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Key Points:
- Dust loading throughout the U.S. Great Plains has increased over the last two decades
- Positive correlations between cropland expansion and dust trends downwind suggest that agriculture contributed to these increases
- In the event of enhanced drought due to climate change, results support an increased risk of desertification from agricultural development

Supporting Information:
- Supporting Information S1

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Dust Impacts of Rapid Agricultural Expansion on the Great Plains

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Abstract Climate change and land use are altering the landscape of the U.S. Great Plains, producing increases in windblown dust. These increases are investigated by combining coarse mode aerosol observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor in addition to the Aerosol Robotic Network (AERONET) and Interagency Monitoring of Protected Visual Environments (IMPROVE) aerosol monitoring networks. Increasing trends of up to 5%/year in MODIS aerosol optical depth for dust observations are observed throughout the Great Plains (2000–2018). Cropland coverage has increased 5–10% over the majority of the Great Plains (2008–2018), and positive monthly trends in IMPROVE (1988–2018) and AERONET (1995–2018) coarse mode 90th percentile observations coincide with planting and harvesting seasons of predominant crops. Presently, results suggest increased dust due to agricultural expansion is negatively influencing human health and visibility in the Great Plains. Furthermore, results foreshadow a future where desertification becomes an increasing risk in the Great Plains.

Plain Language Summary Throughout the U.S. Great Plains, satellite data combined with surface networks have shown a significant increase in airborne dust over the last two decades. This airborne dust is negatively influencing human health and visibility and coincides with increases in agricultural production.

1. Introduction

In the 1930s, the U.S. Great Plains was ravaged by intense and widespread dust storms brought about through severe drought. The drought was driven by anomalous tropical sea surface temperatures (Schubert et al., 2004a, 2004b); however, its intensity and location can only be explained by considering land degradation via agricultural activity (Cook et al., 2009). In the 1920s, the invention of the mechanical plow allowed farmers to rapidly expand onto grasslands, converting previously stable soils to surfaces characterized by high drought risk and soil erosion susceptibility (McLeman et al., 2014). A rapid land degradation process followed, including crop failures during intense drought that left soils barren and exposed. This combination of poor agricultural practices and widespread drought resulted in dust storms that literally and figuratively darkened the lives of those already living in the economic darkness of the Great Depression.

Agricultural practices have improved greatly since the 1930s (McLeman et al., 2014), resulting in a Great Plains environment and economy much more resistant to occasional drought. However, rapid agricultural expansion, spurred by the biofuel boom in the late 2000s, is once again replacing soil-stabilizing grasslands with drought-sensitive crops (Hendricks & Er, 2018; Lark et al., 2015). Between 2006 and 2011, 530,000 ha of grassland was lost to new cropland in North Dakota, South Dakota, Nebraska, Minnesota, and Iowa (Wright & Wimberly, 2013). Furthermore, the most rapid expansion is within marginal lands, or lands characterized by high drought sensitivity and susceptibility to soil erosion (Lark et al., 2015).

Meanwhile, drought duration and severity increased during the twentieth century in the U.S. southwest, South, and southern Great Plains (Andreadis & Lettenmaier, 2006). These changes in hydroclimate threaten to increase aerosol loading in these regions. Looking to the future, climate model estimates of drought risk for the Great Plains suffer from substantial uncertainty (Hoegh-Guldberg et al., 2018). Recent Coupled

Model Intercomparison Project Phase 5 (CMIP5) simulations project a 50% to 200% increase in summertime drought risk in the Great Plains in response to a warming of 1°C to 4°C (Swain & Hayhoe, 2015). This combination of drought vulnerability and agricultural expansion could drive the Great Plains into another Dust Bowl situation (Wright, 2015).

