CSIRO PUBLISHING

SPECIAL ISSUE | RESEARCH PAPER
https://doi.org/10.1071/RJ22059

THE RANGELAND JOURNAL
Australian Rangeland Society

Dust-storm frequencies, community attitudes, government policy and land management practices during three major droughts in New South Wales, Australia

John Leys[A,B,C,*], Stephan Heidenreich[A], Stephen White[D], Juan Guerschman[C] and Craig Strong[B]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
John Leys
Fenner School of Environment and Society, Australian National University, Canberra, ACT, Australia
Email: johnleys58@outlook.com

Received: 26 March 2022
Accepted: 24 February 2023
Published: 27 April 2023

Cite this:
Leys J *et al.* (2023)
The Rangeland Journal
44(5–6), 343–355. doi:10.1071/RJ22059

ABSTRACT

This study assessed whether dust-storm frequency during major droughts in New South Wales (NSW), Australia, has changed and what may have caused any change. The frequency of days with dust storms, i.e. when visibility is <1000 m, is presented for the dust storm year (July to June), with the maximum number of dust storms for three major droughts, namely, 2017/20, Millennial and World War II droughts. Community attitudes, government policy and land management practices have changed since the 1940s, and these factors were reviewed to determine whether they explain changes in dust-storm frequency. Two data sources were used: meteorological weather codes from the Australian Bureau of Meteorology and dust particulate matter <10 μm (PM10) from the DustWatch/Rural Air Quality Monitoring Network. The particulate-matter data were converted to dust-storm days (DSD) to create a yearly time series. The meteorological data records were coded as dust storms and required no modification. Results showed that 1944/45 was the dustiest year, with 4.4 times more DSD than in 2019/20 and 9.9 times more DSD than in 2009/10. One reason for the higher DSD in 2019/20 than in 2009/10 was the area protected from wind erosion by vegetation cover above 50%. In 2019/20, 69% of NSW was protected from wind erosion, compared with 79% in 2009/10. We suggest the primary reasons for lower DSD in 2019/20 and 2009/10 than in 1944/45 were community attitudes, government policy and land management practices; these, in combination, help maintain vegetation cover. Since the 1940s, the focus of land management has changed from 'taming the land' to 'sustainably using the land'. Government policy in the 2000s is focused on supporting farming businesses and communities to manage and prepare so as to successfully manage drought. Land management practices that maintain ground cover are now widely practised.

Keywords: community attitudes, drought, dust storm, government policy, land management, wind erosion, PM10, visibility, dust.

Introduction

Dust storms attract a great deal of attention because they are spectacular phenomena. They affect the soil and vegetation from which they emanate, air quality, and the communities they pass over (Leys *et al.* 2011; Tozer and Leys 2013). Wind erosion and the resultant dust storms are a function of climate and land management practices (Love *et al.* 2019). When vegetation cover is >50% (Leys 1999), the soil is protected from wind, and dust emission decreases. Dust storms increase when the climate is dry and windy, and when protective vegetation levels are low, such as during droughts. Land management plays a significant role in wind erosion levels (McTainsh and Leys 1993; McTainsh *et al.* 2011), and can exacerbate or mitigate wind erosion by modifying vegetation cover and surface soil aggregation (Leys 1990; Middleton 2018). In his book Flying Fox and Drifting Sand, Ratcliffe (1938, p. 323) said, 'I have described nothing less than a battlefield, on which men is engaged in a struggle with the remorseless forces of drought, erosion and drift.'. That struggle is reflected in community attitudes, government policy and land management practices. These social factors can exacerbate or mitigate soil erosion, with social factors that lead to increased vegetation cover and improved surface soil aggregation, especially during droughts, helping to reduce dust storms (McTainsh *et al.* 2011).

Dust storms and droughts are episodic and require time-series data of considerable length to determine any changes in frequency and effect. Meteorological observation records are the most widely used method to measure dust storm frequency in both Australia (Goudie 1983; O'Loingsigh *et al.* 2014) and elsewhere (Goudie and Middleton 1992; Middleton and Goudie 2001; Novlan *et al.* 2007), although other methods include satellite imagery (Prospero *et al.* 2002; Querol *et al.* 2019) and ground-based measurements with instruments (Tong *et al.* 2012; Lei *et al.* 2016; Leys *et al.* 2018). Each method has strengths and weaknesses. For example, meteorological records have long time series, but low daily observation frequencies, whereas satellite imagery has good spatial but limited temporal coverage. Ground-based measurements have limited spatial coverage but excellent temporal resolution.

Dust storms represent a hazard to human society and the natural environment (Middleton 2019; APDIM 2021). Understanding the trends and drivers of dust storm frequency enhances the ability to (1) assess whether land management and government policy can effectively mitigate soil erosion, and (2) develop responses to where and what actions need to be implemented (Australian Government 2018; RM Consulting Group 2018).

Common questions during the 2017/20 drought, when multiple dust storms occurred in New South Wales (NSW) (Nguyen *et al.* 2019), included the following: 'Are the number of dust storms per year changing, and if so, what is causing the change?'. This study aimed to answer these questions by examining the dust storm frequency time series during three major droughts between 1940 and 2020. To explain what caused the dust storms, we reviewed three social factors that have changed over that period. This study had two aims: (1) to determine the dust-storm year (DSY = July to June) with the highest frequency of dust storms for three droughts between 1940 and 2020, and (2) to review community attitudes, policy, land use and land management practices to determine whether they could subjectively explain any differences in dust storm frequencies.

Methods

Dust storm frequency

The World Meteorological Organisation's (WMO) definition of a dust storm is when visibility is < 1000 m (Engelstaedter *et al.* 2003; Australian Government Bureau of Meteorology 2016), and has been used to describe dust storm trends in space and time for many decades (Goudie 1983). In this study, the period used to count dust storms was dust storm year (DSY = July to June) because dust storms in Australia generally occur in the austral spring (September to November) and summer (December to January) (McTainsh *et al.* 1998; Leys *et al.* 2018).

There is no consistent data set of dust storm frequency for the past 80 years for NSW. To build this time series, the following two data sources were used: (1) The Australian Bureau of Meteorology (BoM) meteorological weather-coded observations for the WWII (1937–1946) and Millennial (2001–2010) droughts as previously reported (O'Loingsigh *et al.* 2015), and (2) DustWatch and Rural Air Quality Network (hereafter called (DW; Leys *et al.* 2008; Riley *et al.* 2019) hourly averaged particulate matter (PM) concentrations for the 2005–2010 period, the later part of the Millennial drought, and the 2017/20 drought. With this time series, a count of dust storms was performed for each DSY of the three drought periods. The DSYs with the highest frequency of dust storms for each drought were: 1944/45, 2009/10 and 2019/20.

Meteorological weather code data

Meteorological weather codes describe weather phenomena, e.g. dust storms, mist, and haze. They are standardised international protocols of the World Meteorological Organisation (WHO 2019). Seven meteorological weather codes record dust storms (table 1 in O'Loingsigh *et al.* 2014). Weather observations are taken every 3 h throughout the day and night, although this is inconsistent across all stations. Two types of observations are taken, namely, present weather codes, which describe what phenomena are visible at the time of observation, and past weather codes, which record all weather phenomena since the last observation taken at the station. The 12 stations used for 1944/45 and 2009/10 are shown in Fig. 1. Some of the 1944/45 stations have since closed, so data from the closest station for the 2009/10 observations were used. We counted dust storm

Table 1. Count of average dust-storm days (DSD) for each dust-storm year (DSY) and the ratio of DSD to 2009/10 for New South Wales sites.

Item	1944/45	2009/10	2019/20	Ratio DSD to 2009/10
Average DSD (BoM, *N* = 12)	5.8	0.6		9.7
Average DSD (DustWatch, *N* = 20)		5.0	11.0	2.2

N, the number of observation sites.

days (DSD) as any day with a dust storm code in the past or present weather code for a calendar date.

