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Successes of soil conservation in the Canadian Prairies highlighted by a historical decline in blowing dust

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Abstract
Blowing dust from agricultural fields has serious health and economic effects, which can be mitigated by soil conservation techniques. However, it is difficult to isolate improved land management in downstream records of airborne dust. In this letter we present multi-decadal (1961–2006) records of airborne dust frequency from seven weather stations across the Canadian Prairies. We related temporal changes in dust frequency to the climatic wind erosion potential and agricultural census data. We identified a statistically significant regime shift in the region-wide dust time series at 1990, with a substantial reduction in dust frequency thereafter. The correspondence between dust frequency and the climatic wind erosion potential improved from 1961–90 ($r^2 = 0.154$, $p < 0.001$) to 1991–2006 ($r^2 = 0.429$, $p < 0.001$). We interpret this as indicating that the climate signal was obscured by poor soil conservation practices in 1961–90, leading to dustier conditions. Post 1990, improved land management reduced the impact of land-use practices; only the most severe climate forcings resulted in detectable dust. The dramatic reduction of dust from 1990 onward appears to represent a region-wide threshold crossing, where the effects of soil conservation efforts began to materialize. Overall, the results suggest that soil conservation initiatives have had an impact in reducing airborne dust on the Canadian Prairies.

Keywords: dust, wind erosion, Canadian Prairies, land-use management, soil conservation

1. Introduction

Wind erosion of agricultural soil has numerous negative economic and health effects. Locally, erosion reduces yields by decreasing soil water holding potential (Colacicco *et al* 1989), soil nutrient content (Larney *et al* 1998), and often requires increased application of herbicides and pesticides (Wheaton 1992). Adjacent to farms, erosion reduces air quality (Hagen and Woodruff 1973) and visibility (Hagen and Skidmore 1977). Furthermore, airborne dust can act as an allergen (Kellogg and Griffin 2006), increase skin and eye irritations, and augment risk of various cancers (Norton and Gunter 1999, Nordstrom and Hotta 2004).

Wind erosion and blowing dust on the northern Great Plains and Canadian Prairies (figure 1) is largely an anthropogenic land-use problem. The climate and land cover are generally not conducive, at present, to recurrent, large-scale dust outbreaks as seen in drier settings (e.g., Bodélé depression, Washington *et al* 2006). The dust footprint caused by anthropogenic land-use activities is evident in many proxy records and direct observations. For instance, lake cores from Colorado indicate a 500% increase in dust deposition coincident with settlement in the late 1800s (Neff *et al*

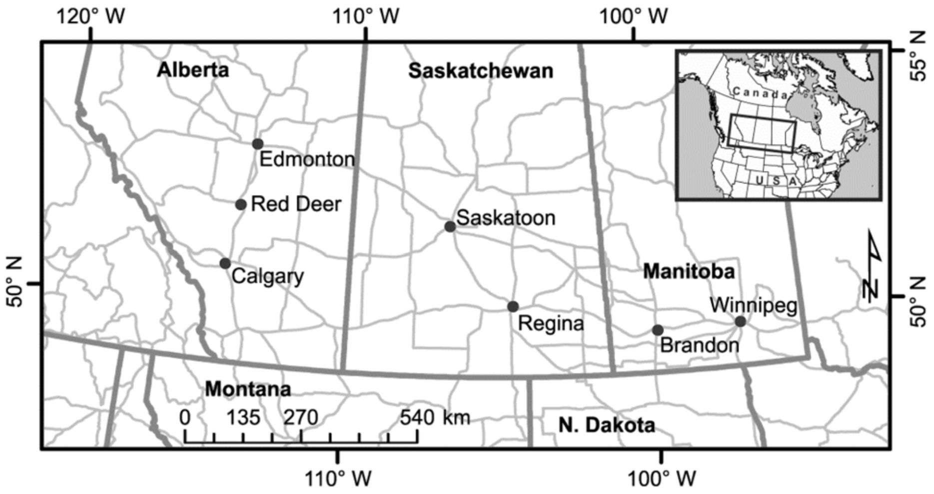

Figure 1. Study site locations on the Canadian Prairies.

Table 1. Initiatives developed to help reduce wind erosion on the Canadian Prairies.