Even marginal increases in dust due to agricultural expansion have societal, environmental, climatic, and human health effects. Dust, among other aerosols, interacts directly with solar and terrestrial radiation and indirectly through its role as ice nuclei and cloud condensation nuclei (Houghton, 1996), contributing to a large source of uncertainty in radiative forcing estimates (Stocker et al., 2013). Upon deposition, dust decreases the albedo of snow and contributes to faster and earlier snow melt, affecting hydrologic resource availability (Painter et al., 2007, 2010). Additionally, dust acts as a carrier of soil nutrients, removing nutrients through soil wind erosion (Duniway et al., 2019; McTainsh & Strong, 2007) and enriching other soils upon deposition (Reynolds et al., 2001; Swap et al., 1992). Cases of high dust loading, or dust events, are associated with increased doctor and emergency room visits related to respiratory complications (Hefflin et al., 1994; Miri et al., 2008) as well as other illnesses, such as the valley fever experienced in the southwestern United States (Tong et al., 2017) and meningococcal meningitis (Goudie, 2014). During dust events visibility is reduced, potentially creating dangerous road conditions (Ashley et al., 2014) and once compromising efforts to comply with the Environmental Protection Agency's (EPA) Regional Haze Rule (RHR) (US EPA, 2015), which seeks to improve visibility in national park and wilderness regions (Kavouras et al., 2009). EPA's updated 2017 RHR guidance characterizes most dust as natural aerosol (Gantt et al., 2018); however, anthropogenic dust can still be an important contributor to visibility degradation on the most anthropogenically impaired days.

This study investigates how dust loading has changed in the U.S. Great Plains over the last two to three decades and how agricultural expansion influenced the dust loading. The results are paramount to understanding the risk that recent increased agricultural activity poses to the region. Given the uncertainty in future drought estimates, it behooves scientists and lawmakers to understand the region's trajectory relative to the 1930s Dust Bowl in order to properly mitigate risks of a repeat in the future.

Trends in dust loading are investigated in the U.S. Great Plains states of North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, and Missouri, where agricultural expansion is prevalent (Lark et al., 2015). Aerosol optical depth (AOD) observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite are analyzed to provide spatial coverage. Observations are also analyzed from two ground-based networks: Interagency Monitoring of Protected Visual Environments (IMPROVE), which provides in situ measurements of coarse and fine particulate matter (PM) mass and aerosol speciation, and the Aerosol Robotic Network (AERONET), which provides column measurements of AOD and a coarse mode data product.

2. Materials and Methods

2.1. Data Collection

MODIS AOD observations were obtained from the Collection 6.1 MOD08 (Terra) Level 3 global atmosphere product containing gridded 1° by 1° daily averages of AOD over land derived using the dark target (DT) over land algorithm for bands centered at 470, 550, and 660 nm (Levy et al., 2013). Validation of this product against AERONET AOD is found in Wei et al. (2019). Results in this study are based on measurements of AOD at 550 nm. Measurements are available dating back to 2000, and temporal resolution is roughly 2 days depending on latitude. An Ångström exponent (AE) threshold of <0.75 was sufficient to remove the U.S. northwest wildfire signal for MODIS AOD observations and produce a seasonal cycle of observations with peaks in the spring for much of the northwest United States and northern Great Plains and in the summer for the southern Great Plains and southwest United States (see supporting information Figure S1), consistent with previous literature on regional (Hallar et al., 2015; Hand et al., 2017; Pu & Ginoux, 2017) and Asian (Chin et al., 2007; Fischer et al., 2009) dust in the United States. Furthermore, AE thresholds as low as 0.9, 0.5, and 0.3 have been shown to separate dust from finer aerosol types (Eck et al., 1999; Gautam et al., 2009; Moulin et al., 1997; Pinker et al., 2001). Thus, observations with AE below 0.75 were assumed to reasonably represent coarse mode aerosol and are termed AOD_{dust} in this paper.