DustWatch/Rural Air Quality Network data

The NSW dust monitoring network, DustWatch, began in 2005, but underwent a significant upgrade in 2017, forming the Rural Air Quality Network. Twenty sites in NSW have been operational for over 15 years (i.e. since 2007/08) and form the basis of the data used. All data are quality controlled using the methods outlined in Leys *et al.* (2018). The two models of DustTrak® used are manufactured by Thomson Scientific Instruments (TSI). Between 2019 and 2021, the original TSI 8520 DustTrak® instruments have been progressively replaced with TSI 8533 DRX DustTrak®.

The 8520 DustTrak® uses light scattering to measure particulate matter in one size fraction corresponding to approximately 10 µm for aerodynamic particle diameter (TSI Incorporated 2002). The DRX 8533 model simultaneously provides measurements for five size-segregated fractions. They are PM1, PM2.5, PM4, PM10 (the mass fraction used in this study) and total suspended particles (TSP; Wang *et al.* 2009; TSI incorporated 2022). The DRX 8533 is operated in this network with a gently heated inlet, whereas the 8520 model did not operate with a heated inlet. Hereafter, we refer to the output of both DustTrak® models as particulate matter less than 10 µm (PM10), noting that it is not the same as aerodynamic PM10 measured by other instruments. Different particle sizes are critical for classifying dust hours (Chang *et al.* 2018). During the 'Black Summer' bushfires (July 2019 to March 2020; Rodney *et al.* 2021; Ryan *et al.* 2021), particle measurements could be dust, smoke, or a mixture of both. Only those measurements classified as predominantly dust were used in this study, by using the quality-assurance method outlined in Leys *et al.* (2018).

Two DustTrak® models were used to measure PM10. A conversion factor between the 8520 and 8533 DRX was developed on the basis of co-located instruments at Coombah, which operated for 1 year between September 2019 to September 2020 (Fig. 1). Only dust aerosols, i.e. those aerosol readings with a PM2.5:10 ratio of less than 0.2

Fig. 1. Map showing locations of DustWatch and the Bureau of Meteorology (BoM) sites in New South Wales in 2009/10 and 1944/45.

were used in the analysis. This analysis resulted in 463 hourly dust readings and a correction factor of 8533 DRX to 8520 for PM10 of 1/2.9383.

The Dust Trak® PM10 values were converted to visibility, a necessity because dust storms are classified by visibility, i.e. <1000 m. We used the same data source as Baddock *et al.* (2014). Instead of the instantaneous minute PM10 values, we used the hourly average PM10 values (Eqn 1). We acknowledge the limitation of comparing an hourly PM10 average value to an instantaneous visibility reading; however, these were the best data available.

$$V = 240 \times PM10^{-0.98} \quad (1)$$

where V = visibility in km, PM10 = DustTrak® 8520 concentration μg/m³. Using Eqn 1, a PM10 concentration of 240 μg/m³, as measured by the 8520 DustTrak® model, equates to the visibility of 1000 m. We then counted dust storm days (DSD) as any calendar date when any hour in the day has a PM10 concentration greater than 240 μg/m³.

The conversion of 8520 DustTrak® PM10 to visibility should be applied only when using the same instrument or equivalent. The correction factor is not recommended for other instruments such as the tapered element oscillating microbalances (TEOM). Chang *et al.* (2018) reported no PM10 relationship between the 8532 DRX and the TEOM.

Total vegetation cover

Vegetation cover is strongly related to soil erosion. Soil is protected from wind erosion when vegetation cover is above 50% (Leys 1999); dust emission increases as the area protected from erosion declines. We used satellite imagery to estimate the total vegetation cover (Guerschman and Hill 2018). Spectra from the moderate resolution imaging spectroradiometer (MODIS) sensor (MODAPS 2017) were unmixed to determine the fractions of green vegetation, non-green vegetation, and bare soil within each pixel. The resulting product, called 'fractional cover' (Guerschman and Hill 2018), has been available every 8 days, at a 500-m resolution, since 2000. Total vegetation cover is the sum of the green and non-green vegetation fractions and includes all vegetation – trees, shrubs, grass, and forbs that are photosynthetically and non-photosynthetically active. Fractional cover data maps and statics are freely available from the RaPP Map website.

Land management data

The land management data were sourced from a literature review of land management practices, policies, and attitudes. Much of the information was sourced from the supplementary information of the Australian State of the Environment 2011 report (McTainsh *et al.* 2011).

Results

Dust storm day frequency

The count of the average DSD for each DSY is provided in Table 1. For the BoM weather code data, 1944/45 DSD frequency was nearly 10 times higher than that in 2009/10. For the DW data, 2019/20 was about twice that of 2009/10. These data suggest that 1944/45 had 4.4 times more DSD than did 2019/20, thus making 1944/45 much dustier than 2019/20.

For stations in NSW, the peak DSD count was 66 for Williamtown Royal Australian Air Force base in 1944/45. Using meteorological observations, the peak DSD count for Broken Hill was 10 in 2009/10. The peak DSD count for Pooncarie was 17 by using DW data in 2009/10 and for Coombah, south of Broken Hill, it was 31, by using DW data in 2019/20 (see Fig. 1).

Total vegetation cover in 2009 and 2019

The total vegetation cover levels for NSW, calculated from the Guerschman and Hill (2018) method, are shown in Fig. 2*a* for 2009/10 and Fig. 2*b* for 2019/20. NSW had 10% less area protected from wind erosion in 2019/20 (69% of the state) compared with 2009/10 (79%).

A historical account of land management changes in the 1940s and 2000s

A technical report (McTainsh *et al.* 2011) was commissioned by the Commonwealth Government Department of Sustainability, Environment, Water and Population and Communities to help inform the Australian State of the Environment 2011 report. The technical report reviewed three social factors: (1) community attitudes towards the environment, (2) government policy, and (3) the land management practices of the two periods – 1940/49 and 2000/09. A review of the same social factors is described below, and further examples are provided in Table 2.

Community attitudes in the 1940s emphasised expanding the agricultural industry to increase food and fibre production (McCormick 2011). There was a philosophy that the land needed to be 'tamed' to enable this development (Lines 1991). However, the dust storms of the 1940s also raised community and political awareness of land degradation (Lowe 1943; Reeve 1988; Cattle 2016).

Community attitudes post-1940s changed over the decades (Table 2), partly driven by a change in the ratio of rural to urban as people drifted to the city (N. Able and A. Langston, unpubl. data). As dust storms affected urban areas during the 1960s, 1980s, 1990 and 2000s (Leys *et al.* 2011), environmental awareness further developed. By the 1980s, the community focused more on sustainable development (Brundtland and Khalid 1987) than solely production-based development. These changes in community attitudes ultimately led to changes in policy.

