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# Dust storms – what do they really cost?

P. Tozer[A,B] and J. Leys[C,D,E]

[A]University of New England, Armidale, NSW 2350, Australia.
[B]School of Economic Sciences, Washington State University, Pullman, WA 99164-6210, USA.
[C]NSW Office of Environment and Heritage, Gunnedah, NSW 2380, Australia.
[D]Atmospheric Environment Research Centre, Griffith University, Brisbane, Qld, Australia.
[E]Corresponding author. Email: john.leys@environment.nsw.gov.au

**Abstract.** Dust storms are frequent in Australia and can have a large impact on the soil resource, the economy and people. There have been few economic studies of the impact of wind erosion worldwide and only one in Australia before this study. While wind erosion impacts on the soil resource at the point of the erosion, the level of economic impact rises as the population and associated infrastructure affected by dust increases. This study estimates the impact on the economy of the state of New South Wales of a single large dust storm called Red Dawn that passed over the eastern coast of Australia on 23 September 2009. Estimates for rural and urban areas are presented with both on- and off-site costs evaluated. The estimated cost is A$299 million (with a range of A$293–A$313 million) with most of the cost being associated with household cleaning and associated activities. The dust storm also impacted on many cities on the coast of the state of Queensland, but their costs are not included in this study. This study demonstrates some, but not all, of the major economic costs associated with wind erosion in Australia. Given the annual average cost of dust storms it is suggested that A$9 million per year would be a conservative estimate of the level of investment required in rural areas for dust mitigation strategies, based on improved land management that could be justified to achieve a positive impact on soil condition and reduce economic losses in rural towns and the more populous coastal cities.

**Additional keywords:** dust storms, ecosystem services, Red Dawn, resource economics, soil erosion, Sydney dust storm 2009, wind erosion.

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## Introduction

Dust storms are the result of soil erosion by wind. They cause considerable economic and physical damage both at their site of origin (e.g. the farm paddock, Leys and McTainsh 1994) and downwind as they deposit unwanted dust and reduce air quality (Chan *et al*. 2005). On-site damage occurs through the loss of top soil, which can result in lowering of the soil surface and scalding, and loss of soil nutrients, organic matter and soil carbon (Leys and McTainsh 1994; Leys 2002). Windblown sand can also damage vegetation by burying it or abrading and sand-blasting it off (Bennell *et al*. 2007). On-site damage can also occur by burying or sand-blasting infrastructure such as fencing and watering points for livestock (Huszar and Piper 1986).

Off-site damage occurs downwind where dust can drastically limit human activities, including closure of transport networks and increased accidents caused by low visibility (Ekhtesasi and Sepehr 2009), health impacts (Miri *et al*. 2009), loss of sales by businesses and damage to utility systems, such as electricity lines and transformers, or buildings. Deposited dust also increases cleaning costs and can damage high-value crops (e.g. vegetables) (Huszar and Piper 1986; Williams and Young 1999). The magnitude of the off-site impact of dust events is to some extent determined by the number of people affected or the location of significant damage or interruptions to infrastructure services, such as transport facilities. Ai and Polenske (2008) suggested that the impacts of dust storms in China are higher in cities, such as Beijing, due to the large populations and the level of infrastructure and economic activity in these areas, when compared with rural regions where population and infrastructure levels are lower.

Wind erosion and dust storms can also have several positive effects downwind of the erosion site. These benefits are soil and nutrient deposition on land and on water. Dust from wind erosion when deposited downwind contributes to soil build up in these areas (McTainsh 1989). This deposited dust also carries organic carbon and nutrients, such as nitrogen or phosphorus, which contribute positively to soil health (Raupach *et al*. 1994; Cattle *et al*. 2009). Nutrients in dust can also be used by various microorganisms in the oceans, such as phytoplankton (Boyd *et al*. 2004), perhaps leading to increased fish stocks and the other soil components contribute to marine sediments (Hesse and McTainsh 2003).

Much is understood about the physical aspects of wind erosion and dust storms but very few economic studies have been undertaken, even in countries regularly affected by dust storms.

There has only been one study of the economic impact of wind erosion in Australia (Williams and Young 1999). Their report on the costs of dust in South Australia, included health costs, and incorporating mortality and morbidity costs, concluded that a major cost of dust from wind erosion in South Australia was due to adverse health effects, particularly on the portion of the population that suffered from respiratory diseases, especially asthma sufferers.

This is only the second study of the economic impact of wind erosion in Australia after that of Williams and Young (1999). Both studies rely on the North American research of Huszar and Piper (1986) because of the difficulty of obtaining objective economic data for wind erosion and dust storms in particular. The scarcity of dust storms in urban areas with large populations in Australia makes the collection of objective data difficult. Additionally, there has been no on-going research into the economics of wind erosion, particularly the off-site impacts. This has resulted in a lack of survey data collected shortly after dust storms have occurred, and so this work is confined to the 23 September 2009 dust storm, denoted Red Dawn by local media, for which a range of data and information is available.

This study calculates the economic impact of a large Australian dust storm (Red Dawn) on the economy of New South Wales (NSW), focusing on off-site costs incurred in Sydney. The analysis is extended to regional areas, using Mildura as an example, where smaller more frequent dust events occur. The analysis outlines how the impact of dust storms varies between urban and regional areas as a function of population and infrastructure. The study does not attempt to fully analyse the on-site costs associated with soil loss, lost agricultural production and/or production potential, although an estimate is provided based on previous work using off-site data. Finally, the study considers the investment in strategies of erosion control and improved land management practices in rural areas that the economic cost of dust storms might justify.

## Methods

### *Impact cost model*

The economic impact of dust storms is strongly driven by the population and the associated infrastructure of large urban areas, as suggested by Ai and Polenske (2008). This concept is illustrated in Fig. 1. This figure shows three damage curves – for a city and two rural locations. The graph does not have a scale as it is for illustrative purposes only. Although the severity of a dust storm, as measured by dust concentration, may be similar in all locations, due to lower populations and absolute levels of infrastructure and economic activity the impact in regional areas ($A_1$ or $A_2$) would be lower than that in cities (B). The difference between points $A_1$, $A_2$ and B varies with the shape of the damage curves. Larger rural centres such as Wagga Wagga or Mildura ($A_2$), would have a curve (Rural 2) closer to the shape of the city curve, whereas smaller centres, such as Balranald or Tilpa ($A_1$), may have a curve (Rural 1) below that of the Rural 2 curve. The essential point is that the shape of the three damage functions, City, Rural 1 and Rural 2, determine the relative impact of a dust storm of equal severity on each location.

