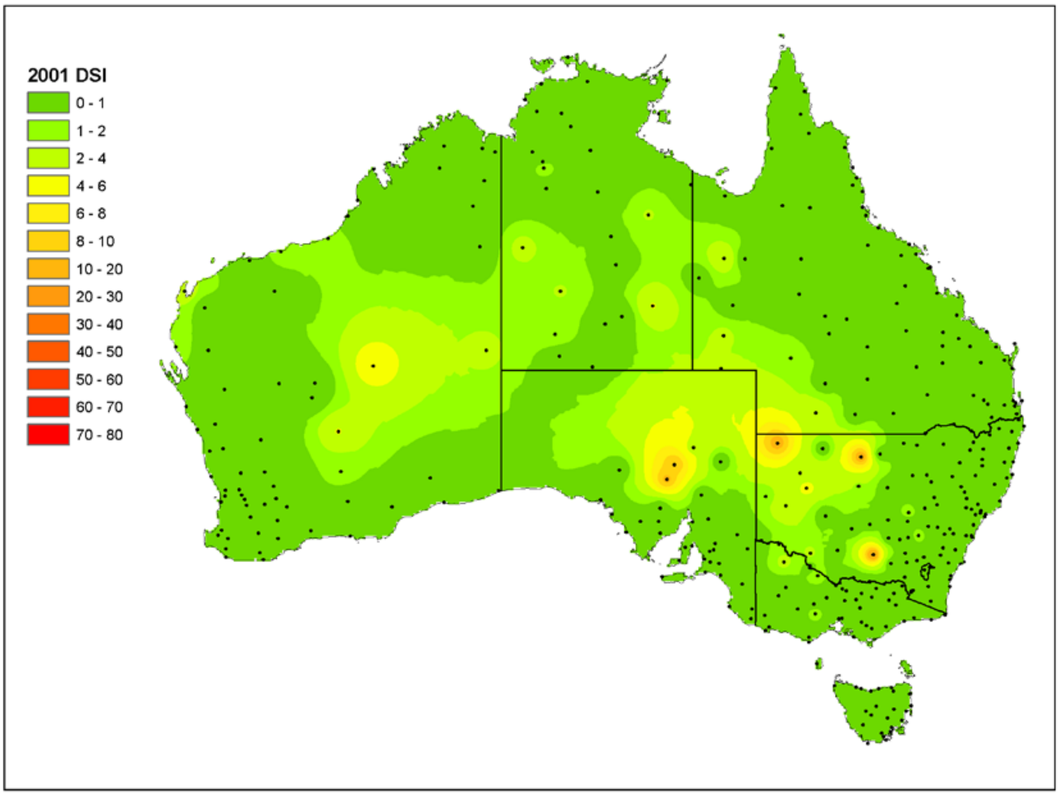
Woody weeds
A second wave of woody weed encroachment occurred in the 1950s in NSW and Queensland. In those days fire was rarely used as a land management tool, therefore woody weeds became established. This wave was aided by a rainfall-driven germination event in 1949 to 1951, along with further rain in 1955 to 1957. A third wave of wood weed encroachment in 1973-74 followed another run of above average rainfall years.