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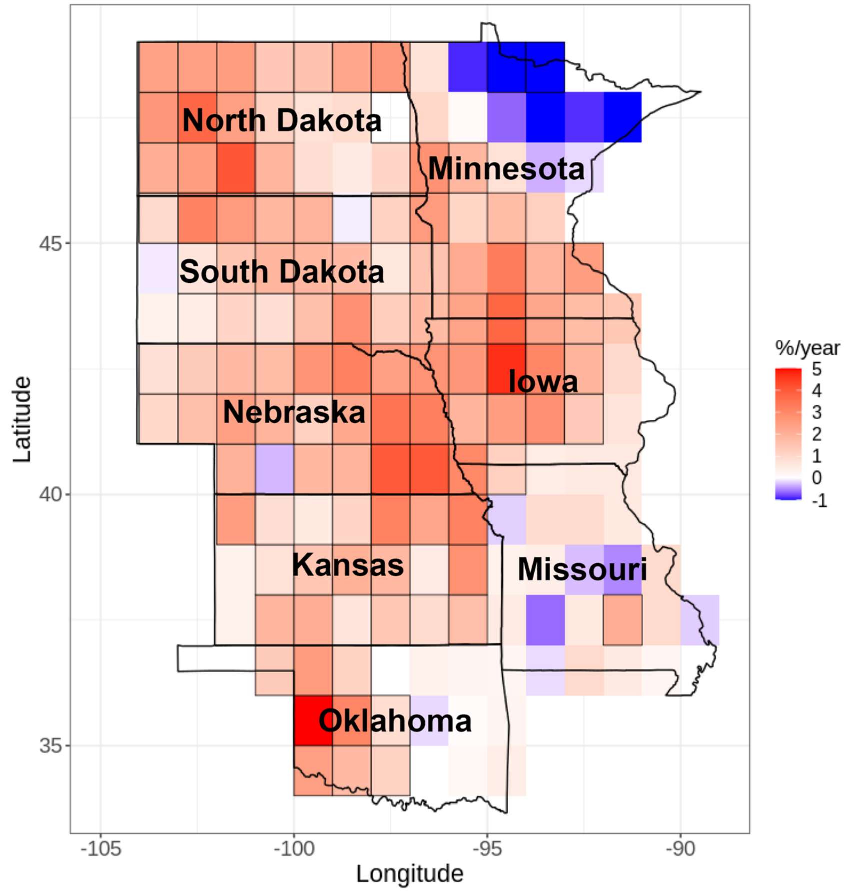

Figure 1. Trends in all MODIS AOD_{dust} observations at 550 nm for 2000–2018 in the U.S. Great Plains. Percent change is based on the median AOD_{dust} for each tile. Outlined tiles indicate statistical significance ($p < 0.05$).

AERONET's version 3 product provided the ground-based AOD measurements used in this study. The network deploys Cimel Electronique CE318 Sun photometers at four sites in the U.S. Great Plains states with at least 10 years of data and three of those sites with at least 15 years of data. For analysis, it is verified that each site made at least one observation per day on average for every year containing observations. AOD measurements are available every 3 or 15 min (during clear sky, daytime periods) depending on instrument model, so a 15 min average was applied to maintain consistent temporal resolution across sites. AERONET measures sky radiances and Sun irradiance between 340 and 1,640 nm; however, only results using the 500 nm band for AOD are shown in this paper. Lastly, to isolate the dust signal, we used the coarse mode AOD (AOD_{coarse}) parameter produced through the Spectral Deconvolution Algorithm, which takes advantage of the assumed bimodal nature of the aerosol size distribution by using differing curvature of measured aerosol optical properties to separate fine and coarse AOD components. These observations begin in 1994 at the Cart Site in Oklahoma and between 2000 and 2004 for the other three sites. Of the four, two sites are still providing a coarse mode product in 2018.