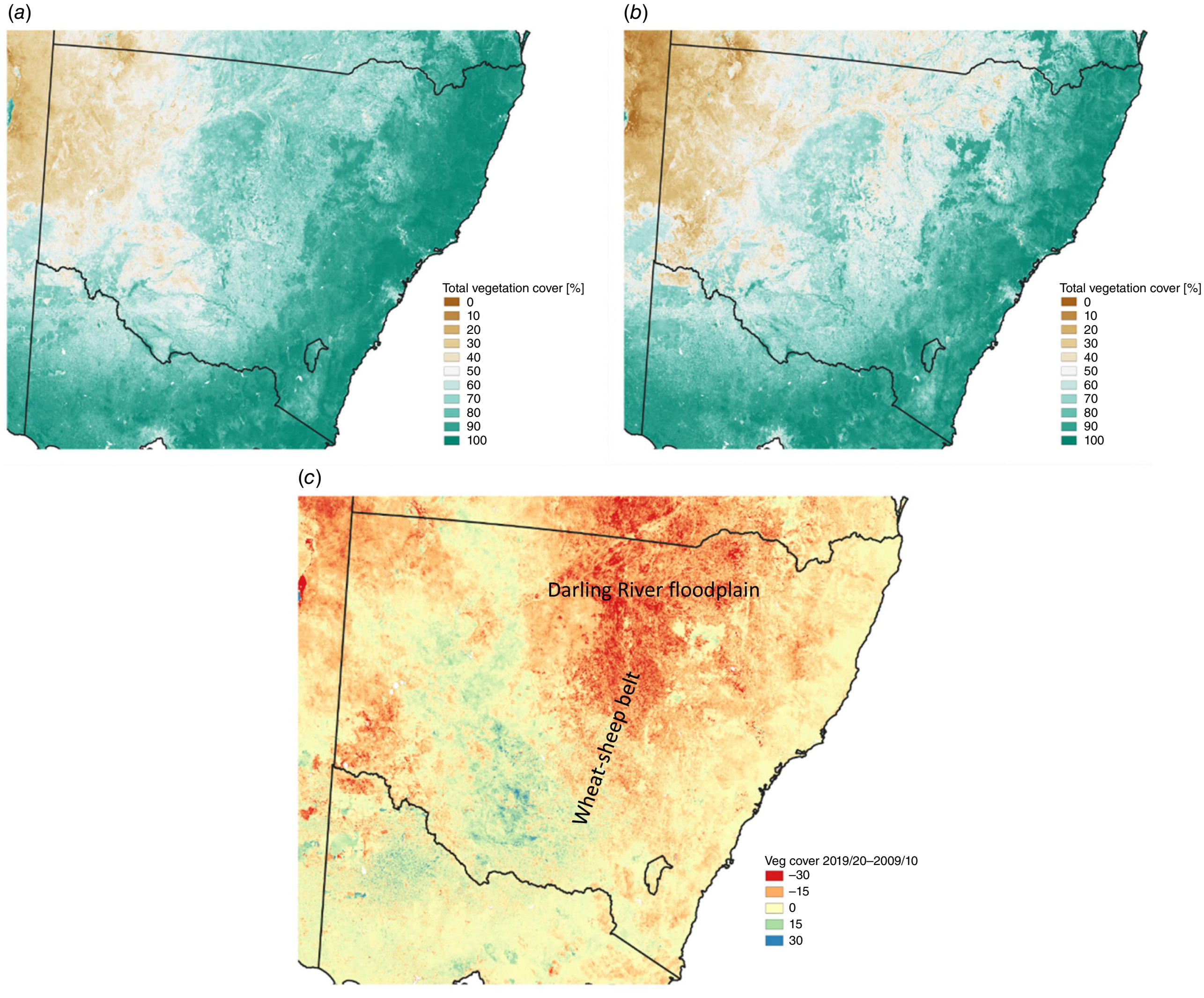

Fig. 2. Map of total vegetation cover in New South Wales derived from factional cover data for (*a*) 2009/10, (*b*) 2019/20 and (*c*) difference in vegetation cover data between 2009/10 and 2019/20.

In the 1940s, agricultural development was supported by government policies that encouraged land clearing (Harris 1990), increased rural population with solider settlements (State Library NSW 2021), and drought assistance in the form of financial credit (Downing *et al.* 2016). Although the support was described as 'relief' in the *Unemployed Occupiers and Farmers Relief Act* of 1931 and the *Drought Relief Acts* of 1940, 1944 and 1947, financial assistance was mainly in the form of loans (Downing *et al.* 2016). The Second World War resulted in over a million Australians joining the armed services (Frost *et al.* 2014), about 15% of the total population, reducing the agricultural workforce and resulting in fewer workers for land management activities. State governments organised efforts to meet the shortfall in labour under the Australian Women's Land Army (Australian War Memorial 2020). Soil conservation policy was developed and implemented (Table 2).

Government policy post-1940s was multifaceted (Table 2). Property amalgamation was encouraged to help improve the financial viability of rural holdings (Khairo *et al.* 2008), and drought policy was reviewed several times (Botterill 2003), with a focus on sustainable management of the resource base and agricultural production. These policies encouraged self-reliant approaches to prepare and manage extreme climatic stress periods (Drought Policy Review Expert Social Panel 2008). Drought relief aimed to ensure that farm families were provided with adequate welfare support commensurate with that available to other Australians (Department of Agriculture Water and the Environment 2018).

Federal and State governments invested in numerous natural resource management programs (Table 2) to improve land managers' capacity to use those land management practices that would better protect the environment and the community, e.g. Australian Government (2008).

Table 2. Further examples of community attitudes, government policy and land management practices and management.

Community attitudes in the 1940s
Promotion of widespread land settlement on small blocks under the Soldier Settlement schemes (State Library NSW 2021).
Wind erosion on cropping lands was severe, and the 'Dust Bowl' implications began to be understood (Lowe 1943).
Community attitudes post-1940s
Optimism toward sustainable agricultural systems that deliver profitability and maintain resource condition (McTainsh *et al.* 2011).
Awareness that natural resources are finite and their degradation results in a loss of environmental services such as clean air and water (Leys *et al.* 1994).
Concern for the environment is evidenced by the Landcare movement (Polkinghorne 1999).
Increased community environmental awareness and urban communities began to have an increasingly influential voice on issues affecting rural communities (McTainsh *et al.* 2011).
Use of pastoral lands that accommodates societal preferences, e.g. biodiversity and landscape function (Hacker and McDonald 2021).
The desire for sustainable agriculture to deliver the growing need for food and fibre (Clune 2021).
Government policy in the 1940s
Multiple committees were formed, and government reviews were undertaken into the cause of dust storms. This led to the formation of the NSW Soil Conservation Service (Breckwoldt and New South Wales Soil Conservation Service 1988).
National Standing Committee on Soil Conservation was formed to coordinate programs, train staff and facilitate information exchange (McTainsh *et al.* 2011).
Government policy post-1940s
Between 1975 and 1986, there was a 20% decrease in property numbers in the Western Division of NSW (Macleod 1990).
The Federal and State Government investment in sustainable development policies via programs such as The National Soil Conservation Programme (NSCP) (1983–1992), Natural Heritage Trust (1997–2008), the *NSW Native Vegetation Act* 2003, the *Local Land Services Act* 2013, *Biodiversity Conservation Act* 2016, and the National Landcare Program (1992–2022).
In 2018, the Council of Australian Governments agreed and signed a new National Drought Agreement (NDA) (Department of Agriculture Water and the Environment 2018). It recognises the need to support farming businesses and farming communities to manage and prepare for climate change and variability.
Joint industry/government programs were implemented (Australian Beef Sustainability Framework 2022).
Land management practices on cropping land in the 1940s
Successive cropping and burning eventually killed the vegetation and left the soil clean (Lines 1991).
Deep ploughing and cultivation up to 12 times a year destroyed soil structure (Lines 1991).
Bulldozers were used for clearing (Lines 1991).
Land management practices on cropping land post-1940s
Cropping systems had dual objectives of profitability of agricultural production and sustainability of the land resource (National Land & Water Resources Audit 2001).
Maintenance of adequate plant residue cover for soil erosion protection through adopting stubble retention systems (Scott *et al.* 2010).
Farm planning with retention and/or establishment of perennial vegetation (Woodman 2012).
Land reclamation of degraded areas for production and conservation (Dobes *et al.* 2013).
Land management practices on pastoral land in the 1940s
Subdivision of large pastoral properties often resulted in small, financially unsustainable family-owned properties where overgrazing was common (McTainsh *et al.* 2011).
In the Western Division of NSW, 50% stock losses were expected, and by 1944 up to 70% of stock had perished (i.e. over 1 million sheep) in the western Riverina (McKeon *et al.* 2004).
While fencing and windmills were considered property improvements (Ratcliffe 1938), they allowed the stock to remain on the country when feed had run out (Russell and Isbell 1986).
Stock numbers were the highest on record before the 1940s drought (approx. 120 million sheep and 14 million cattle), resulting in overstocking as the drought developed (McKeon *et al.* 2004).
Woody weeds or invasive native scrub increased in density and reduced grazing capacity (McKeon *et al.* 2004).
Overgrazing and soil compaction from stock (Beadle 1948).