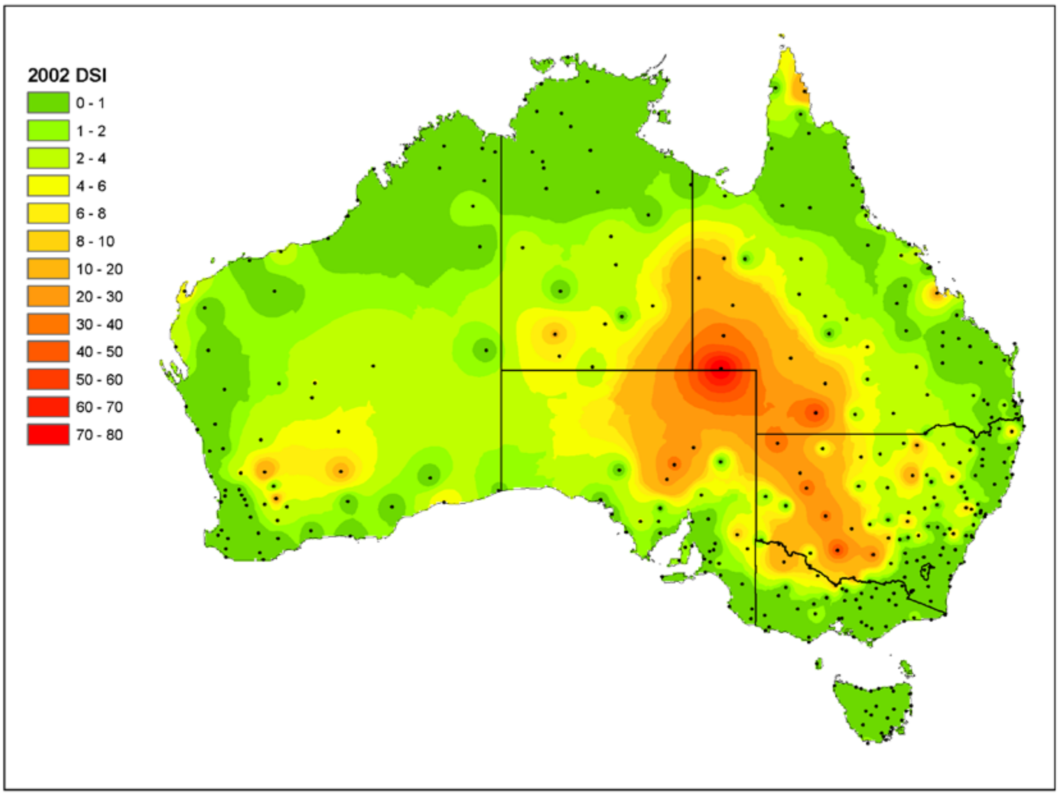
Road Infrastructure
Infrastructure improvements to roads took place in cattle grazing areas after World War II, with 2400 km of roads sealed as part of the Commonwealth and State Government funded Beef Roads Program. This improvement in roads was aimed at improving the movement of cattle from breeding areas to fattening areas, and on to market. It enabled breeding properties to increase their annual turn-off and thus improve productivity. The program had the advantage from a wind erosion perspective, that during droughts stock could be moved more readily to non-drought regions (Pearson and Lennon, 2010) reducing grazing pressure on pasture grasses which protect soils against wind erosion.

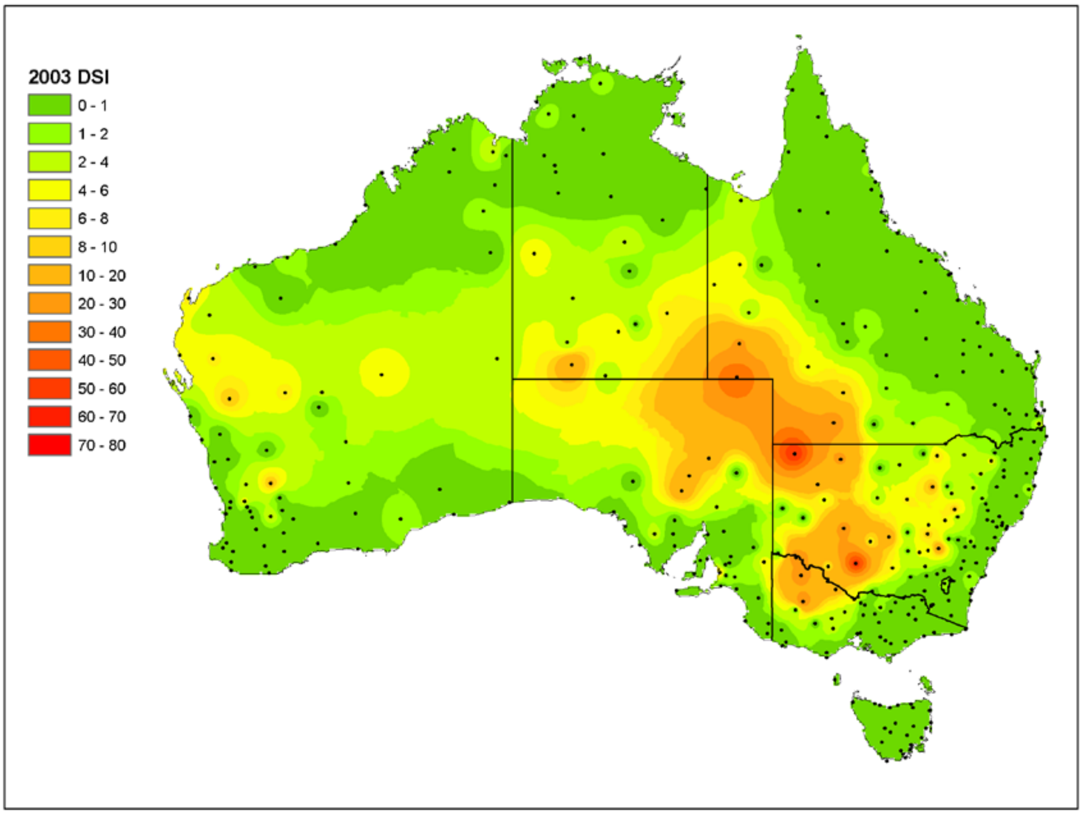
A bibliography is provided in Section 6 of all the land management references accessed during this study.