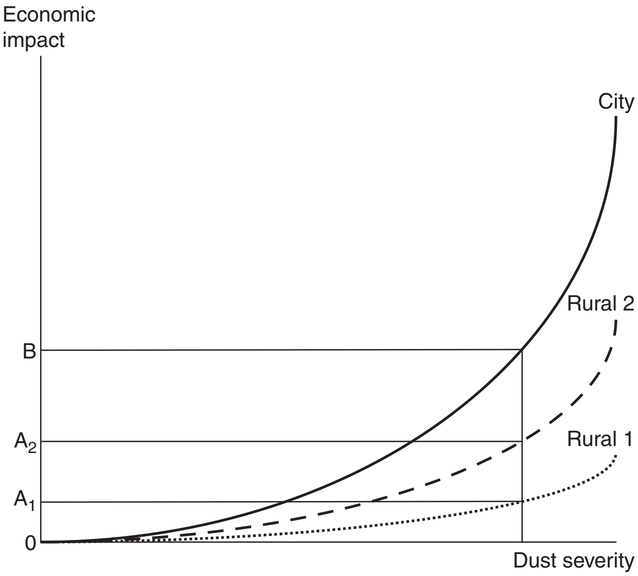


**Fig. 1.** Impact of dust storms on different populations or regions, Rural 1, Rural 2 and City are damage functions in rural areas and metropolitan regions, respectively. $A_1$, $A_2$ and B are the impacts in small rural towns, large rural cities, and metropolitan areas, respectively.

### *Measuring costs*

Measuring the costs associated with dust storms requires knowledge of the frequency and severity of dust storms and the impacts of these storms on the economy. A large storm such as Red Dawn caused major disruptions to many sectors of the economy. Dust storms of similar or slightly lower severity, which may not reach major population centres, but affect smaller regional centres at more regular intervals still impact on the economy of the region, but at a lower level (Fig. 1). However, the cumulative effect of many smaller events may still be significant; hence the need to know both the severity and frequency of dust events.

To apply the model of impact costs, data on dust severity and frequency is required along with economic data on the cost of interruption to, or increased demand for, services. Information on dust severity and frequency was obtained for both a rural (Buronga, near Mildura, Victoria) and an urban (Sydney, NSW) site (Fig. 2). Buronga was chosen as the rural site because (i) it has the longest rural dust concentration record in Australia and (ii) is a rural city with a known dust storm history. Sydney was chosen as it had a dust (air quality) record, and the most economic and other data available as a result of the recent Red Dawn event.

### *Severity and frequency of dust events*

Two data sources were used, one rural from DustWatch (www.environment.nsw.gov.au/dustwatch/, accessed 5 May 2013) and one urban (www.environment.nsw.gov.au/aqms/, accessed 5 May 2013). Data on major dust events has been collected for the last 22 years at the Buronga DustWatch site near Mildura. The best data (i.e. daily sampling) is from the period March 2001 to the present. Prior to March 2001, the samples were weekly or when dust events were known to be coming. The 2001–10 period was extremely dry in eastern Australia and so the frequency of dust events at Buronga is above the average. The time series was used to identify major dust events, defined as those with total suspended particles (TSP) greater than 100 μg m$^{-3}$ (Fig. 3).

Records of TSP are not available for Sydney but Particulate Matter <10 μm (PM10) is available from 1994. During dust storms the mass component of PM10 is about half that of the TSP, so a dust event was said to have occurred when Buronga recorded a TSP >100 μg m$^{-3}$ and Sydney recorded a PM10 >50 μg m$^{-3}$.

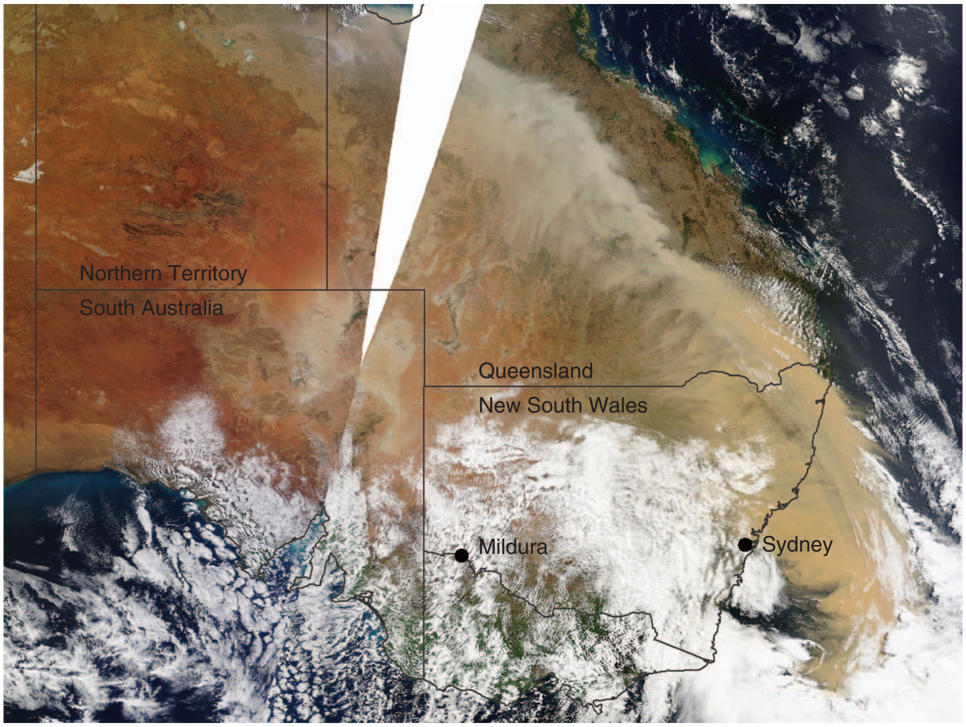


**Fig. 2.** MODIS image for 0000 UTC 23 September 2009 showing the Red Dawn dust storm plume extending from south of Sydney to the north of Queensland.

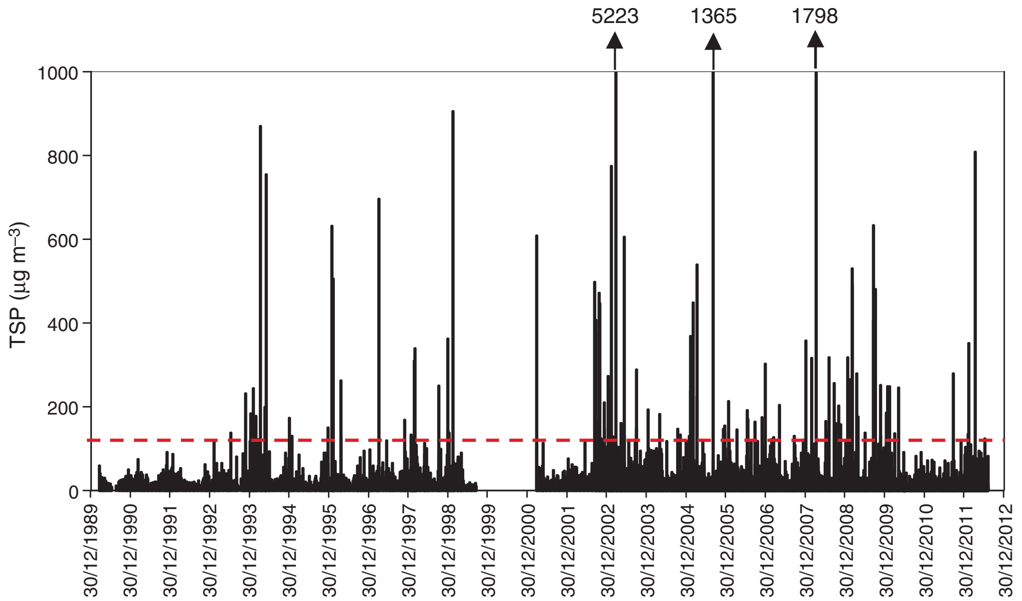


**Fig. 3.** Total suspended particulate (TSP) matter concentrations at Buronga DustWatch site. Dashed line denotes TSP of 100 μg m$^{-3}$. Numbers at top of graph indicate the measured TSP level for that day above the maximum *y*-axis value.