(*Continued on next page*)

Table 2. (*Continued*)

Land management practices on pastoral land post-1940s
Road infrastructure and stock transport have improved, enabling agistment, better market access, and the ability to move stock more easily (Lennon and Pearson 2010).
Government drought-relief programs exist to encourage early destocking and 'drought-proofing' (Bell 2006).
Improvement in animal characteristics, animal husbandry, grazing system knowledge and landholder education levels (McKeon *et al.* 2004).
Better control of total grazing pressure (native, feral and domestic stock, e.g. kangaroo culling, goat trapping and camel shooting) (Hacker *et al.* 2019).
Town commons and railheads were now revegetated (Cunningham *et al.* 1978).

Land management practices on cropping land in the 1940s were based on European mixed-farming methods, which left the soil bare because of a high frequency of tillage and burning for weed control (Sauter 2017) (Table 2). There was also strong demand for food, so continuous cropping was used, resulting in soil fertility decline and poor crops (McTainsh *et al.* 2011). With low numbers of rural workers, feral plant, and animal control, especially rabbit control, was not undertaken, leading to reduced vegetation cover.

Land management practices on cropping land post-1940s were based on multiple objectives (Table 2) and utilised mechanisation and fertilisers, introduced legumes and improved cereal varieties in a rotational cropping and conservation farming system that improved yield and soil health (Young 1996; Scott *et al.* 2010; Norton 2016). The move to more sustainable farming began in the 1990s, with various natural resource management programs. Landcare was one major initiative aimed at delivering production and environmental outcomes (Polkinghorne 1999). In the 2000s, other programs such as Caring for Our Country (Australian Government 2008) were implemented with the additional focus of delivering ecosystem services, such as clean air and water. Many agricultural industry organisations also began promoting sustainability programs, such as, for example, Mallee Sustainable Farming Inc (2022).

Small holdings characterised the pastoral industry in the 1940s, with high rabbit numbers and high stocking rates resulting in overgrazing (McKeon *et al.* 2004; McTainsh *et al.* 2011). Stock were moved on foot; so, if forage or water availability declined, stock could not be moved elsewhere, and overgrazing resulted. Railheads for stock transport and commons around rural towns were also overgrazed (Walker 1976; Lennon and Pearson 2010). Overgrazing was attributed to multiple practices (Table 2).

Pastoral management practices post-1940s improved incrementally and in several ways (Table 2). Pastoral holdings became larger, and road transport meant stock could be moved to available forage. Improved rabbit control as a consequence of the introduction of myxomatosis and rabbit calicivirus diseases (Cooke *et al.* 2013), animal characteristics (McKeon *et al.* 2004), more defined grazing systems and the understanding of the management of total grazing pressure (Hacker *et al.* 2019) all reduced overgrazing. As for the cropping country, the government and industry practitioners, such as beef, grains and dairy, also implemented natural resource management and sustainable agriculture programs (Australian Government 2018). For example, the Beef Sustainability Framework aims to have 'the production of beef in a manner that is socially, environmentally, and economically responsible' (Australian Beef Sustainability Framework 2022).

Discussion

The premise of this study was to answer the frequently asked question of 'Are the number of dust storms per year changing, and if so, what is causing the change?' To answer this required two lines of investigation, namely, (1) one concerning the dust storm frequency for three major droughts between 1940 and 2020, and (2) the other concerning how changes in community attitudes, policy, land use and land management practices could potentially explain any differences in dust-storm frequencies of the three droughts. These are discussed below.

Dust storm-day frequency

Discussing the two methodologies used to measure dust storms in this study is important because it helps explain the uncertainty in the measurements and the results. The largest uncertainty comes from the change in method from meteorological weather code data to DW PM10 data; however, other uncertainties are also noted below.

Meteorological weather code observations rely on meteorological observers recording the reduced visibility caused by dust. This is simple, especially for dust storms that have low visibility. In contrast, DW uses instruments that measure all aerosol types, e.g. fog (only the 8520 model), smoke, and dust. The eastern Australia Black Summer mega-fires caused a considerable amount of smoke in 2019/20 (Rodney *et al.* 2021; Ryan *et al.* 2021). The quality assurance methods used by DW, as outlined in Leys *et al.* (2018), plus our experience with discriminating dust from other aerosols using DustTraks, as outlined in Chang *et al.* (2018), provide confidence that the aerosol data used in this study were dust.

Additionally, the 8533 DRX models deployed at many stations in 2019/20 allowed discrimination of sources based on particle size response, with a predominance of smaller particles of smoke ($\leq$PM2.5) contrasted against larger particles of dust ($\geq$PM10). This significantly aided classification. This situation was less of an issue in 2009/10 with the 8520 model, where bushfire smoke was not encountered.

The first difference between the methods is the frequency of observation, which affects the count of dust storms. A complete analysis of the issues of using weather codes for counting dust storms is detailed in O'Loingsigh *et al.* (2010). The meteorological weather code data rely on human observations, and the number of observations varies depending on the site. Some sites, such as airports, take three hourly readings, others taking only two readings daily at 09:00 hours and 15:00 hours. In contrast, DW data are taken every minute during dust events, i.e. when the dust concentration is $>25\ \mu g/m^3$ and summarised to hourly PM10 concentrations. Therefore, the DW data have a higher chance of observing dust storms, particularly those that occur during night-time hours.

The second difference is spatial sampling distribution, with 12 sites for the BoM data and 20 sites for the DW data; so, DW data have a higher chance of observing dust storms. These two differences explain why, in 2009/10, DW counted an average of five DSD, whereas the BoM data counted an average of 0.6 (Table 1).

The third difference is observation-site distribution. Of the 12 BoM sites, five are on the NSW coast, plus one in Canberra, being distant from the well documented western NSW dust sources (Leys *et al.* 2018). In contrast, DW sites are in the western three-quarters of NSW. This increases the likelihood of measuring a dust storm because the DW sites are closer to dust source areas, and there are more DW sites than BoM sites.

The fourth difference relates to the way dust events are measured in Australia. O'Loingsigh *et al.* (2015) used dust-event days (DED), which differ from DSD in that DED include localised dust events and dust storms. The DED count will therefore be higher than DSD count because DSD is a subset of DED. Also, the O'Loingsigh *et al.* (2015) study reported total DED, whereas this study used average DSD, due to changing site numbers over time. Therefore, care is required when comparing dust observation data. We used DSD because, internationally and historically, dust storms have been the unit of measure (Goudie 1983; Middleton 1984*a*, 1984*b*, 2019; Goudie and Middleton 1992).

Acknowledging the above differences, the earlier Australian study (O'Loingsigh *et al.* 2015) compared eastern Australia for the entire WWII drought (1937/38–1944/45) with the Millennium drought (2001/20–2009/10). It showed the entire WWII drought had 4.6 times the DED of the Millennium drought, with a total of 730 DED for the 52 stations, compared with 275 DED for 2009/10 (O'Loingsigh *et al.* 2015, Fig. 1). Comparing the DED for the DSY with the highest frequency of dust storms, 1944/45 was 2.7 times higher than 2009/10. In comparison, using the DSD of this study, NSW had 9.9 times higher DSD count in 1944/45 than in 2009/10. These results highlight the spatial variability of dust events across Australia and support the contention that, in NSW, 1944/45 was dustier than 2009/10.

DustWatch was established because the BoM changed from manual observations to instrumented visibility meters that measure the effect of water, dust, sand or smoke on visibility at airports (Leys *et al.* 2008; Bureau of Meteorology 2012). There is no classification of the visibility data into fog, dust or smoke, as was previously done with manual BoM observations. For this reason, BoM weather observations of dust are now less widely available in Australia. However, it is fortunate that the BoM and DW data overlap in 2009/10. This enabled the combination of the two data sets and comparison of the three droughts, which showed that there had been a 22% decline in DSD since 1944/45 (Table 1).