4.4 Annual DSI maps, 2000 to 2009

The above comparison of wind erosion during the 1940s and 2000s has shown that wind erosion rates have decreased very significantly since the 1940s. Over the same period overall land management has improved significantly. This is due to general improvements in: (i) economic conditions from the 1940s (in the wake of the Great Depression of the 1930s and imposed by World War II), (ii) improved community awareness of environmental issues, and (iii) major policy initiatives to improve the management of agricultural and pastoral land. In the above analysis of long term changes in wind erosion the spatial resolution of patterns of erosion in the 2000s is constrained by the need to use the same (limited number) of BoM stations for both periods. In the interests of describing annual changes in wind erosion in the 2000s at as high a resolution as possible, and of comparing the current SoE reporting period (2005-2009) with the previous period (2000-2004), higher resolution annual DSI maps are presented throughout the 2000s (Fig. 5).


2001 DSI
0 - 1
1 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80


2002 DSI
0 - 1
1 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80


2003 DSI
0 - 1
1 - 2
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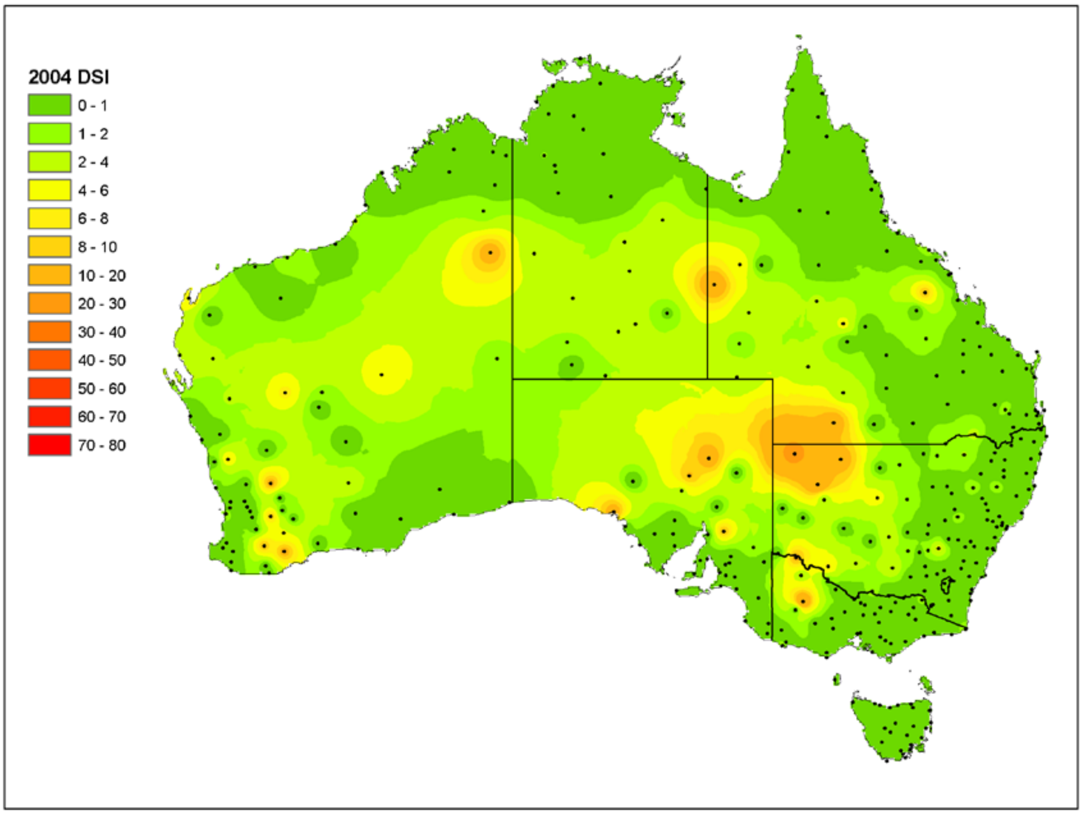
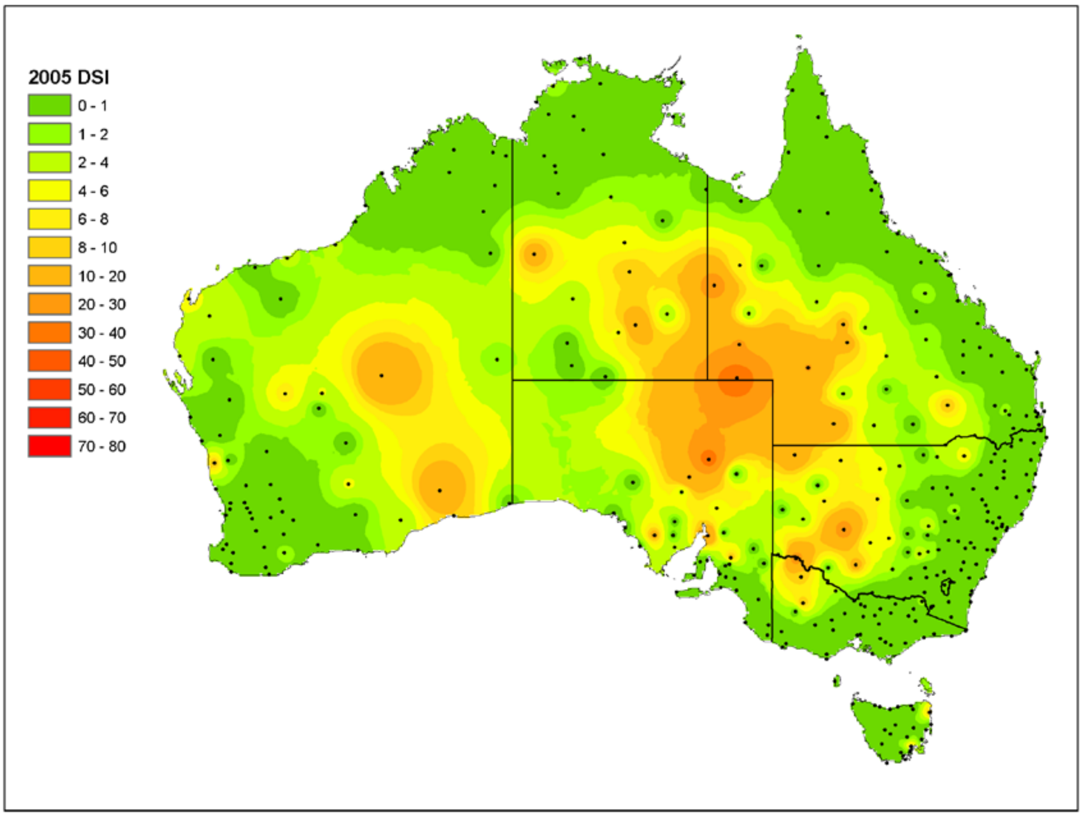
4 - 6
6 - 8
8 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80