### Cost analysis data

A variety of data was required, both on- and off-site, to undertake the cost impact analysis. Due to uncertainties in the assumptions, a range of costs is calculated and the median value reported in the final estimate. The cost analysis was based on data either provided by those primarily affected by the dust storm or derived from previous studies in Australia and overseas. The off-site economic impacts of dust events are spread across all sectors of the community. Huszar and Piper (1986) determined that the major off-site impact of dust storms was on households, principally due to interior cleaning and domestic landscaping clean-ups. Huszar and Piper's method (Huszar and Piper1986) was used as the basis for the cost calculations as there are no other methodological reports to follow. However, their technique was adjusted in several ways. First, inputs were reduced to a one-off event, for example labour usage for cleaning was estimated at 2 h. Second, while many households may not have used commercial cleaners for domestic cleaning it was assumed that the cleaning was undertaken and, therefore, an opportunity cost was assigned to the labour required. The opportunity cost for domestic cleaning was set at the average hourly wage in 2009 (Australian Bureau of Statistics 2011*b*). Finally, the estimated costs of Huszar and Piper (1986) were utilised as a gauge to ensure the costs generated in this research were conservative and within reasonable limits compared with previous measures. As the costs of dust storms could not be measured accurately, due to data limitations, a range of costs for most sectors of the economy was also estimated.

One significant factor that Huszar and Piper (1986) did not address was the impact on health of dust storms. Saxton (1995) discussed the many respiratory effects of dust inhalation and the potential diseases caused by inhalation of particulate matter in dust storms, especially PM10 particles. Barnett *et al.* (2011) suggested that dust storms increase health problems, such as respiratory and cardio-vascular problems, but can also act as vectors for diseases caused by microorganisms, like coccidiomycosis or meningitis. Williams and Young (1999) found that health costs were the most significant contributor to the overall costs of dust storms, followed by household costs, but household costs constituted only 13% of the total off-site costs of wind erosion. Saxton (1995) and Williams and Young (1999) mention motor-vehicle accidents or include the costs to society of these types of events, but do not include an analysis of the attendance at these events of emergency services. Miri *et al.* (2009) estimated the impact on the Iranian economy of a series of severe dust storms in south-eastern Iran over a period of 4 years and included in their analysis the costs of school closures and removal of sand accumulations in residential areas. Many other studies of the off-site costs of dust have not considered effects on other sectors of the economy such as transport, construction or emergency services.

As indicated earlier, population is a major factor in the impact model. In the analysis several assumptions are made regarding the population and number of households in Sydney and NSW (Australian Bureau of Statistics 2010*a*, 2010*b*). The number of households in the Sydney Statistical Division was 2 718 172 and the population was 7 068 287 in September 2009; the proportion of the population of NSW in Sydney was ~63% (Australian Bureau of Statistics 2009). Included in the cost analysis is the impact on households and businesses outside the Sydney Statistical Division. Given the approximate path of the dust plume, it was assumed that areas north of a line running approximately from Broken Hill to Bathurst and then to Newcastle were also affected but not to the same extent as Sydney. This segment of the state represents a further 25% of the population. Costs in this area were reduced by a factor of 50% for two reasons; (i) the heaviest part of the storm was at the southern end of the plume, and (ii) the lower economic activity is in regional areas compared with Sydney. These divisions are consistent with the path of the dust storm, as the southern boundary of the area affected is captured within the Sydney Statistical Division, and the northern regions are captured in the area outside the Sydney Statistical Division.

### Transport

Flight information was received from several airlines with respect to the number of flight cancellations, diversions, delays and an estimate of the number of passengers accommodated due to these flight problems. Williams and Young (1999) provided three estimates of the costs of aircraft diversions; A$15 000, A$31 500, and A$63 000 per flight, representing low, median and high costs of extra flying time, and a once-off cost of A$20 154 for on-ground incidental costs. These costs were updated, using data from Australian Consumer Price Index (ABARES 2010), and were used to represent domestic commuter, domestic jet, and international jet costs, respectively. The on-ground costs were assumed to represent the incidental costs of aircraft operations such as additional staff costs, meal vouchers and passenger accommodation. In the case of a delay, the on-ground costs were multiplied by a factor of 0.25 to represent the costs associated with moving aircraft, holding aircraft outside a gate or a delay in getting to a gate, and other associated costs. The 25% of on-ground costs accounts only for additional fuel and staff time, as other costs such as meal vouchers and accommodation, are not incurred. This value is consistent with feedback received from airline staff.

### Commercial activity costs

Commercial activity costs are separated into two categories; (i) retail/service activities, including retail sales and cleaning costs after the dust event, and (ii) slow down or stoppage of construction activity due to occupational health and safety issues related to breathing, visibility, and slipperiness of work surfaces.

Huszar and Piper (1986) surveyed businesses to ascertain the costs incurred by them in the event of dust storms. In the current study their estimates of business costs were utilised as there were no such survey data for Sydney. These estimates were adjusted for population, and inflation and exchange rate effects using ABARES (2010) $A/$US exchange rates and US inflation rates. The estimates of Huszar and Piper (1986) are based on a series of events over a 6-month period. To account for this, the severity of the 23 September 2009 event, and differences in the affected populations, the estimates were halved to remain consistent with the original values.

Estimation of construction sector costs is novel in dust research, hence a method is not provided by previous research. After discussions with the Master Builders Association of NSW data reported by the Australian Bureau of Statistics (Australian Bureau of Statistics 2011*a*) were used which measures the value of construction activity and make an estimate of the percentage reduction in total construction activity on 23 September 2009. The data put the total value of construction, private and public, in the September quarter of 2009 at $4.315 billion which, assuming 80 working days per quarter, yields a daily value of construction of ~$54 million. Two questions arise in determining the cost of lost production. The first is how many sites were closed on the day of the dust storm and their location throughout the affected area. The second is how to treat the loss in value. The loss in value of construction is due to the delay in the overall project as well as costs that are incurred whether construction is undertaken or not. Furthermore, some construction projects may have penalties associated with completion times. The delay in construction can be reduced if overtime is worked to complete the work not undertaken due to the storm, thus imposing on the firm additional labour costs.