Initiative[a]	Established	Jurisdiction	Authority	Purpose/mission
PFRA	1935	Canada	Federal	Stimulate drought rehabilitation; economic security
SWCS	1943	International	Nonprofit	Foster study of soil and water conservation
ANTFA	1978	Alberta	Nonprofit	Promote use of tillage practice to reduce soil erosion
MNDZTFA	1982	MB/ND[b]	Nonprofit	Publish information to encourage no-till practice
ACTS[c]	1986	Alberta	Nonprofit	Develop and implement innovative tillage systems
SSCA	1987	Saskatchewan	Nonprofit	Promote soil conservation production systems
SCCA	1987	Canada	Nonprofit	Provide public forum for soil conservation issues
ASCA	1988	Alberta	Provincial	Impose duty on landholders to protect soil resources
PVCD	1989	Regional	Nonprofit	Address concerns related to loss of topsoil
NTOTP	1991	North America	Nonprofit	Provide information to farmers on adopting no-till
ZTPM[d]	1991	General	MNDZTFA	Provide answers to questions about no-till farming

[a] Abbreviations as follows: (PFRA), Prairie Farm Rehabilitation Administration; (SWCS), Soil and Water Conservation Society; (ANTFA), Alberta No-Till Farmer's Association; (MNDZTFA), Manitoba-North Dakota Zero Tillage Farmer's Association; (ACTS), Alberta Conservation Tillage Society; (SSCA), Saskatchewan Soil Conservation Association; (SCCA), Soil Conservation Council of Canada; (ASCA), Alberta Soil Conservation Act; (PVCD), Pembina Valley Conservation District; (NTOTP), No-Till on the Prairies; (ZTPM), Zero Tillage Production Manual.

[b] Manitoba, Canada, and North Dakota, USA.

[c] Formed as a result of a change in name and mandate of the ANTFA.

[d] Freely available 99pp publication of the MNDZTFA.

2008). Agricultural wind erosion peaked in the 'dust bowl' event of 1933–1938, where a severe drought and poor land management resulted in significant soil losses and economic hardship across much of the North American Great Plains (Schubert *et al* 2004, Marchildon *et al* 2008). Over the long term, estimates of income foregone due to soil degradation in Canadian Prairie Provinces are as high as \$700 million yr^{-1} (USD), with wind erosion as the costliest component (Dregne 2002). As a result, many initiatives have been instigated to educate farmers on effective wind erosion control techniques (table 1; also see Marchildon *et al* 2008).

Despite extensive funding to develop and promote wind erosion prevention techniques, especially in the late 1980s, there has been minimal large-scale monitoring of the results or outcomes. Individual farmers may have identified increased yields associated with preventing wind erosion, but improvements in the downstream quantity of airborne dust remain poorly assessed. Both Canada and the United States of America have extremely limited capacity for monitoring airborne dust and assessing changes over long baselines (Wheaton *et al* 2008, Trimble and Crosson 2000), and as such, researchers are relegated to using meteorological observations not specifically designed for the task. Despite this, several studies have been performed across North America indicating that a reduction of dust events could be related to improvements in field-scale farm management. In the Southern High Plains of Texas a gradual decline in the frequency of historical dust events was identified (Lee *et al* 1993, Stout and Lee 2003). Similarly, in the Red River Valley of North Dakota, Todhunter and Cihacek (1999) found declines in historical dust events. Wheaton and Chakravarti (1990) conducted a short study on the Canadian Prairies (1977–85) and found no trends. This has left a gap in the research, where the decadal-scale patterns of wind erosion and dust frequency on the Canadian Prairies remain un-assessed.

To this end, we investigated multi-decadal (1961–2006) changes in dust event frequency from seven sites across the southern Canadian Prairies and explored relations with suspected explanatory variables. The specific motivation for this research was to determine whether soil conservation practices and initiatives (see table 1) have been successful in reducing blowing dust. First, we outline recent historical changes in dust frequency, climatic wind erosion potential (*CWEP*) and agricultural practices. Second, we identify the timing of a regime shift in the annual dust frequency time series. This single changepoint establishes a marker for the onset of a step change in blowing dust frequency. We then relate the time series of dust frequency to the time series of *CWEP* and agricultural census data. Overall, we find that a reduction of dust event frequency has occurred, coincident with an improvement in agricultural practices. This suggests that soil conservation initiatives have impacted airborne dust.