2004 DSI
0 - 1
1 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80


2005 DSI
0 - 1
1 - 2
2 - 4
4 - 6
6 - 8
8 - 10
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30 - 40
40 - 50
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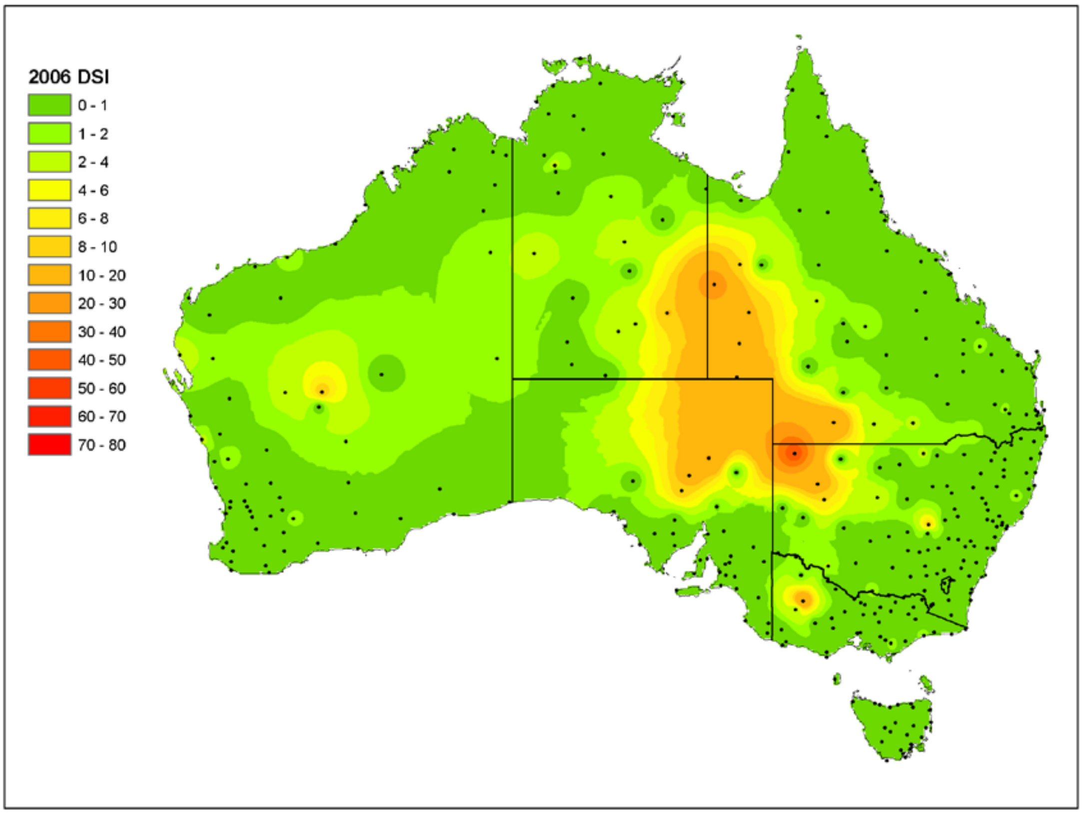
60 - 70
70 - 80