In this analysis the loss or delay in construction work was measured with two costs – the opportunity cost of money and a penalty cost, which includes additional costs such as overtime and penalties for delayed completion. Opportunity cost is the value of alternative uses of a resource, in this case interest foregone on the lost investment opportunity. The opportunity cost of money is set at 5%, the discount rate, plus a risk premium to bring the total cost to 7% per annum (ABARES 2010). An additional 3% was added to account for penalties and additional costs. The cost of construction delays was thus set at 10% per annum of the value of construction not undertaken on the day of the storm.

Also, in this study it was assumed that construction activity is proportional to population; therefore, 63% of construction activity took place in the Sydney Statistical Division, and it was further assumed that different levels of reduction in total construction activity in the Sydney Statistical Division – 75, 50, or 25%, rather than estimate the number of sites closed down on the day of the storm. Reductions of 25 or 50% were assumed to occur in the other affected regions of the state. In the costs reported, the range was calculated based on the above reductions and then report for the median (50%) level of activity in both the Sydney Statistical Division and regional areas.

### *Cleaning*

Cleaning was divided into commercial, municipal, domestic and utilities. Commercial cleaning costs have been included in the calculation of overall commercial (retail) costs described above. Municipal costs were obtained from a sample of the 101 affected municipalities and were averaged from data received. Williams and Young (1999) determined that electricity utilities in South Australia were required to clean transformers and lines after dust storms to ensure power leakages were minimised. Reports for this type of cleaning in NSW were investigated.

Domestic cleaning costs were estimated utilising the approach of Huszar and Piper (1986), incorporating inflation and exchange rate corrections as suggested by Williams and Young (1999). One difference between the costs estimated in this study and those of Huszar and Piper (1986) and Williams and Young (1999) is that Red Dawn was a once-off event, whereas the estimates of the other two analyses were average annual costs and, in the case of Huszar and Piper (1986), based on the period from November 1983 to May 1984. These authors also included costs of landscaping damage and loss of recreational activities. In the current study these costs are not included in the estimate of costs to households, given the once-off nature of the event and that it occurred on a working day. We estimated household cleaning costs in the current study at 50% of the costs of Huszar and Piper (1986). This estimate was confirmed by a survey of the websites of service providers in the Sydney metropolitan area. The survey collected information on the individual components of cleaning costs, e.g. labour, car washing, domestic cleaning and laundry, from which costs for the Sydney metropolitan area were estimated. These differed only marginally from estimates based on the 50% of the Huszar and Piper (1986) values. We therefore set domestic cleaning costs reported in this study at 50% of the values generated from the Huszar and Piper (1986) analysis.

### *Other costs*

Two other costs were estimated: absenteeism and fire-alarm callouts. A potential cost is an increase in school absenteeism as parents keep children home due to concerns regarding the health effects of the dust in the atmosphere. Coupled with children remaining at home would be an increase in parent absenteeism from employment. Due to the uncertainty surrounding the number of workers absent on a particular day, estimating a cost requires assumptions to be made based on average attendance and the costs of work absenteeism. In the model these assumptions were based on workforce size (Australian Bureau of Statistics 2011*b*) and the cost of absenteeism (Direct Health Solutions 2010).

Using survey data, Direct Health Solutions (2010) estimated that average absenteeism is ~4% of the workforce on any day and that the cost of absenteeism is A$379 per absentee per day. This is the cost to the employer of lost productivity, not the cost to the employer of leave expenses as these are already incorporated into the employer's cost of production. The daily cost of absenteeism was based on a weighted average of the number of full-time and part-time workers in the labour force in the September quarter of 2009 (Australian Bureau of Statistics 2011*b*), assuming part-time workers were employed 50% of the time.

The fee charged for a false alarm is $750 (Fire and Rescue NSW 2011). It could be reasonably assumed that part of the fee is for cost recovery, i.e. labour and other variable costs incurred in responding to the call, and that part of the fee is a penalty. In this study, as no information is available as to the division of the $750 between these two components, it is assumed that 50% of the fee was operational costs and the other 50% a penalty.

### *On-site costs*

Huszar and Piper (1986) suggest that an approximation of the on-site costs of wind erosion can be obtained from the off-site costs. On-site costs include all immediate costs, such as stock losses and or replacement purchases, feed purchases, and infrastructure repair or maintenance. In this study we followed Huszar and Piper (1986) and determined on-site costs as 2% of the cost of household cleaning.

## Results and discussion

### *Frequency and severity of dust events*

To apply the impact cost model required a description of the frequency and severity of dust events. Data from a rural city (Mildura) and from a metropolitan city (Sydney) were analysed.

At the DustWatch station at Buronga (near Mildura), for the period from March 2001 to May 2010 there were 123 dust events with a TSP greater than the 100 µg $m^{-3}$ threshold (equivalent to a visibility reduction of ~10 km). Of these dust events, 27 had dust concentrations greater than 260 µg $m^{-3}$ (the United States Environmental Protection Agency 24-h health standard of 1989 used in Australia before adoption of the Environment Protection and Heritage Council PM10 standard in 1998), and nine events had TSP concentrations greater than 500 µg $m^{-3}$. The highest concentration (5224 µg $m^{-3}$) occurred on 19 March 2003 and the second highest (1719 µg $m^{-3}$) on 3 April 2008. The dust from the event on 19 March 2003 reduced visibility in the region surrounding Mildura to ~50 m at its peak (Berry 2003). The impact in the Mildura region on 19 March 2003, other than visibility and dust accumulation, was an increase in respiratory-related illnesses and the cancellation of two air ambulance flights, which were not considered emergencies (Berry 2003). This event was local and did not reach Melbourne due to rain washing out the dust during transport. Dust on the event on 3 April 2008 came from the South Australian desert regions and again the major impact was reduced visibility (down to 400 m) and the deposition of dust in the region surrounding Mildura.

After analysing the data for Buronga, we concluded that although there were many dust events with relatively high dust concentrations at the Buronga DustWatch site, many of these were localised or regional events and were not recorded in capital cities. This is demonstrated by comparing the dust record for Buronga with dust records for Sydney. Sydney has recorded only one dust storm since March 2001. The dust that reached Sydney on 23 September 2009 tended to be from north-western NSW, the upper south-east of South Australia and south-west Queensland (Leys *et al*. 2011).

Other dust storms have reached capital cities such as on: 1 December 1987 in Brisbane (Knight *et al*. 1995), 1 February 1983 in Adelaide (Williams and Young 1999), 1 February 1983 in Adelaide and 8 February 1983 in Melbourne (Raupach *et al*. 1994) and 23 October 2002 in Sydney and Brisbane (McTainsh *et al*. 2005).