The IMPROVE network provides in situ aerosol measurements of total and speciated $PM_{2.5}$ (particulate matter smaller than 2.5 μm) and total PM_{10} (particulate matter smaller than 10 μm). Every third day, 24-hr aerosol filters are collected, lending to a 3 day temporal resolution. IMPROVE has 23 sites within the study region with at least 7 years of data, 5 with at least 10 years, and 15 with at least 15 years of data. For analysis, it is verified that each site made at least half of the total annual possible number of observations (60 observations) for every year containing observations. IMPROVE's $PM_{10-2.5}$ parameter, which is the difference between PM_{10} and $PM_{2.5}$ measurements, was used to analyze changes in dust, given that soil is the largest contributor to $PM_{10-2.5}$ in the majority of the United States (Malm et al., 2007). Five IMPROVE sites in the study region begin making coarse mode observations prior to 2000, 17 others begin before 2003, while the Stilwell site in

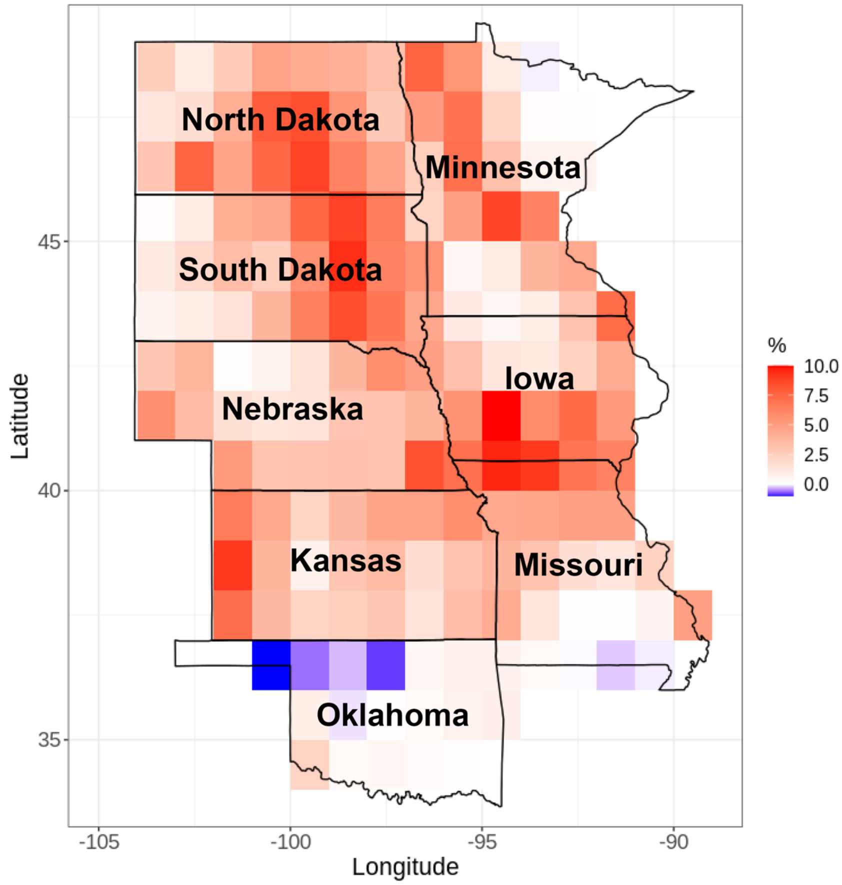

Figure 2. Percent change in cropland coverage as classified in CDL between 2008 and 2018.

Oklahoma did not begin measurements until 2010. Of the 23 sites, 16 sites are still making coarse mode measurements in 2018, 4 ended in 2015, and 3 others ended between 2008 and 2011.

Lastly, cropland changes were analyzed using U.S. Department of Agriculture's Cropland Data Layer (CDL), which employs satellite imagery to classify cropland annually at 30 m resolution and covers the years 2008 through 2018 for the conterminous United States. A technique similar to that used by Lark et al. (2015) (Lark et al., 2015) was used, where all crop features were reclassified as “crop” and all noncrop features were classified as “noncrop.” Changes from crop to noncrop or vice versa were quantified over the full record of available data, producing a percent change in cropland coverage (2000–2018) at a reduced spatial resolution to match the MODIS 1 by 1° grid.