2006 DSI
0 - 1
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6 - 8
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40 - 50
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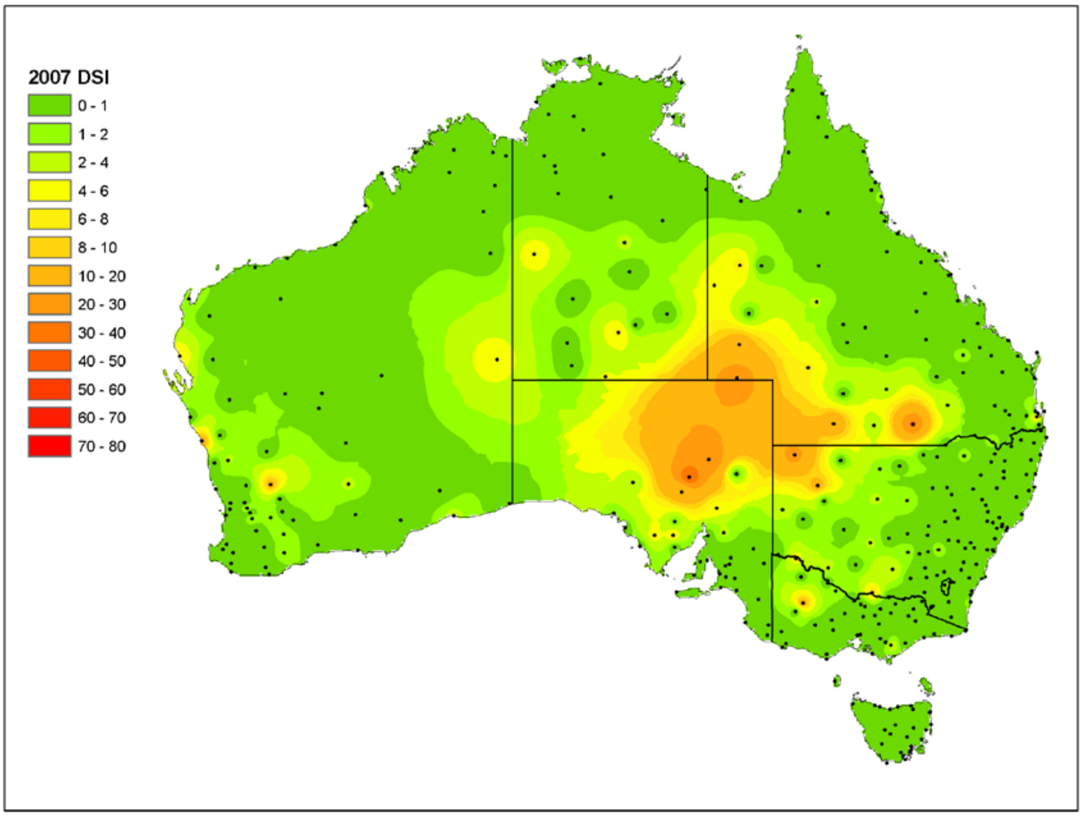
70 - 80