Goudie and Middleton (1992) and Middleton (2019) have extensively described worldwide trends in dust storms by using meteorological data. On the basis of a literature review, only Bahrain and the USA have sufficiently long meteorological records to compare with this study. In the United States of America (USA), observations have been reported for Kansas and Texas from 1922 to 1961. They show that dust storm frequency peaked in 1935 (120 days with blowing dust) in Dodge City, Kansas. Many other sites peaked in the 'Dust Bowl' years of the 1930s on the Great Plains. The trend in the USA is the same as in this study; that is, earlier droughts had higher DSD. In the Middle East, Bahrain's record (1946–1983) peaked in 1948 with 17 DSD, then declined to about 6 DSD in the 1980s, again being similar to the counts in this study and the USA experience.

Total vegetation cover data from satellite measurements have been available for 40 years, with high-quality monthly data being available from the early 2000s. Conversely, there are no state-wide data for total vegetation cover levels in the 1940s, although comparisons of vegetation cover are possible for the 2009/10 and 2019/20 years. The 2017/20 drought was the hottest and driest on record (Bureau of Meteorology 2022*a*), and, unsurprisingly, 2019/20 had a 10% greater area susceptible to wind erosion than did 2009/10, with 79% of the state being protected. In 2019/20 (Fig. 2*b*), the areas susceptible to erosion were further east than in 2009/10, and had lower cover levels in the far west of the state. The larger the area with low cover, the higher the dust emission, which is one of the major reasons why 2019/20 was dustier than 2009/10. Fig. 2*c* shows the difference in cover between 2019/20 and 2009/10. Of note is the lower cover on the floodplain of the upper Darling River, the wheat–sheep belt, and the far south-west of the state. The severity of the 2017 to 20 drought in the eastern parts of NSW meant that regular drought management practices failed to sustain cover in that DSY. The drought frequency is of greater importance for the eastern areas with low cover. We hypothesise that land managers on the rangelands in western NSW (ABARES 2021) are more familiar with drought management strategies. In contrast, the landholders in the higher-rainfall sheep–wheat belt (ABARES 2021) experience drought less frequently, and are less familiar with drought management strategies and their implementation. Wilson *et al.* (2016) described the loss of social memory as a key constraint of land managers in effectively responding to local land-degradation issues. Austin *et al.* (2018) found that unexpected, protracted droughts had a more significant impact on rural mental wellbeing than did 'crisis' droughts because of the unfamiliarity and unpredictability of the circumstances people were experiencing. These social and mental health issues potentially impeded good cover management decisions.

Changes in land management between the 1940s and 2000s

Land management change is slow. As outlined below, it can take decades to move from awareness of an issue to on-ground change. Australia's agricultural history has been interspersed with phases of failure in landscape management, followed by the building of social awareness, and finally, political action.

In the 1940s, the primary driver for agriculture was food and fibre supply for an increasing Australian population (McCormick 2011). This led to a 'pioneer' attitude where 'perseverance was elevated to a primordial virtue of the settler' (Sauter 2017, p. 368). Failure to tame the land, i.e. clear it, was not socially acceptable, with settlers saying, 'If we did not destroy all the scrub we were called slackers' (Sunraysia Daily newspaper quoted in Sauter 2017, p. 368). The land management practices of the 1940s invariably resulted in low vegetation cover and a reduction in surface soil aggregation through high levels of stocking and cultivation. A lack of stock transport infrastructure also exacerbated low ground cover, with stock dying on-site due to a lack of forage and water (McKeon *et al.* 2004). The result was a very high number of dust storms in 1944/45 (Table 1).

The Government's agricultural policy in the 1940s was not wholly focused on production. The formation of the NSW Soil Conservation Service (SCS) in 1938 shows how changing community and government attitudes led to new policies to protect the environment. Breckwoldt and New South Wales Soil Conservation Service (1988, p. 21) stated the following: 'It [soil erosion] was, however, a problem that would not go away, indeed, it appeared to be getting worse. Townsfolk were reminded of it by the nuisance of dust storms carried in by the summer westerlies. Thoughtful members of the farming community were asking whether production could be increased if the basic resource on which they relied was being washed and blown away.'. It was community action via government reviews of the state of the soil that led to pressure being put on the government to form the SCS. Over the next 60 years, the SCS focused on conserving the soil, so it could sustain rather than just maximise production (Breckwoldt and New South Wales Soil Conservation Service 1988). Change was assisted by a mixture of on-ground works, demonstrations, research, farm and land use planning and, most importantly, advisory staff to support decision-makers in changing their land management practices.

By the 1990s, natural resources were recognised as finite and not resilient against all management practices (Leys *et al.* 1994). The community in the 2000s aspired to maintain and protect Australia's agricultural and environmental resource base, even during periods of extreme climatic stress such as drought (Table 2). This is demonstrated by the Landcare program (Australian Government 1995, 2018) and industry sustainability programs (Australian Beef Sustainability Framework 2022; Mallee Sustainable Farming Inc 2022) and regional natural resource management groups (Polkinghorne 1999). Markets, government policy and community attitudes all now play a significant role in the daily management of agricultural lands (Annett 2002). Land management practices now have a focus on maintaining ground cover as well as maximising production. This is one of the main reasons why there were 4.4. times fewer dust storms in the 2019/20 DSY than in the 1944/45 DSY.

One of the best examples of this policy change was in the 1980s and 1990s after a dust storm engulfed Melbourne in 1982. This iconic event reminded urban Australia of the fragility of the soil during droughts (Raupach *et al.* 1994). In 1989, Landcare was launched by the Federal government as a collaborative approach between land managers, agricultural industries and the government. The aim was to improve land management to achieve sustainable agriculture and natural resource management (Polkinghorne 1999). The challenge identified for the first stage of the Decade of Landcare was to increase land managers' adoption of sustainable land management practices (Australian Government 1995). Since then, successive rounds of Federal and State government funding have supported Landcare and other programs, such as, for example, Natural Heritage Trust (1997–2008), Caring for Our Country 2008–2013, and National Landcare Program (2015–2023).

Land management has changed in Australia. A companion paper (Leys *et al.* 2023) outlines several examples of practice change and the consequential impact on wind erosion.

Conclusions

This study answers the following question: 'Are the number of dust storms per year changing and if so, what is causing the change?'. The DSD record illustrates that dust storm frequency in any one DSY was less in the Millennial and 2017/20 droughts than the 1944/45 DSY, although using different measurement methods raises some uncertainty in this finding. The result is supported by the O'Loingsigh *et al.* (2015) eastern Australia study, which reported a 4.6 times difference between the WWII and Millennium droughts using a similar dust index, i.e. dustevent days. Similarly, international results spanning the 1940s to the 1960s and 1980s show DSD reductions over time (Goudie and Middleton 1992; Middleton 2019).

A review of community attitudes, government policy and land management practices in the 1940s and post-1940s suggests that changed land management practices led to higher vegetation cover levels in the 2000s than in 1940s. Stubble retention, total grazing pressure management and rabbit control, among other practices, supported by the community, government and industry programs and services, improved vegetation cover during droughts. These programs focused on sustainable natural resource use and the negative soil erosion impacts on agricultural production and the community. Government policy now focuses on drought preparedness, sustainable development and maintaining and protecting Australia's agricultural and environmental resource base during extreme climatic stress. For example, drought policy now focuses on ensuring that farm families receive adequate welfare support to alleviate family stress and the need to over-utilise the land.

Although dust storms still occur, their frequency is lower than in the 1940s, because land management practices that maintain ground cover have improved.