The largest dust event in the Sydney region was Red Dawn on 23 September 2009, during which the maximum hourly PM10 concentration measured was 15 366 µg $m^{-3}$ at Bringelly in western Sydney (Leys *et al*. 2011). The Red Dawn dust event was used for this study because: (i) it was severe and impacted on a large area (described below), and (ii) there was sufficient media and science data to undertake the analysis of impact. Although the print and electronic media did not provide direct data, media reports aided in identifying segments of the economy affected by the storm thereby improving the estimation of the cost.

Red Dawn affected much of eastern Australia due to the coincidence of several climatic factors. A series of hot dry seasons, particularly in the semiarid regions of NSW, South Australia and Queensland, led to a dry landscape that had low vegetation cover. The lack of vegetative cover left the surface soil prone to wind erosion. A deep low pressure system over south-eastern Australia and associated cold fronts generated winds of up to 100 km $h^{-1}$, with directions varying from north-westerly to westerly. These strong westerly winds, picking up the dust in north-eastern South Australia, south-west Queensland and western NSW, created the dust storm that covered the eastern seaboard of Australia (Leys *et al*. 2011). The dust plume was ~3000 km long and stretched from Eden, south of Sydney, to the Gulf of Carpentaria in northern Queensland (Fig. 2). In NSW, the major areas affected by dust were north of a line running approximately from Broken Hill to Albion Park[1], near Wollongong. However, there were also reports of some dust in Wagga Wagga in the south of NSW. Depending on location the dust event lasted between 1 and 6 h, with Sydney in the upper end of the storm's duration. The concentration of dust in the plume varied along its length, but concentrations were highest in the southern end of the plume, i.e. in the Sydney and Newcastle areas (Leys *et al*. 2011).

The major off-site impact of the storm was caused by the high dust concentrations in the eastern cities. Red Dawn significantly exceeded the Australian air quality PM10 standard (50 µg $m^{-3}$ per 24 h) at Randwick (Sydney) (1734 µg $m^{-3}$), Newcastle (2426 µg $m^{-3}$), Brisbane (990 µg $m^{-3}$), South Gladstone (210 µg $m^{-3}$), West Mackay (281 µg $m^{-3}$), Townsville (562 µg $m^{-3}$) and Mt Isa (550 µg $m^{-3}$). Overall, total soil loss from the storm has been estimated to be over 2 540 000 tonnes (Leys *et al*. 2011).

### *Transport*

Red Dawn had a major effect on transport services with the closure of Sydney Airport and the subsequent need for airlines to divert, delay or cancel flights. The costs of these practices are the extra costs of fuel and labour required to align passengers and aeroplanes to their correct destination and schedules, and the need to accommodate and cater for passengers whose flights are delayed or cancelled.

In total, over 700 flights were impacted on by the dust. Most flights were delayed with a relatively low number of cancellations; however, some international flights were diverted to Melbourne or Brisbane. Special dispensations were also issued by Infrastructure Australia for several flights to land after the Sydney curfew due to both delayed departures and air traffic control holding requirements caused by the dust (Infrastructure Australia 2009). The estimated cost of Red Dawn on the airline industry was ~A$10.8 m.

Road transport was affected in several ways. The first is simply the potential reduction in travelling speed due to lower visibility. This reduction in speed increases the total travelling time and costs for drivers and passengers, and also road-based public transport such as buses. One of the major road impacts was the closure of the M5 tunnel in south-western Sydney due to extremely high particulate concentrations in the tunnel. This increased the travel time of commuters from south-west Sydney.

[1]In the analysis of cost Albion Park is included in the Sydney Statistical Division, rather than in the other affected areas of NSW, hence the difference in the line of impact discussed earlier.

However, given the number of workers absent on the day of the storm, traffic delays may not have occurred in other parts of the Sydney region. Data from the NSW Roads and Maritime Authority (RMA) indicated that on the day of the storm there were ~5% fewer cars on major Sydney roads compared with the same day in the weeks before and after the event (NSW RMA, pers. comm. 2012). Therefore, no cost for impacts on road transport is included in the total cost of the storm.

### *Commercial activity costs*

These costs include the impacts on retail activities and the construction sector. In the case of retail purchases, the major effect would be on discretional expenditures, such as coffee shop purchases, as many discretional purchases may not be undertaken on other days. The impacts on non-discretional expenditure, i.e. essential purchases, such as food, may be large on the day of the event, but much of the reduced expenditure would be recovered in subsequent days. Losses in commercial activity amounted to A$8.4 million in the Sydney Statistical Division and A$1.7 million in the regions outside the Sydney area. These costs capture the loss in revenue from lower retail and service sales, costs of cleaning premises, and losses in productivity due to the dust reducing activity such as transport and outside/outdoor work. These two values equate to ~5% of the daily retail turnover in the September quarter of 2009 (Australian Bureau of Statistics 2011*c*).

The cost to the construction industry, estimated as the cost of investment opportunities foregone together with penalties and additional costs, ranged from A$1.2 to A$3.2 million and the median value of A$2.4 million was used. The median value is based on a reduction in total construction activity of 50% in both the Sydney Statistical Division and regional areas.

### *Cleaning*

Cleaning costs may be separated into four categories; commercial, municipal, domestic and utilities. Commercial cleaning costs are included in the commercial activity costs in the preceding section. Municipal and domestic cleaning costs were estimated separately. There were no reports in NSW associated with cleaning electricity utilities and so these costs, if any, are not included in this analysis.

Based on data supplied, most municipalities either did not incur significant additional costs to clean up after the dust storm or incurred costs that were not directly measurable. The municipalities reported that cleaning after the dust event was undertaken by crews that would have otherwise been employed on other tasks and, therefore, the costs incurred are due to later completion times of other projects, or that cleaning was completed in the normal course of regular cleaning cycles. Information from several councils indicated that some specific cleaning costs were incurred, mostly for higher profile locations, and these averaged ~A$2000 per council. In this case it was assumed that all councils incurred some minor costs of cleaning and the average of A$2000 was used across all 101 municipalities affected, yielding a total cost of A$202 000.

Estimates for domestic cleaning costs per person yielded a value of A$115 per household. These costs include cleaning and laundry, car washing and repairs, i.e. new air filters, and water for washing down surfaces, as well as a cost of labour for sweeping and other cleaning activities. On the day after the dust storm, water restrictions in Sydney region were relaxed to allow households and businesses to clean and wash down surfaces etc. (Costa 2009). On the 2 days following the dust storm, daily water use increased by 260 Ml and 280 Ml, respectively, or 20%, above the average use for 2008 (1310 Ml) and 2010 (1285 Ml) (SCA 2011). In 2009, water for domestic use was valued at A$1.87 $kl^{-1}$; thus additional water cost users ~A$1 million or ~A$0.60 per household. At a cost of A$115 per household, the total cost to households in the Sydney Statistical Division was A$196.5 million, and A$58.3 million to households elsewhere in NSW.