2007 DSI
0 - 1
1 - 2
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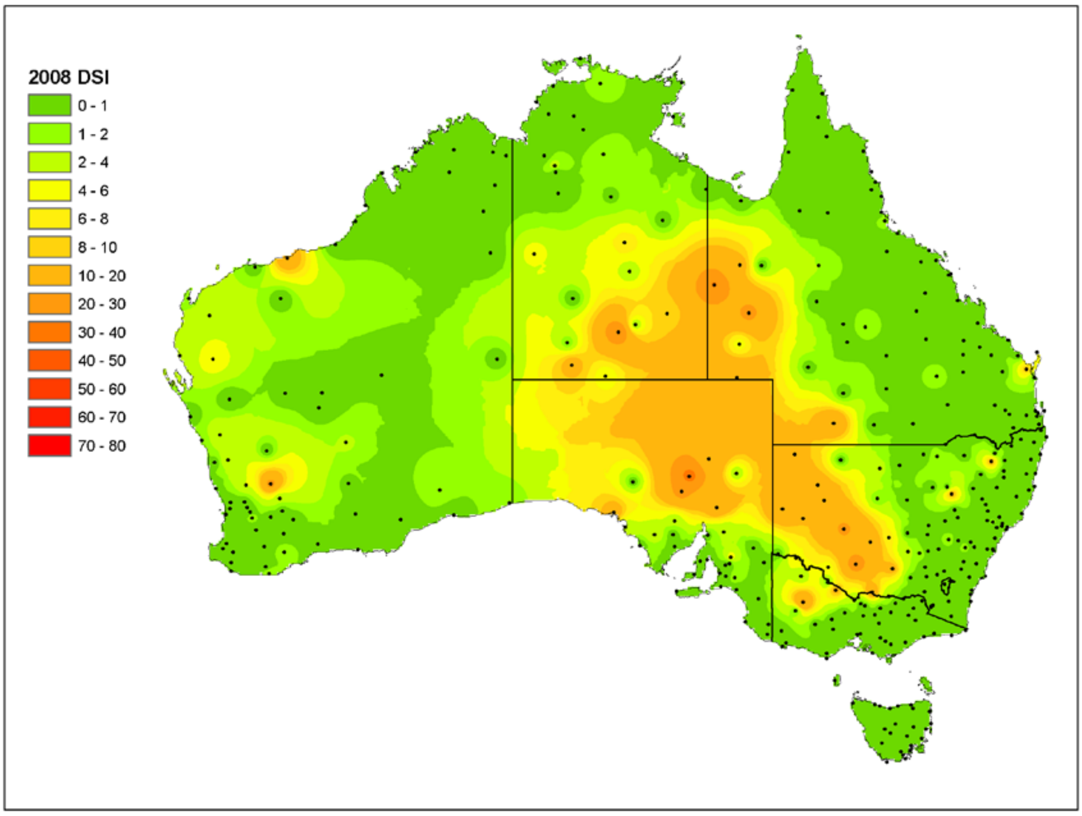
4 - 6
6 - 8
8 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80


2008 DSI
0 - 1
1 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80

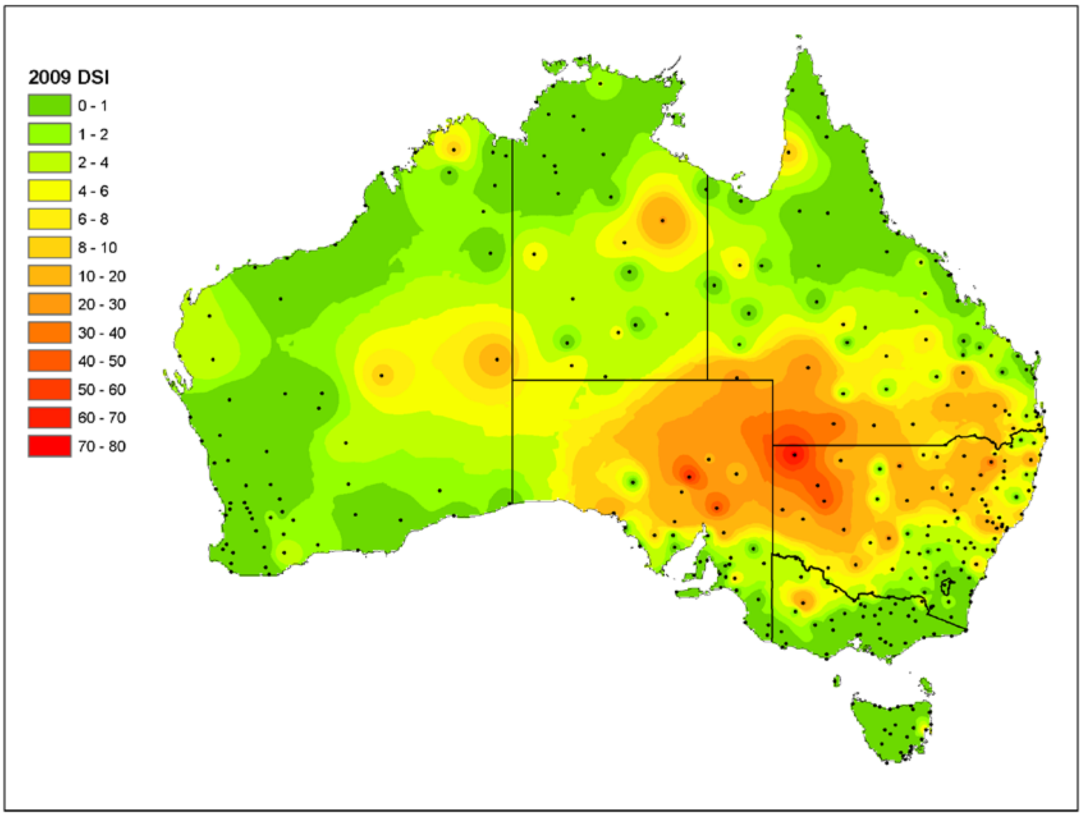


Figure 5: Annual DSI maps based on 356 stations (2000-2009).