2. Site and methods

The Canadian Prairies consist of the southern portions of the provinces of Alberta, Saskatchewan and Manitoba (figure 1). The region represents the northernmost tip of the North American Great Plains and has been under extensive agricultural land use for over 100 years. Four data sets were compiled and analyzed: (i) records of observed dust from prairie weather stations, (ii) homogenized wind data, (iii) homogenized precipitation data, and (iv) land management data. These data were used to produce time series of: (i) observed dust frequency (hours per year and per month), (ii) *CWEP*, and (iii) a qualitative measure of anthropogenic land-use forcing, in the form of land management data from Canadian Agricultural Census.

Airborne dust records were acquired from the online Environment Canada Historical Weather database for the cities of Edmonton, Red Deer, Calgary, Saskatoon, Regina, Brandon and Winnipeg (figure 1). These sites were selected for their even spatial distribution across the Prairies; each also had a minimum of 45 yr of hourly weather observations (1961–2006). Each observation of 'dust', 'blowing dust', 'duststorm', 'sand', 'blowing sand' or 'sandstorm' was used to denote 1 h of dust. Measurement protocols are standardized across all measurement stations and are strictly defined by the Environment Canada Manual of Surface Weather Observations (Environment Canada 1961, 1977). These protocols closely follow World Meteorological Guidelines for observations (O'Loingsigh *et al* 2010), but are unique to Canada (Environment Canada 1961, 1977). A review of archival metadata and station reports indicates that no significant changes in manual observation methods occurred throughout the period of record.

To quantify *CWEP* for a given time period, we developed a metric relating the erosive power or transport capacity (*TP*) of wind to aridity:

$$CWEP = \left(\sum TP\right) / (P/PE) \qquad (1)$$

where P/PE is a measure of aridity (precipitation divided by potential evapotranspiration). Erosive conditions correspond to higher *CWEP* values, which indicate either windy and/or arid conditions.

First, *TP* was calculated for every hour using wind data from the Environment Canada 'Homogenized Surface Wind Speed' database (Wan *et al* 2010). *TP* was calculated with the Kawamura (1951) transport equation:

$$Q = C(\rho_a/g)(u_* - u_{*t})\,(u_* + u_{*t})^2 \qquad (2)$$

where Q is streamwise sediment transport, C is a constant (2.78), ρ_a is air density (1.22 kg m^{-3}), g is the acceleration of gravity (9.81 m s^{-2}), u_* is surface shear stress, and u_{*t} is wind erosion threshold (constant at 0.185 m s^{-1}). Q was related to *TP* by:

$$TP = Q(t/\rho_s) \qquad (3)$$

where t is the interval of measurement (3600 s), and ρ_s is the density of sediment (1600 kg m^{-3}). Surface shear stress was calculated with the Law of the Wall using parameters $\kappa = 0.4$, $z = 10$ m, $z_0 = 0.01$ m (see Shao 2000).

Monthly precipitation (P) data were obtained from the Environment Canada 'Adjusted Precipitation' database, which are standardized and corrected for evaporation, wind, and gauge wetting losses (Mekis and Hogg 1999). Potential evapotranspiration (PE) was calculated using the Thornthwaite (1948) method. Average monthly temperatures used to derive PE were acquired from the Environment Canada Historical Weather database. This produces a *CWEP* for each month and site of the study. Although specific to this study, our *CWEP* metric effectively describes the climatic forcing on wind erosion and builds on the widely used dune mobility index (Lancaster 1988).

Land management data came from the Agricultural Census data available from Statistics Canada. Data were collected during the agricultural censuses of 1976–2006, which are conducted at 5 yr intervals. Over the period of study, an average of 283 270 farms reported on activities in each census, each representing an average of 242 hectares. Two of the most common practices for reducing wind erosion are reduction of summerfallow and the use of reduced tillage direct seeding systems. Summerfallow is the practice of leaving fields unused through the growing season. These fields are often exposed and susceptible to wind erosion. Direct seeding is a method of injecting seeds directly into the soil with minimal or no tillage, which helps reduce erosion by minimizing disturbance of the soil. Summerfallow data were available from 1976 to 2006. Direct seeding data were only available from 1991 for Canada, and were extrapolated to 1976 using data from the United States of America (Coughenour and Chamala 2000). We base this extrapolation on the assumption that agricultural technology has seen roughly similar adoption rates between the United States and Canada.