References

ABARES (2021) 'Catchment scale land use of Australia – Update December 2020.' CC BY 4.0. (Australian Bureau of Agricultural and Resource Economics and Sciences: Canberra, ACT, Australia) doi:10.25814/aqjw-rq15

Annett S (2002) Victorian agriculture 1904-2000: land use change or transition? In Proceedings of the conference on rural land use change. August 2002. (Department of Sustainability and Environment: Victoria, Australia).

APDIM (2021) Sand and dust storms risk assessment in Asia and the Pacific. (Asian and Pacific Centre for Development of Disaster Information Management (APDIM) and Economic and Social Commission for Asia and the Pacific (ESCAP): Tehran, Iran) Available at https://apdim.unescap.org/knowledge-hub/sand-and-dust-storms-risk-assessment-asia-and-pacific [accessed 10 February 22]

Austin EK, Handley T, Kiem AS, Rich JL, Lewin TJ, Askland HH, Askarimarnani SS, Perkins DA, Kelly BJ (2018) Drought-related stress among farmers: findings from the Australian Rural Mental Health Study. *Medical Journal of Australia* **209**, 159–165. doi:10.5694/mja17.01200

Australian Beef Sustainability Framework (2022) 'The Australian Beef Sustainability Framework.' (The Australian Beef Sustainability Framework: Sydney, NSW, Australia) Available at https://www.sustainableaustralianbeef.com.au/

Australian Government (1995) 'Decade of landcare plan.' (Department of Agriculture Fisheries and Forestry: Canberra, ACT, Australia) Available at https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/natural-resources/landcare/communiques/decade_plan_overview.pdf [accessed 2 October 2022]

Australian Government (2008) 'Caring for our country: Business Plan, 2009-2010.' (Department of Sustainability, Environment, Water, Population and Communities, Canberra, ACT; Department of Agriculture, Fisheries and Forestry, Canberra, ACT, Australia) Available at https://webarchive.nla.gov.au/awa/20130409002039/http://nrmonline.nrm.gov.au/catalog/mql:2263 [accessed 2 October 2022]

Australian Government (2018) 'National Landcare Program Phase Two.' (Commonwealth of Australia: Canberra, ACT, Australia) Available at http://www.nrm.gov.au/national-landcare-program [accessed 22 September 2019]

Australian Government Bureau of Meteorology (2016) 'Aerodrome weather observer. METARAWS/SPECIALWS. Reporting and Recording.' (Bureau of Meteorology Training Centre: Melbourne, Vic., Australia)

Australian War Memorial (2020) 'Australian women's land army.' (Australian War Memorial: Canberra, ACT, Australia) Available at https://www.awm.gov.au/articles/encyclopedia/homefront/land_army [accessed 17 February 2022]

Baddock MC, Strong CL, Leys JF, Heidenreich SK, Tews EK, McTainsh GH (2014) A visibility and total suspended dust relationship. *Atmospheric Environment* **89**, 329–336. doi:10.1016/j.atmosenv.2014.02.038

Beadle NCW (1948). 'The vegetation and pastures of western New South Wales.' (Government Printer: Sydney, NSW, Australia)

Bell S (2006) Concerned scientists, pragmatic politics and Australia's green drought. *Science and Public Policy* **33**(8), 561–570. doi:10.3152/147154306781778687

Botterill LC (2003) Uncertain climate: the recent history of drought policy in Australia. *Australian Journal of Politics & History* **49**(1), 61–74. doi:10.1111/1467-8497.00281

Breckwoldt R, New South Wales Soil Conservation Service (1988) 'The dirt doctors: a jubilee history of the Soil Conservation Service of NSW.' (Soil Conservation Service of NSW: Sydney, NSW, Australia)

Brundtland GH, Khalid M (1987) 'Our common future: Brundtland Commission (WCED) report to World Commission on Environment and Development.' (Oxford University Press: Oxford, UK) Available at https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf [accessed 1 October 2022]

Bureau of Meteorology (2012) 'Ceilometers and visibility meters.' (Bureau of Meteorology: Melbourne, Vic., Australia) Available at http://www.bom.gov.au/aviation/data/education/ceilometer-visibility.pdf [accessed 5 January 2023]

Bureau of Meteorology (2022a) 'Annual climate statement 2021.' (Bureau of Meteorology: Melbourne, Vic., Australia) Available at http://www.bom.gov.au/climate/current/annual/aus/ [accessed 10 February 2022]

Cattle SR (2016) The case for a southeastern Australian dust bowl, 1895–1945. *Aeolian Research* **21**, 1–20. doi:10.1016/j.aeolia.2016.02.001

Chang LT-C, Leys J, Heidenreich S, Koen T (2018) Determining aerosol type using a multichannel DustTrak DRX. *Journal of Aerosol Science* **126**, 68–84. doi:10.1016/j.jaerosci.2018.08.009

Clune T (2021) Conceptualising policy for sustainable agriculture development. *Australian Journal of Public Administration* **80**(3), 493–509. doi:10.1111/1467-8500.12436

Cooke B, Chudleigh P, Simpson S, Saunders G (2013) The economic benefits of the biological control of rabbits in Australia, 1950–2011. *Australian Economic History Review* **53**(1), 91–107. doi:10.1111/aehr.12000

Cunningham GM, Walker PJ, Green DR (1978) Revegetating the Cobar country: a ten-year study. *Journal of the Soil Conservation Service of New South Wales* **34**(3), 139–144.

Department of Agriculture Water and the Environment (2018) 'National drought agreement.' (Department of Agriculture, Water and the Environment: Canberra, ACT, Australia) Available at https://www.awe.gov.au/agriculture-land/farm-food-drought/drought/drought-policy/national-drought-agreement [accessed 23 March 2022]

Dobes L, Weber N, Bennett J, Ogilvy S (2013) Stream-bed and flood-plain rehabilitation at Mulloon Creek, Australia: a financial and economic perspective. *The Rangeland Journal* **35**(3), 339–348. doi:10.1071/RJ12098

Downing K, Jones R, Singley B (2016) Handout or hand-up: ongoing tensions in the long history of government response to drought in Australia. *Australian Journal of Politics & History* **62**(2), 186–202. doi:10.1111/ajph.12244

Drought Policy Review Expert Social Panel (2008) It's about people: changing perspective. A Report to Government by an Expert Social Panel on Dryness. Report to the Minister for Agriculture Fisheries and Forestry, Canberra, ACT, Australia. Available at https://www.awe.gov.au/sites/default/files/sitecollectiondocuments/ag-food/drought/publications/dryness_report.pdf

Engelstaedter S, Kohfeld KE, Tegen I, Harrison SP (2003) Controls of dust emissions by vegetation and topographic depressions: an evaluation using dust storm frequency data. *Geophysical Research Letters* **30**(6), 1294. doi:10.1029/2002GL016471

Frost G, Malam K, Williams L (2014) 'The evolution of Australian towns.' (Department of Infrastructure and Regional Development, Bureau of Infrastructure, Transport and Regional Economics: Canberra, ACT, Australia)

Goudie AS (1983) Dust storms in space and time. *Progress in Physical Geography: Earth and Environment* **7**(4), 502–530. doi:10.1177/030913338300700402

Goudie AS, Middleton NJ (1992) The changing frequency of dust storms through time. *Climatic Change* **20**(3), 197–225. doi:10.1007/bf00139839

Guerschman JP, Hill MJ (2018) Calibration and validation of the Australian fractional cover product for MODIS collection 6. *Remote Sensing Letters* **9**(7), 696–705. doi:10.1080/2150704X.2018.1465611

Hacker RB, McDonald SE (2021) Prospects for sustainable use of the pastoral areas of Australia's southern rangelands: a synthesis. *The Rangeland Journal* **43**(4), 185–209. doi:10.1071/RJ21036

Hacker RB, Sinclair K, Waters CM (2019) Total grazing pressure: a defining concept for extensive pastoral systems in the southern rangelands of Australia. *The Rangeland Journal* **41**(6), 457–460. doi:10.1071/RJ19026