Figure 5 shows that spatial patterns of wind erosion have changed significantly within the 2000s. The most active wind erosion years were 2002/2003 and 2009, and within these years the majority of the erosion occurred in a small number of very large dust storms. On the 23rd October, 2002 there was a very large event that entrained 4.85 million tonnes of dust (McTainsh et al., 2005) and on 23rd September, 2009 the "Red Dawn" dust storm engulfed Sydney and Brisbane and exported between 2.2 and 7 million tonnes of valuable topsoil as dust off the east Australian coast (Leys et al., 2011). These active wind erosion years were also the driest years in eastern Australia during the 2000s.

During 2010 and 2011 (for which maps are not yet available) there has been period of sustained and widespread high rainfall which has largely shut down wind erosion, however in the near future there is likely to be a period of renewed wind erosion, once the rainfall decreases. This situation can arise because, while widespread and intense rainfall initially causes flooding over the vast floodplains of the internally-draining rivers in the LEB and MDB (converting them into some of the most productive rangelands in the world), when these floodplains dry out and their protective grass cover is reduced, the fine sediments deposited during the floods become highly erodible and are blown away. The scene may well be set for such a sequence of events when the current period of high rainfall is over.

5. Summary

It is well documented that wind erosion was very active during the drought periods of the 1890s, 1901-1903, 1920s, 1930s and 1940s. During the "Dust Bowl" years of the 1940s this activity peaked, with numerous large dust storms sweeping across south east Australia and passing off the coast. In the 2000s several large dust storms again engulfed eastern Australian cities increasing public awareness of wind erosion as a land degradation process. These recent dust storms have raised the questions of; whether they are the largest events in Australian history, and to what extent they are “natural” or land management induced. This report aims to answer these questions, by making a quantitative comparison of wind erosion activity in the 1940s and the 2000s, then by reviewing the literature on land management in the two periods, comes to conclusions about the role of land management in wind erosion

This analysis has used Bureau of Meteorology records of wind erosion events to calculate a Dust Storm Index (DSI) to quantify wind erosion. The mean on-site wind erosion in the 1940s produced a DSI of 11.4; almost 6 times higher than in the 2000s (DSI of 2.0). These events in the 1940s also reached the coast. South east coastal cities (from Brisbane to Melbourne) had a decadel mean DSI of 5.0 during the 1940s, then this dropped sharply to 0.15 in the 2000s; evidencing the much lower erosion activity then.

There were also significant regional differences within and between the two periods. In the 1940s the hotspots of wind erosion activity were the Mulga (Qld) and the Riverina (NSW/Vic), plus Central Australia. In contrast, the DSI levels in the south and west of the continent were around 30% of those in the east and centre. In the 2000s erosion activity plummeted in the Mulga to 2% (of 1940s levels) and in the Riverina DSI decreased to 16%. In the south, centre and west of the continent in the 2000s, the DSI decreases were less, because these more arid regions have higher “natural’ wind erosion rates.

Land management has improved significantly across the continent from the 1940s to the 2000s, as a result of changed community attitudes towards the environment, government policy initiatives and better land management practices. In the 1940s, the aftermath of the 1930s depression, coupled with World War II meant that there was a limited funding and people available on the land to maintain infrastructure, control pests (e.g. rabbits were in plague proportions) and protect soils. There was also several large land settlement projects (including soldier settlement schemes) and land development projects (including irrigation schemes) which increased the pressure on the land. Other impediments to good land management in the 1940s were; limited drought assistance to farmers, poor roads, and limited trucking available to move stock out of drought areas. Lastly, the expansion of military airfields and army bases into rural towns (including Charleville in the Mulga, Alice Springs and Katherine-Darwin) during World War II significantly increased local wind erosion.

In the 2000s the national economy is strong, and without a world war to distract public attention, community attitudes towards the environment have significantly improved. There have been numerous government programs which actively support sustainable land management, with the result that land management practices have improved enormously. Improved rural roads and more efficient stock transport systems all help to reduce the impact of drought upon the land. Rabbits are now at very low levels due to effective pest control programs. The knowledge base that landholders can access is now vastly greater, with industry and government promoting science and technology findings to landholders.

Finally, while circumstances which encourage sustainable land management have improved greatly, not all land holders have adopted these management practices, and it is for this reason that accelerated wind erosion still occurs. Furthermore, even if all the sustainable management practices available are adopted, climate changes and extreme weather events will continue to test land management systems, to the point that they may still fail to control accelerated erosion. Therefore, we cannot afford to slow the momentum of improving land management systems.

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7. Appendices

Appendix 1: Relative contributions percentages of the stations used to produce a Riverina region composite DSI.