Media reports indicated that many car owners did wash their cars on or after the event, and our survey of car washing sites showed that the average cost of a car wash in Sydney, in 2009, was ~A$35 per car. However, our estimate of domestic cleaning costs did not include items such as caravans, boats or private swimming pools. One estimate suggested that the cost was ~A$1000 per pool. These items were not included as there was (i) no reliable estimate of the number of items in the region, and (ii) no information on the respective cleaning costs. While acknowledging the uncertainty of the estimates, due to the items not included it is believed that they are not unrealistic.

### *Other costs included*

Media reports for the day suggested absentee rates were 25% higher than the daily average of 4% (Hohenboken 2009), which equates to a 5% absentee rate. However, since the level of absenteeism is uncertain, and some associated costs have been captured in the loss in value of construction, the costs for three levels of absenteeism – 4.5, 5 and 6% – were estimated. These values represent the lowest, most likely and highest levels of absenteeism thought to have resulted from the event. The associated costs were, respectively, A$2.5, A$7.5 and A$17.3 million. The lowest (4.5%) and highest (6%) rates represent lower/higher increases in absenteeism that may have occurred but were not observable. Also, included in the absenteeism costs are the costs of carer absenteeism for health-related issues.

One minor cost included is that of false fire alarm callouts directly attributable to dust activation of alarms. NSW Fire and Rescue reported a substantial increase in false alarms on 23 September 2009 – 504 additional alarm callouts compared with 2008. At an estimated direct cost of A$375 per callout, these additional calls represented a cost of A$189 000 to the service.

### *Off-site costs not estimated*

In previous studies, motor vehicle accidents and health costs have been included in the costs of dust storms, see for example Williams and Young (1999) or Saxton (1995). However, data received from various sources suggest that there was no increase in motor-vehicle accidents in the Sydney metropolitan area on 23 September 2009 (NSW Roads and Traffic Authority, pers. comm.). Indeed, data from the NSW Roads and Traffic Authority indicate that there may have been a reduction in accidents on that day, possibly attributable in part to the higher worker absenteeism and reduced traffic volumes.

With respect to health costs, the Bureau of Health Information (Bureau of Health Information 2010) reports that there was no significant increase in emergency room visits or hospital admissions in the week of the Red Dawn event when compared with 2008 or 2010. However, this does not indicate that respiratory problems did not affect certain groups within the population, e.g. asthma patients. It merely indicates that, if a problem did arise, these patients may have treated themselves or at least did not seek emergency department treatment. Several studies in Australia and the US have shown that in some cases increasing rural dust does not lead to increased hospital admissions (Schwartz *et al*. 1999; Rutherford *et al*. 2003).

One possible reason for the minimal impact of the dust storm on health could be the proactive role of the Department of Health and the then Department of Environment, Climate Change and Water with respect to air-quality monitoring and issuance of health alerts due to poor air quality. On the day of the dust storm, Health Alert SMS and emails were sent to subscribers to the health-alert system advising of a high pollution-level event. Alerts were sent from 02.00 to 09.00 hours on the morning of the storm (S. Quigley, pers comm.), thus those at risk could make individual decisions regarding the impact of the dust level on their health.

### *On-site costs*

Due to the complexity of the interactions between soil, vegetation, animal and plant production and the lack of data for on-site costs, a value of 2% of the costs of household cleaning was used as the basis for determining on-site costs based on the calculations of Huszar and Piper (1986). Therefore, the estimated on-site costs are ~A$5.1 million. On-site costs incurred by landowners would include repairs or reconstruction of farm infrastructure such as fences, water facilities, and roads or tracks. Additional costs could also be incurred by stock-owners for fodder to replace that destroyed by the dust storm, for sale of stock necessitated by the loss of feed or fences, or by the direct loss of stock. These were the types of costs included in a Natural Disaster Relief Assistance submission to the NSW Government by the Pastoralists Association of West Darling (Kelly 2009). They estimated the cost of damage from Red Dawn to their area at A$4.5 million. This cost was only for NSW producers and did not include those adjacent parts of South Australia affected by the wind erosion or the costs associated with soil loss, vegetation and decline in soil quality and the impact on future production. It must, therefore, be viewed as a very conservative cost estimate.

A comprehensive analysis of on-site costs would require quantification of variables such as: amount of soil loss, the nutrient value of soil lost, the recovery rate of lost nutrients, short-term loss of crop, pasture and animal production, and estimates of the reduced production potential associated with the soil and nutrient loss. While such an analysis would require a substantial modelling effort, and is beyond the scope of this paper, estimates of some of the components can be made readily.

The calculation of soil lost is possible via modelling and measurement. Leys *et al*. (2011) estimated from dust concentration measurements on the east coast of Australia that 2.54 million tonnes of dust were lost. Application of the Computational Environmental Management System wind erosion model (CEMSYS version 5) (Shao *et al*. 2007) to calculate the soil loss in the dust storm source area (i.e. dust emission plus dust deposition) resulted in an estimate of 3.45 million tonnes. The difference in the two estimates is acceptable since the modelled result is for the area eroded and the measured result is for the mass lost off the coast. Unfortunately there is no published method for valuing a tonne of soil loss.

An alternative approach is to estimate the level of soil deflation and calculate the soil and nutrient loss from the source area. This is not the full cost of soil loss, rather an estimate of the nutrient loss. The CEMSYS was again used to calculate the area where soil was lost. The model was applied to the 22–23 September 2009 period and the output is shown in Fig. 4. The area eroded was 776 180 $km^2$, i.e. the yellow and red tones and 3.45 million tonnes of dust was lost, this equates to 4.45 tonnes $km^2$. Since there is ~120 tonnes of soil in the top 1 mm of soil per $km^2$, the level of deflation, when averaged over the erosion area, is very small – much less than 1 mm. In reality, however, different land units would have experienced different rates of deflation depending on their erodibility. Further, since nutrient loss is determined by the mass of dust that contains the clay and organic matter winnowed from the soil rather than the depth of soil lost (Leys and McTainsh 1994), and information on the nutrient status of the soils of the semiarid and arid parts of Australia after a long drought is not readily available, this approach is not likely to prove feasible. Another approach is required.

Estimation of the cost of fertiliser equivalent to the nutrients in the lost dust (Raupach *et al*. 1994; Leys 2002) does allow an estimate to be made of the cost of nutrients lost. Raupach *et al*. (1994) calculated a nitrogen content of 0.17% and phosphorus content of 0.0055% for the dust storm in Melbourne in 1983. These nutrient contents where based on the fraction of soil <44 μm from three soils of different texture from the semiarid region of south-west NSW, probably similar to soils in the source area of the Red Dawn event. They estimated that dust from the Melbourne dust storm had a typical N : P : K ratio of 32 : 10 : 0 valued at A$0.37 $kg^{-1}$ at 1994 prices. Red Dawn resulted in the loss of 2.54 million tonnes of dust off the coast (with 1.73 million tonnes off the NSW coast) containing nutrients with an estimated value of ~A$8.8 million for the total storm (or A$6.0 million for the proportion from NSW) based on current prices and nitrogen and phosphorus contents determined by Raupach *et al*. (1994). However, it is assumed that producers in the rangelands would not replace the lost nutrients with fertiliser and consequently this cost has been excluded from the on-site estimates.