The ratio of precipitation to potential evapotranspiration is of limited value in winter in Canada because plants are non-responsive and non-contributing (Allen *et al* 1998), thus we only compared dust frequency and *CWEP* in April and May of each year. The average cumulative proportion of dust hours in April and May for all seven sites is 71.0 ± 17.7%

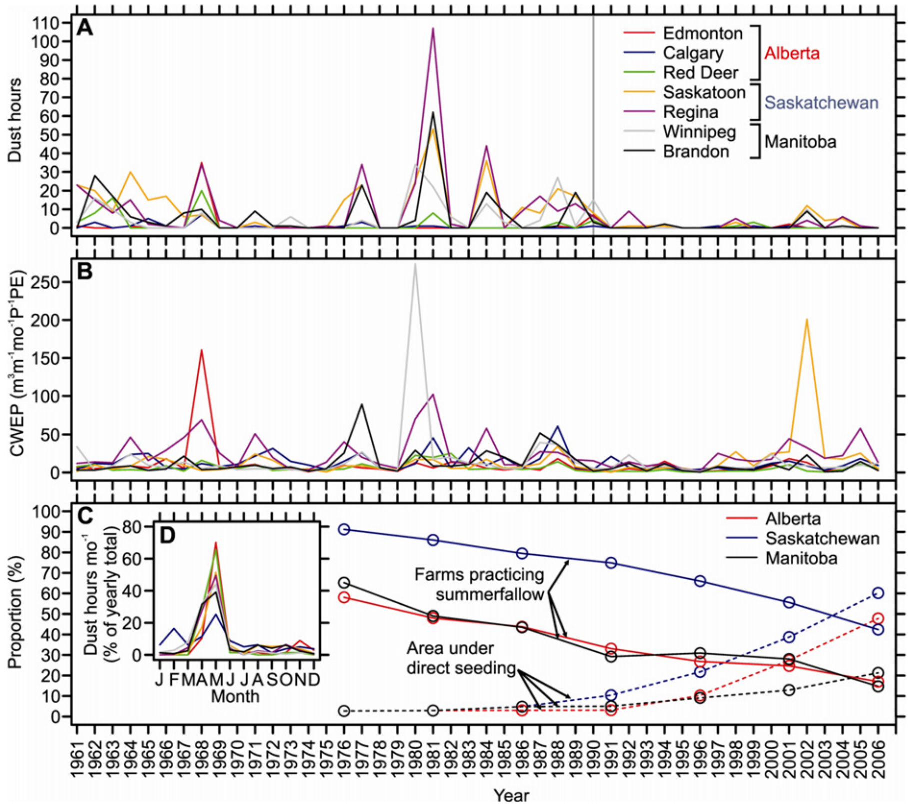

Figure 2. (A) Total dust hours recorded in April and May for each study site. (B) Climatic wind erosion potential (*CWEP*) for each study site, averaged for April and May of each study site. (C) Farming practices for Alberta, Saskatchewan and Manitoba. (D) Average dust hours monthly, as proportion of total. Gray line at year 1990 marks boundary described in text between dusty and clear periods.

(figure 2(D)), indicating that these months are representative of the most prevalent dust conditions since they experience the overwhelming majority of dust events.

3. Results

Between 1961 and 2006, a total of 1342 h of springtime airborne dust were reported at the seven sites across Alberta, Saskatchewan and Manitoba (figure 2(A)). Sites in Saskatchewan experienced the greatest number of dust events (Saskatoon: 380 h; Regina: 393 h), followed by Manitoba (Brandon: 235 h; Winnipeg: 185 h) and Alberta (Edmonton: 54 h; Red Deer: 66 h; Calgary: 29 h). When all sites are considered together, there is a subtle declining trend over the period of record, suggesting a broad-scale decline in recorded dust across the southern prairies.