Station	%
Deniliquin	19.72
Tocumwal	18.31
Uranquinty	8.45
Wagga	53.52

Appendix 2: List of the 39 BoM stations with records in both decades, plus nearby replacement stations in the 2000s.

Stations in the 1940s	**Stations in the 2000s**
Darwin, Katherine, Alice Springs, Cooktown, Cairns, Townsville, Rockhampton, Charleville, Coffs Harbour, Williamtown RAAF, Sydney, Canberra, Wagga Wagga, Tocumwal, East Sale, Hobart, Mount Gambier, Ceduna, Kalgoorlie, Pearce RAAF, Perth, Geraldton, Onslow, Port Hedland, Broome, Halls Creek	Same station
Daly Waters	Larrimah
Karumba	Burketown
Archerfield	Brisbane
Rathmines AMO	Newcastle
Richmond	Sydney
Uranquinty	Wagga Wagga
Deniliquin	Tocumwal
Essendon	Melbourne
Bairnsdale	East Sale
Launceston	Devonport
Mallala	Adelaide
Parafield	Adelaide
Forrest Aero	Eucla

Appendix 3 Estimates of percentage changes in DSI as a result of variable dust code adherence by BoM Observers

	1940s			**2000s**		
Station	Decade mean DSI (Original)	Decade Mean DSI (Vis. Adj.)	% over/ under estimate	Decade mean DSI (Original)	Decade Mean DSI (Vis. Adj.)	% over/ under estimate
PARAFIELD (SA)	3.6	3.0	21.8	0.0	0.0	0.0
ALICE SPRINGS (NT)	10.9	8.4	30.1	2.1	2.3	-9.2
BRISBANE (QLD)	1.2	0.6	89.8	0.2	0.2	0.0
BROOME (WA)	0.2	0.2	0.0	0.2	0.2	0.0
CAIRNS (QLD)	0.8	1.3	-66.7	0.0	0.0	0.0
CANBERRA (ACT)	2.5	1.1	132.6	0.0	0.0	0.0
CEDUNA (SA)	3.4	3.8	-11.8	0.7	0.9	-29.2
CHARLEVILLE (QLD)	10.1	12.6	-24.3	0.6	0.7	-15.8
COFFS HARBOUR (NSW)	4.7	6.0	-28.6	0.1	0.2	-86.4
COOKTOWN (QLD)	2.0	0.2	852.4	0.0	0.0	0.0
DALY WATERS LARRIMAH (NT)	1.7	1.3	28.8	0.0	0.0	0.0
DARWIN (NT)	4.8	4.6	4.6	0.0	0.0	0.0
DENILIQUIN (NSW)	16.6	8.5	94.6	-	-	-
EAST SALE (VIC)	2.9	1.8	61.3	0.1	0.1	0.0
MELBOURNE (VIC)	0.5	0.4	23.2	0.0	0.0	0.0
FORREST – EUCLA (WA)	5.1	3.7	37.9	0.3	0.3	0.0
GERALDTON (WA)	0.5	1.0	-87.0	0.4	0.9	-137.5
HALLS CREEK (WA)	0.9	0.5	59.4	0.3	0.3	0.0
HOBART (TAS)	0.5	0.2	172.7	0.0	0.0	0.0
KALGOORLIE (WA)	5.9	3.8	57.7	0.4	0.5	-21.8
KARUMBA – BURKETOWN (QLD)	6.8	5.9	15.4	0.4	0.4	0.0
KATHERINE (NT)	7.6	6.3	21.2	0.0	0.0	0.0
LAUNCESTON - DEVONPORT (TAS)	0.0	0.0	0.0	0.0	0.0	0.0
MOUNT GAMBIER (SA)	0.5	0.2	88.4	0.0	0.0	0.0
ONSLOW (WA)	5.4	1.2	342.6	0.0	0.0	0.0
RATHMINES (NSW)	0.2	1.1	-400.0	0.6	1.0	-65.6
PEARCE RAAF (WA)	1.1	1.1	0.0	0.0	0.0	0.0
PERTH (WA)	3.2	3.2	0.0	0.0	0.0	0.0
PORT HEDLAND (WA)	5.8	5.0	15.7	0.6	0.6	0.0
ROCKHAMPTON (QLD)	0.7	0.7	0.0	0.1	0.1	0.0
RICHMOND RAAF (NSW)	1.7	3.0	-75.8	0.1	0.1	0.0
SYDNEY (NSW)	2.9	1.6	87.1	0.1	0.1	0.0
TOCUMWAL (NSW)	14.4	23.5	-62.5	1.2	1.6	-34.6
TOWNSVILLE (QLD)	1.1	0.8	34.8	0.2	0.2	0.0
URANQUINTY (NSW)	5.0	5.1	-2.0	-	-	-
WAGGA WAGGA (NSW)	3.5	5.5	-56.8	0.3	0.3	0.0

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