Dust contains a high proportion of organic material (Leys and McTainsh 1999). At the time of writing, soil carbon is a non-Kyoto compliant activity but there are efforts to make it compliant (Sabto and Porteous 2011). The Red Dawn dust in Sydney was reported to contain 10.6% organic matter (Aryal *et al*. 2012). Applied to the soil loss reported by Leys *et al*. (2011) this equates to 254 000 tonnes of soil carbon or 987 213 tonnes $CO_2$-equivalent. Kyoto-compliant emissions are worth A$23 $tonne^{-1}$ so that the $CO_2$-equivalents emitted in Red Dawn would be worth A$22.7 or A$15.4 million for NSW. As soil carbon is not currently Kyoto-compliant, a discount rate of 50% of the compliant market price, i.e. A$11.4 million in lost $CO_2$-

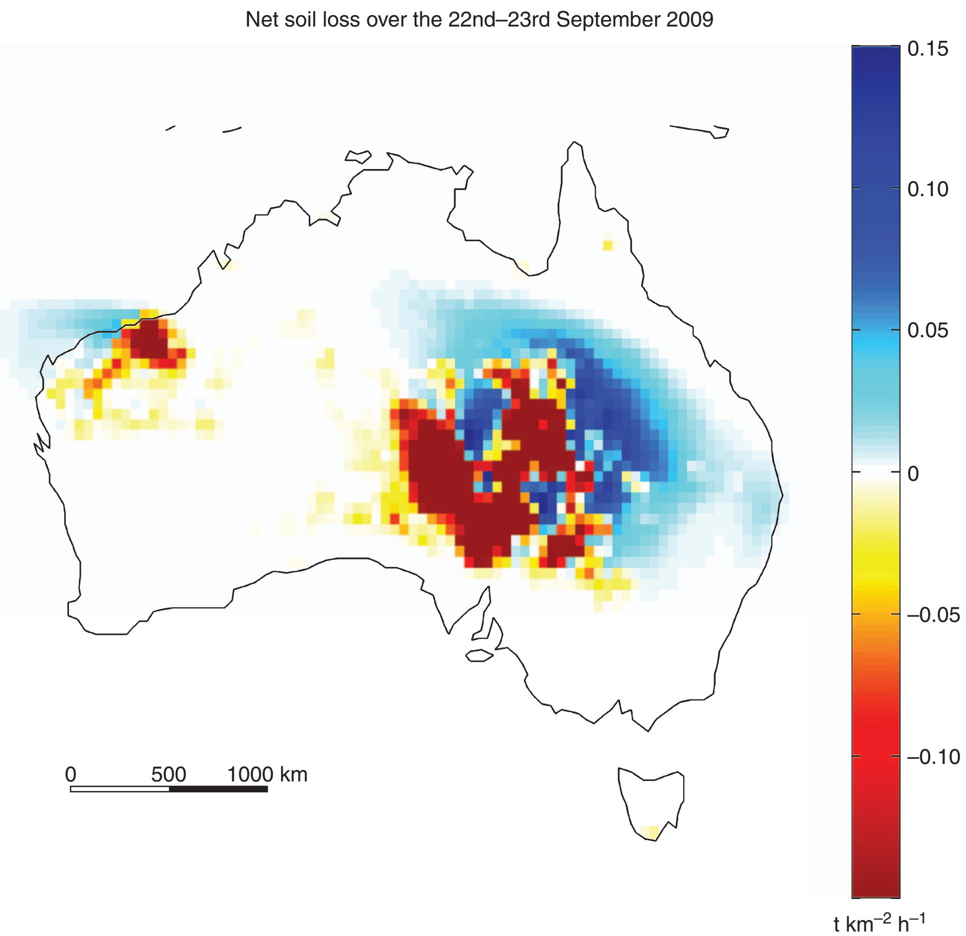


**Fig. 4.** Modelled data showing area of soil loss (red and yellow tones) and areas of dust deposition (blue areas) for Red Dawn (22–23 September 2009) (Butler and Pudmenzky 2012).

equivalents for Red Dawn or A$7.7 million for NSW, is assumed. The total on-site cost for NSW, excluding fertiliser, is estimated at A$12 800 000.

### *Potential benefits of dust storm*

Several benefits could be generated by the dust storm although measuring some of these may be extremely difficult. The first is the deposition of sediment (McTainsh 1989) and nutrients in the dust (Cattle *et al*. 2009) on land in the path of the dust storm. Nutrients in the dust could provide some benefit to landholders in the form of increased nutrient application at no cash cost. At the state-wide scale of this study, however, soil and nutrients have simply been redistributed, with the exception of that dust that leaves the coast. While there may be losses and benefits to individual landholders, there is no benefit to the state overall, only a loss as described in the preceding section.

A second benefit could result from the value of the nutrient-laden soil to sea life. Nutrients in the dust, particularly iron, when deposited on the ocean provide additional nutrients for phytoplankton growth, leading to increased feedstock for other sea life (Cropp *et al*. 2005) and possibly an increase in fish stocks. However, the time horizon for this benefit is difficult to determine. A potential third benefit is that of carbon sequestration by phytoplankton after fertilisation of the ocean water with iron-rich dust (Blain *et al*. 2007). Measurement of any of these potential benefits is difficult and beyond the scope of this paper.

### *Impacts of dust events on a smaller community*

The impact cost model (Fig. 1) indicates that the costs of any given event to a rural community are lower than for a large urban area. Using the method described above, it is possible to estimate the cost of dust storms on a smaller rural community. Mildura is used as an example of such a community and two of the major dust events identified in Fig. 3, those of March 2003 and April 2008, are considered as they were of a similar or greater intensity to Red Dawn. In the Mildura statistical area, the numbers of households in the censuses of 2001 and 2006 were 16 496 and 17 770, respectively (Australian Bureau of Statistics 2006). Given the magnitude of the dust storms on these two dates, it is assumed they had a similar impact on the Mildura community as on the non-Sydney population.

The estimated costs of the events in 2003 and 2008 were A$1.6 and A$1.9 million, respectively. The cost of the event in 2003 includes the cost of a traffic accident reported in the media.