Dust event frequency shows variability at a number of temporal scales (figure 2(A)). First, a high degree of inter-annual variability suggests that the average frequency of dust hours in a given year does not closely relate with adjacent years (figure 2(A)). Most stations showed correspondence in the frequency of dust events, indicating that certain years were dustier across the prairies, rather than just at one site. Dust frequency distributions are highly skewed; many years have little to no dust recorded, the mean values are influenced by highly dusty years (e.g., 1981). Broad-scale trends emerge at the decadal scale, with clusters of heightened activity occurring prior to 1991 and less dusty conditions occurring from 1991 to 2006. Visual inspection of the series in figure 2(A) indicates a change in dust regime sometime in the early 1990s. Individually, the time series for each station do not reveal statistically significant changepoints; however, when the data from all stations are totaled for each year, the combined time series reveals a significant changepoint or regime shift in dust frequency at 1990 based on two separate homogeneity tests (Pettitt and Buishand). This is also demonstrated by the dramatic difference in means (μ) for 1961–90 ($\mu = 2.99$ h month^{-1}) and 1991–2006 ($\mu = 0.38$ h month^{-1}). Thus, average dust frequency after 1990 was statistically different from the preceding period of the record.

The *CWEP* shows a similar long-term trend to dust frequency in that *CWEP* forcing has reduced; however, the difference in distribution is less pronounced (means: 1961–90: 15.35, 1991–2006: 11.13; medians: 1961–90: 6.71, 1991–2006: 5.26; all units m^3 m^{-1} mo^{-1} P^{-1} PE). Results of the homogeneity tests do not reveal any evidence of changepoints in the individual *CWEP* series from each station, or in the combined series from all stations. The *CWEP* shows inter-annual patterns in variability similar to the dust series (figure 2(B)). There is temporal correspondence between years with high *CWEP* and years with more dust hours (e.g., 1968, 1977, 1980–81, 1987–88). Throughout the record, values showed similar decadal-scale levels, although there was a notable drop in *CWEP* between 1991 and 1996.

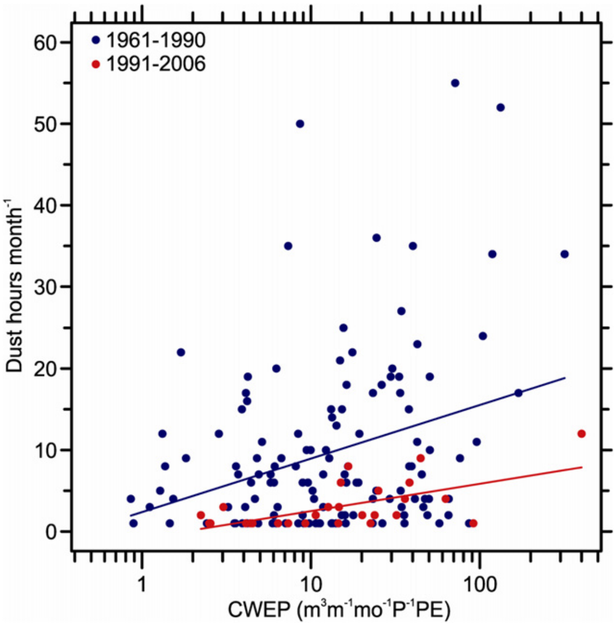

Figure 3. Duration of recorded dust per month versus climatic wind erosion potential (*CWEP*) for April and May in 1961–90 and 1991–2006 that had a minimum of 1 h of dust recorded. Lines represent regressions between dust duration and $\log_{10}$ (*CWEP*).

Farming practices changed substantially from 1976 to 2006 (figure 2(C)), albeit in a more gradual manner. Trends were consistent among all three provinces. The percentage of farms under summer fallow, whether by means of tillage or herbicide, declined substantially (∼40%) from 1976 (over 90% of Saskatchewan farms) to 2006 (fewer than 20% of Manitoban farms). Use of direct seeding in 1991 was approximately 10% of the area under cultivation, rising to over 60% in Saskatchewan in 2006.

To examine the potential role of *CWEP* in explaining dust frequency, we split the dataset at the sharp reduction of dust frequency in 1990 (figure 2(A)). We base this distinction on a visual assessment of a step reduction in dust frequency after 1990, which is supported by results of the homogeneity tests. Results in figure 3 show that the relation between the *CWEP* and dust frequency was poor prior to 1990 ($r^2 = 0.154$, $p < 0.001$), but improved following 1991 ($r^2 = 0.429$, $p < 0.001$) (figure 3). Figure 3 also shows that under a given climate forcing, the average expected response in dust frequency was higher on average during 1961–90 than 1991–2006.