Harris CR (1990) The history of mallee land use: Aboriginal and European. In 'The Mallee Lands, A conservation perspective', 1989, Adelaide, SA, Australia. (Eds JC Noble, PJ Joss, GK Jones) pp. 147–151. (CSIRO: Melbourne, Vic., Australia)

Khairo S, Mullen J, Hacker R, Patton D (2008) 'Farming systems in the pastoral zone of NSW: an economic analysis.' (NSW DPI: Trangie, NSW, Australia) Available at https://ageconsearch.umn.edu/record/42655/ [accessed 29 September 2022]

Lei H, Wang JXL, Tong DQ, Lee P (2016) Merged dust climatology in Phoenix, Arizona based on satellite and station data. *Climate Dynamics* **47**(9–10), 2785–2799. doi:10.1007/s00382-016-2997-7

Lennon J Pearson M, (2010) 'Pastoral Australia: fortunes, failures & hard yakka: a historical overview 1788–1967.' (CSIRO Publishing: Melbourne, Vic., Australia)

Leys JF (1990) Blow or grow? A soil conservationist's view to cropping Mallee soils. In 'The Mallee Lands, A conservation perspective', 1989, Adelaide, SA, Australia. (Eds JC Noble, PJ Joss, GK Jones) pp. 280–286. (CSIRO: Melbourne, Vic., Australia)

Leys JF (1999) Wind erosion on agricultural land. In 'Aeolian environments, sediments and landforms'. (Eds AS Goudie, I Livingston, S Stokes) pp. 143–166. (John Wiley and Sons: UK)

Leys J, Craven P, Murphy S, Clark P, Anderson R (1994) Integrated resource management of the Mallee in South-Western New South Wales. *Australian Journal of Soil and Water Conservation* **7**(3), 10–19.

Leys J, McTainsh G, Strong C, Heidenreich S, Biesaga K (2008) DustWatch: using community networks to improve wind erosion monitoring in Australia. *Earth Surface Processes and Landforms* **33**, 1912–1926. doi:10.1002/esp.1733

Leys JF, Heidenreich SK, Strong CL, McTainsh GH, Quigley S (2011) PM_{10} concentrations and mass transport during 'Red Dawn' – Sydney 23 September 2009. *Aeolian Research* **3**, 327–342. doi:10.1016/j.aeolia.2011.06.003

Leys J, Strong C, Heidenreich S, Koen T (2018) Where She Blows! A Ten Year Dust Climatology of Western New South Wales Australia. *Geosciences* **8**, 232. doi:10.3390/geosciences8070232

Leys J, Shields T, Murphy S, Koen T (2023) Changes in land management practices have reduced wind erosion in the cropping areas of far south-west NSW, Australia. *Rangeland Journal,* in press. doi:10.1071/RJ22028

Lines WJ (1991) 'Taming the great south land.' (Allen and Unwin: Sydney, NSW, Australia)

Love BM, Leys JF, Strong CL, McTainsh GH (2019) Dust climatology of Mildura, Victoria, Australia: transport direction. *Earth Surface Processes and Landforms* **44**, 1449–1459. doi:10.1002/esp.4587

Lowe A (1943) 'Duststorms in Australia. Vol. 28.' (Bulletin of Commonwealth Meteorological Bureau)

Mallee Sustainable Farming Inc (2022) Home page of Mallee Sustainable Farming. Mallee Sustainable Farming: Mildura, Vic., Australia. Available at https://msfp.org.au/ [accessed 2 October 2022]

Macleod N (1990) Issues of size and viability of pastoral holdings in the Western Division of New South Wales. *The Rangeland Journal* **12**(2), 67–78. doi:10.1071/RJ9900067

McCormick A (2011) Drought, dust and despair. *Historian* **111**, 14–18.

McKeon GM, Hall WB, Henry BK, Stone CS, Watson IW (2004) 'Pasture degradation and recovery in Australia's rangelands: learning from history.' (Queensland Department of Natural Resources, Mines and Energy: Indooroopilly, Qld, Australia) Available at https://data.longpaddock.qld.gov.au/static/publications/learning_from_history.pdf

McTainsh GH, Leys JF (1993) Soil erosion by wind. In 'Land degradation processes in Australia'. (Eds GH McTainsh, WC Broughton) pp. 188–233. (Longman Cheshire: Melbourne, Vic., Australia)

McTainsh GH, Leys J, O'Loingsigh T, Strong C (2011) 'Wind erosion and land management in Australia during 1940-1949 and 2000-2009.' (Australian Government Department of Sustainability, Environment, Water, Population and Communities: Canberra, ACT, Australia) Available at http://www.environment.gov.au/soe/2011/report/land/index.html

McTainsh G. H., Lynch A. W., Tews E. K. (1998) Climatic controls upon dust storm occurrence in eastern Australia *Journal of Arid Environments* **39**(3), 457–466. doi:10.1006/jare.1997.0373

Middleton NJ (1984*a*) Dust storms in Australia: frequency, distribution and seasonality. *Search* **15**, 46–47.

Middleton NJ (1984*b*) Dust storms in the Middle East. *Journal of Arid Environments* **10**, 83–96. doi:10.1016/S0140-1963(18)31249-7

Middleton N (2018) Rangeland management and climate hazards in drylands: dust storms, desertification and the overgrazing debate. *Natural Hazards* **92**(1), 57–70. doi:10.1007/s11069-016-2592-6

Middleton N (2019) Variability and trends in dust storm frequency on decadal timescales: climatic drivers and human impacts. *Geosciences* **9**(6), 261. doi:10.3390/geosciences9060261

Middleton NJ, Goudie AS (2001) Saharan dust: sources and trajectories. *Transactions of the Institute of British Geographers* **26**(2), 165–181. doi:10.1111/1475-5661.00013

MODAPS (2017) Level-1B (L1B) Calibration Collection 6.1 Update. Terra and Aqua MODIS. C061_L1B_Combined_v9.pdf. Available at https://modis-atmos.gsfc.nasa.gov/documentation/collection-61

National Land & Water Resources Audit (2001) 'Australian agriculture assessment 2001. Vol. 1.' (National Land and Water Resources Audit: Canberra, ACT, Australia) Available at http://lwa.gov.au/files/products/national-land-and-water-resources-audit/pr010237/pr010237.pdf

Nguyen HD, Riley M, Leys J, Salter D (2019) Dust storm event of February 2019 in Central and East Coast of Australia and evidence of long-range transport to New Zealand and Antarctica. *Atmosphere* **10**(11), 653. doi:10.3390/atmos10110653

Norton R (2016) Australia and New Zealand fertilizer market and fertilizer usage status. In '7th China international fertilizer show', 2016, Shanghai, China. (China International Agrochemical and Crop Protection Exhibition) Available at http://anz.ipni.net/beagle/ANZ-3264&f=Norton% 20CCPIT% 20R% 20.pdf

Novlan DJ, Hardiman M, Gill TE (2007) A synoptic climatology of blowing dust events in El Paso, Texas from 1932-2005. In '16th conference on applied climatology'. No. J3.12. (American Meteorological Society)

O'Loingsigh T, McTainsh GH, Tapper NJ, Shinkfield P (2010) Lost in code: a critical analysis of using meteorological data for wind erosion monitoring. *Aeolian Research* **2**(1), 49–57. doi:10.1016/j.aeolia.2010.03.002

O'Loingsigh T, McTainsh GH, Tews EK, Strong CL, Leys JF, Shinkfield P, Tapper NJ (2014) The Dust Storm Index (DSI): a method for monitoring broadscale wind erosion using meteorological records. *Aeolian Research* **12**, 29–40. doi:10.1016/j.aeolia.2013.10.004

O'Loingsigh T, McTainsh GH, Parsons K, Strong CL, Shinkfield P, Tapper NJ (2015) Using meteorological observer data to compare wind erosion during two great droughts in eastern Australia; the World War II Drought (1937–1946) and the Millennium Drought (2001–2010). *Earth Surface Processes and Landforms* **40**(1), 123–130. doi:10.1002/esp.3668