However, as for the Red Dawn event the major costs are those of domestic cleaning and the impacts on commercial activities, with a minor impact on the construction sector. The major difference between the Red Dawn event and events in the Mildura region is the frequency of occurrence. In the rural region the number of events with significant dust levels is much higher than in Sydney and the associated costs can, therefore, accumulate over time. Figure 3 indicates that another major dust event occurred in 2005 and many smaller events in 2002–03, 2005 and 2009–10. It was assumed that a comparable level of cleaning to Red Dawn is required for events with a TSP greater than 1000 $\mu g\ m^{-3}$ and half that level for those with a TSP greater than 260 $\mu g\ m^{-3}$ but less than 1000 $\mu g\ m^{-3}$. The region has experienced three events with a TSP greater than 1000 $\mu g\ m^{-3}$ and a further 27 events with a TSP greater than 260 $\mu g\ m^{-3}$ since records commenced (Fig. 3). The total costs in the Mildura region are, therefore, ~A\$30 million over a period of 10 years, or ~A\$3.0 million per year excluding health costs or the losses in agricultural production due to sand-blasting of crops or loss of stock and infrastructure in agricultural regions. This figure would thus represent a conservative estimate of the average annual cost incurred by the community due to wind erosion and could greatly underestimate the actual cost in any given year.

## Summary of costs

A summary of the costs estimated above is presented in Table 1. The total costs to the NSW economy of the Red Dawn dust storm of 23 September 2009 was ~A\$299 million, with a range of A\$293–A\$313 million depending on assumptions included in total costs. Most of the cost of the dust storm (A\$255 million) was incurred by households for cleaning and associated activities. Commercial activities, including retail and service industries, (A\$10.1 million) were also significantly affected along with air transport (A\$10.8 million) and construction (A\$2.4 million). In the case of commercial and construction sectors, these are costs incurred in loss of business, cleaning, loss in construction time and other direct costs due to the dust storm. For the transport sectors the costs were due to flight cancellations, diversions and delays, as well as catering for passengers affected by these factors.

One significant cost not considered in previous research is the cost of absenteeism of employees, and in this study this is ~A\$7.5 million. A minor cost (A\$189 000) included was for emergency services responding to false alarms. Two costs that are not included in this study that others have included are health and motor vehicle accidents. Although previous research has included these costs, the data collected for this study indicated that there were no significant increases in emergency room attendances or accidents on the day of the dust storm.

Off-site costs for a rural city (Mildura) are estimated at A\$3 million per year noting that Mildura has a much higher frequency of dust events than Sydney but the economic impact is lower due to the lower population and infrastructure levels. Benefits in terms of nutrient deposition to soils and into the ocean are discussed but require further research to obtain a meaningful estimate.

On-site costs were of the order of A\$12.8 million with A\$5.1 million for direct costs and A\$7.7 million for loss of tradeable $CO_2$-equivalents. However, this cost does not include soil and nutrient loss and the associated production losses which could not be estimated by this study.

Finally, this estimate of A\$299 million is based on NSW alone. Red Dawn also had significant impact on coastal and rural cities in Queensland (Leys *et al*. 2011). The cost of the entire dust storm event, which was 3000 km long, would be significantly larger than the NSW segment of 1000 km but estimating this total cost is beyond the scope of the current work.

**Table 1. Summary of costs to the New South Wales economy for the Red Dawn dust storm of 23 September 2009**

| Activity | Cost (A\$) |
|---|---|
| Cleaning | |
| Household – SSD[A] | 196 500 000 |
| Household – other[B] | 58 300 000 |
| Municipal | 202 000 |
| Transport – air | 10 800 000 |
| Construction – 50% reduction in activity | 2 400 000 |
| Commercial | 10 100 000 |
| Absenteeism – median (5%) | 7 500 000 |
| Emergency services | |
| Fire and rescue | 189 000 |
| Total off-site costs | 28 599 1000 |
| On-site costs – infrastructure and stock | 5 100 000 |
| $CO_2$-e losses | 7 700 000 |
| Total on-site costs | 12 800 000 |
| Total costs | 298 791 000 |

[A]Sydney Statistical Division.
[B]Other: all other parts of NSW.

## Benefits of abatement measures

One of the aims of this study was to consider the level of investment in strategies of erosion control and improved land management practices in rural areas that might be justified by the cost of dust storms. It was assumed that such investment would help mitigate the intensity of large dust storms and, therefore, reduce the off-site impacts on the community. It is also assumed that improvements in land management will not completely stop dust storms but rather reduce their frequency, and more importantly their intensity, thus reducing their impact consistent with the impact cost model (Fig. 1).

A full analysis and discussion of this cost-benefit issue is beyond the scope of this study but data presented above allow some preliminary concepts to be put forward. The dust source, in the Red Dawn event, was from rural areas but its impact was not confined to local communities; it extended to metropolitan areas. Red Dawn was conservatively estimated to cost the NSW economy A\$299 million (Table 1), mostly in Sydney. Assuming this type of event occurs once in 50 years, the average annual cost to NSW would be ~A\$6 million. Thus, if successful dust mitigation programs were undertaken at a cost equal to or less than A\$9 million per year (A\$6 million for NSW as a whole plus A\$3 million for Mildura) then savings could be expected in both on- and off-site costs. This estimate is illustrative only, and highly conservative, as it is based on only one rural city and one metropolitan area. It does illustrate, however, that relatively modest annual investments in improved land management practices could have the potential not only to exert a positive influence on the condition of the soil resource and rural economies, but also to deliver benefits to the more populous coastal and metropolitan areas of NSW.

Further development of policy along these lines will require consideration of several issues, which are beyond the scope of this paper. Relevant questions will include: (i) do urban communities have the right to clean air or do landholders have the right to manage their land as they see fit in order to achieve business goals, (ii) if clean air is deemed a right, then who pays for this ecosystem service to be delivered, and (iii) if there is private benefit to the landholder from public investment in improved land management practices, what proportion of public investment is appropriate?

Many of the source areas of dust are on private land but the great majority in NSW are on public land. Given that the cost of wind erosion and dust storms is borne by the whole community and that most of the impact is off-site, it would be reasonable to assume that much of the investment required to mitigate this cost could be from public funding.

## Conclusions

Few studies have attempted to measure the economic impact of dust storms. In this analysis we attempted to capture as many as possible of the multiple costs or benefits of these events. These included costs measured in previous studies such as domestic and commercial cleaning, and impacts on transport and retail activity. New costs due to absenteeism, emergency response and loss of tradeable carbon credits were included. Unlike other studies, health and traffic costs were not included as there was either a lack of data or no evidence of impact.

The differences in off-site impacts of dust storms have been shown to be dependent on the severity of the dust storm and the level of economic activity in the impacted areas. Comparison of the economic impacts of storms of approximately the same severity on Sydney and Mildura showed that, because of the greater economic activity in Sydney, the costs there are significantly higher. However, regardless of the location of the off-site impact, the on-site costs are much lower than the off-site costs simply due to the level of economic activity affected by the dust.

The cost of the dust storms to both NSW and rural economies suggest that investment of up to A$9 million per year in improved land management practices in rural NSW could be justified so long as it achieved a substantial reduction in dust storm intensity and frequency. However, policy development in this area will need to consider several issues related to property rights and public versus private benefits and costs.

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