4. Discussion and conclusions

The purpose of this study was to examine long-term trends in dust emissions on the Canadian Prairies and determine whether the efforts of soil conservation initiatives have had a measurable impact on downstream airborne dust frequency. Dust frequency before 1991 showed higher peaks and sustained clusters of dust observations (e.g., 1980s, figure 2(A)). Dust frequency post 1991 showed fewer hours of dust. In particular, the droughts of 2001–02 (Wheaton *et al* 2008) were not as dusty as in previous years despite erosive conditions. We attribute this to changes in farming practices, which have trended toward methods that reduce tillage and decrease soil erosion losses (figure 2(C)). This could be the result of numerous initiatives that promoted soil conservation techniques in the late 1980s (table 1).

Our study shows similar results to those by Todhunter and Cihacek (1999) and Stout and Lee (2003) whereby a reduction in observed dust was noted in the past couple decades and attributed to improved land management. However, we provide further evidence to support this by exploring systematic changes in farming practices with census data and establishing a changepoint in the dust series. We also differ in that we use a metric of climate forcing that synthesizes both wind power and aridity, both which can be related more directly to wind erosion potential.

Although changes in farming practices have occurred (figure 2(C)), it is difficult to attribute them directly and quantitatively to the soil conservation initiatives. For example, direct seeding is also promoted to preserve soil moisture in the early season. However, regardless of the rationale made by individual farmers, the techniques do have the overall effect of reducing soil erosion.

The closer correspondence between dust frequency and *CWEP* post 1990 (figure 3) suggests that climate now plays a larger role in determining wind erosion. From 1961 to 1990 it is likely that both poor land management and climate were responsible for airborne dust. This may be viewed as a heightened state of land susceptibility to wind erosion, whereby the magnitude of climate forcing required to initiate dust emission was lower than 1991–2006. However, with improved land management post 1990, only the most severe wind erosion conditions (dry and windy) resulted in measurable observations of dust. This suggests that farmers on the Canadian Prairies are better equipped to handle conditions with moderate climatic erosion forcing now than in the 1980s. However, results also show that it may be difficult to completely eliminate wind erosion; extreme droughts and/or windy periods will always result in some wind erosion as in the droughts of 2001–2, for example (Wheaton *et al* 2008).

Our interpretation is that the strong reduction of dust after 1990 represents a region-wide threshold crossing, whereby the progressive shift in soil conservation practices began effectuating a change in the dust frequency. From our analysis, *CWEP* does not appear to explain the step change. Indeed, there are other factors that could be involved, but in this environment, where wind erosion is naturally restricted by the presence of vegetation cover, the most important factor is whether the soil is exposed to wind by agricultural practices. Thus, any land-use activity that exposes soil will render the surface susceptible to wind erosion, and conversely, any land use that reduces this exposure should decrease dust frequency. We suggest that the landscape was close to the threshold crossing prior to 1990, but required greater effort in soil conservation to tip the scale in favor of reducing dust.

Similar to other studies (Wheaton and Chakravarti 1990, Todhunter and Cihacek 1999, Stout and Lee 2003), our study detail is constrained by data quality. Meteorological measurements are not ideal indicators of airborne dust.

Observations of visibility and meteorological conditions are performed with a variety of people and although concretely defined (Environment Canada 1961, 1977), there is room for variability in reporting. Dust events can be secondary to other weather and therefore can be missing from the record (see O'Loingsigh *et al* 2010). Additionally, meteorological measurements have poor spatial coverage and are likely to be influenced preferentially by dust sources directly upwind from the observation station. Census data describing direct seeding and summerfallow also lack the ability to fully describe all changes in land management that have reduced wind erosion. It is clear that better quality data are required to answer the questions posed in this study with finer spatial and temporal resolution. However, regardless of the limitations of the data, it is clear from our analysis that airborne dust has declined in the southern Canadian Prairies, beginning notably after 1990 (figure 2(A)), and that this decline is coincident with improved farming practices (figure 2(C)), which may signal the success of soil conservation initiatives (table 1), especially those initiated in the 1980s and thereafter.

Given the potential negative economic and health effects of wind erosion, a case for more detailed monitoring is easy to justify. Severe droughts and climatic wind erosion conditions equal to or exceeding those in the 'dust bowl' and 1980s have the potential to occur in the future. Data from our study suggest that improved farming techniques could reduce (but not eliminate) airborne dust in these events. Future studies and increased monitoring of dust frequency are required to further refine the controls of agriculturally derived airborne dust on the Canadian Prairies. Despite this, our synoptic study demonstrates that dust frequency has reduced and can be attributable to soil conservation.

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