Polkinghorne L (1999) 'Decade of landcare success.' (Australian Landcare)
Prospero JM, Ginoux P, Torres O, Nicholson SE, Gill TE (2002) Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 total ozone mapping spectrometer (TOMS) absorbing aerosol product. *Reviews of Geophysics* **40**(1), 2-1–2-31. doi:10.1029/2000RG000095
Querol X, Tobías A, Pérez N, Karanasiou A, Amato F, Stafoggia M, Pérez García-Pando C, Ginoux P, Forastiere F, Gumy S, Mudu P, Alastuey A (2019) Monitoring the impact of desert dust outbreaks for air quality for health studies. *Environment International* **130**, 104867. doi:10.1016/j.envint.2019.05.061
Ratcliffe F (1938) 'Flying fox and drifting sand.' (Chatto and Windus: London, UK)
Raupach M, McTainsh G, Leys J (1994) Estimates of dust mass in recent major Australian dust storms. *Australian Journal of Soil and Water Conservation* **7**(3), 20–24.
Reeve IJ (1988) 'A squandered land: 200 years of land degradation.' REDC publication No. 159. (Rural Development Centre, University of New England: Armidale, NSW, Australia)
Riley M, Kirkwood J, Jiang N, Ross G, Scorgie Y (2019) Air quality monitoring in NSW: from long term trend monitoring to integrated urban services. In 'CASANZ19', 16–18 September 2019, Queenstown, New Zealand. (Clean Air Society of Australia and New Zealand, Mooroolbark, Victoria, Australia) Available at https://www.researchgate.net/publication/336083437_Air_Quality_Monitoring_in_NSW_From_long-term_trend_monitoring_to_integrated_urban_services
RM Consulting Group (2018) Regional Land Partnerships Evaluation Plan. Final report. Department of Environment and Energy, Melbourne, Vic., Australia. Available at https://narvis.com.au/wp-content/uploads/RegionalLandPartnerships.Priorities-2018.pdf [accessed 30 September 2022]
Rodney RM, Swaminathan A, Calear AL, Christensen BK, Lal A, Lane J, Leviston Z, Reynolds J, Trevenar S, Vardoulakis S, Walker I (2021) Physical and Mental Health Effects of Bushfire and Smoke in the Australian Capital Territory 2019–20. *Frontiers in Public Health* **9**, 682402. doi:10.3389/fpubh.2021.682402
Russell JS, Isbell RF (1986) 'Australian soils: the human impact.' (University of Queensland Press in association with the Australian Society of Soil Science: St Lucia, Qld, Australia)
Ryan RG, Silver JD, Schofield R (2021) Air quality and health impact of 2019–20 Black Summer megafires and COVID-19 lockdown in Melbourne and Sydney, Australia. *Environmental Pollution* **274**, 116498. doi:10.1016/j.envpol.2021.116498
Sauter SCA (2017) Dust Bowls Down Under: an Environmental History of Wind Erosion in the South-East of Australia, 1929–1945/46. PhD Thesis, der Eberhard Karls Universität Tübingen, Germany.
Scott BJ, Eberbach PL, Evans J, Wade LJ (2010) 'Stubble retention in cropping systems in Southern Australia: benefits and challenges.' (NSW Government Department of Industry and Investment)
State Library NSW (2021) 'Soldier settlement schemes.' (State Library NSW: Sydney, NSW, Australia) Available at https://guides.sl.nsw.gov.au/wwi-and-australia/soldier_settlement_schemes [accessed 13 February 2022]
Tong DQ, Dan M, Wang T, Lee P (2012) Long-term dust climatology in the western united states reconstructed from routine aerosol ground monitoring. *Atmospheric Chemistry and Physics* **12**(11), 5189–5205. doi:10.5194/acp-12-5189-2012
Tozer P, Leys J (2013) Dust storms: what do they really cost? *The Rangeland Journal* **35**, 131–142. doi:10.1071/RJ12085
TSI Incorporated (2002) 'DustTrak Aerosol Monitor Model 8520 Spec Sheet.' (TSI United States of America: Shoreview, MN, USA) Available at https://tsi.com/getmedia/923007ed-183a-4ce9-8e5b-3b5055b4c711/2980077_DustTrak_8520?ext=.pdf [accessed 28 September 2022]
TSI incorporated (2022) 'DustTrak DRX Aerosol Monitors Models 8533,8533EP and 8534 Specification Sheet.' (TSI, United States of America: Shoreview, MN, USA) Available at https://www.kenelec.com.au/wp-content/uploads/2022/08/TSI-8533-8533EP-8534-DustTrak-DRX-Aerosol-Monitors-SpecSheet-revH-2022.pdf [accessed 28 September 2022]
Walker PJ (1976) Cobar regeneration area: the first sixteen years. *Journal of the Soil Conservation Service of New South Wales* **32**(3), 119–133.
Wang X, Chancellor G, Evenstad J, Farnsworth JE, Hase A, Olson GM, Sreenath A, Agarwal JK (2009) A novel optical instrument for estimating size segregated aerosol mass concentration in real time. *Aerosol Science and Technology* **43**(9), 939–950. doi:10.1080/02786820903045141
WHO (2019) 'Manual on Codes. International Codes. Vol. 1.1. Annex II to the WMO Technical Regulations, Part A – Alphanumeric Codes.' (World Meteorological Organization) Available at https://library.wmo.int/doc_num.php?explnum_id=10235 [accessed 29 September 2022]
Wilson GA, Kelly CL, Briassoulis H, Ferrara A, Quaranta G, Salvia R, Detsis V, Curfs M, Cerda A, El-Aich A, Liu H, Kosmas C, Alados CL, Imeson A, Landgrebe-Trinkunaite R, Salvati L, Naumann S, Danwen H, Iosifides T, Kizos T, Mancino G, Nolè A, Jiang M, Zhang P (2016) Social memory and the resilience of communities affected by land degradation. *Land Degradation & Development* **28**(2), 383–400. doi:10.1002/ldr.2669
Woodman AP (2012) 'What is the effectiveness of farm planning to increase the adoption of sustainable farming practices? A review of the best-available evidence.' (Environmental Evidence Australia, Pty Ltd: Green Hills, NSW, Australia) Available at http://www.environmentalevidence.com.au/collaboration/review/what-effectiveness-farm-planning-increase-adoption-sustainable-farming [accessed 29 September 2022]
Young ARM (1996) 'Environmental change in Australia since 1788.' 2nd edn. (Oxford University Press: Melbourne, Vic., Australia)

Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. The authors declare no conflicts of interest.

Declaration of funding. DustWatch and the Rural Air Quality Monitoring Network have been partially funded by the New South Wales Government since 2005. Other funding came from the National Landcare program and its predecessors, Western and Murray Local Land Services (LLS) in New South Wales; the New South Wales Environmental Protection Agency, the Mallee, and North Central CMAs in Victoria and Murray Darling Basin NRM in South Australian, CSIRO, and the Australian National University.

Acknowledgements. The authors acknowledge the contribution of the DustWatch volunteers, staff of the Climate and Atmospheric Science Branch of the Department of Planning and Environment, who maintain the dust monitoring network and provide valuable comments on the nature and causes of dust, and CSIRO, with funding from the National Landcare Program, for making the total vegetation cover freely available. We also thank the Rangeland Journal editors and two referees for their editorial assistance in vastly improving this paper.

Author affiliations

[A]Fenner School of Environment and Society, Australian National University, Canberra, ACT, Australia.

[B]Science, Economics and Insights Division, Department of Planning and Environment, Gunnedah, NSW, Australia.

[C]Land and Water – Black Mountain, CSIRO, Canberra, ACT, Australia.

[D]Science, Economics and Insights Division, Department of Planning and Environment, Lidcombe, NSW, Australia.