2.2. Trend and Correlation Analysis

Due to the intermittent nature of dust emissions that would be expected from agricultural sources, quantile regression is applied to the 90th percentile of AERONET and IMPROVE coarse mode observations in addition to trend analysis for the full data set. Quantile regression follows the Barrodale and Roberts algorithm described in Koenker and d'Orey (1987, 1994), while trend analysis for the full data set applies the nonparametric Theil-Sen Estimator method (Sen, 1968; Theil, 1992). For quantile regression, two-tailed p values and confidence intervals were obtained through the *xy* pair bootstrap method based on Parzen et al. (1994). For the full data set trend analysis, the p value was based on Kendall's tau, which can be interpreted similarly to the correlation coefficient (Kendall, 1938), while confidence intervals were calculated using Gilbert's method (Gilbert, 1987) applied to the slopes defining each possible pair of points. Spatially lagged correlations between total cropland changes and MODIS AOD_{dust} trends were tested for statistical significance using a parametric t test assuming one degree of freedom per year, and associated p values are indicated in Figure 3. As noted in the Figure 3 caption, spatial lag indicates the displacement of AOD_{dust} trends relative to the cropland change locations.

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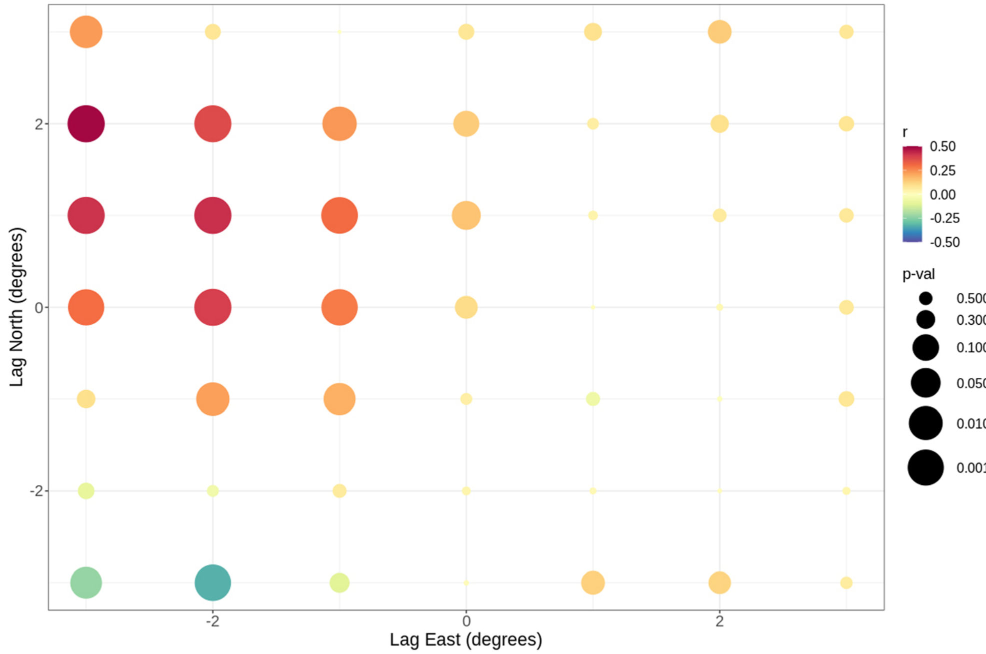

Figure 3. Lag correlation coefficients between MODIS AOD_{dust} trends (2000–2018) and CDL cropland change (2008–2018) at a range of spatial lags, where the lag indicates the spatial displacement of the AOD_{dust} trend relative to the cropland change. The size of the circle is inversely proportional to the *p* value.

3. Results

MODIS AOD_{dust} represents AOD for observations with AE less than 0.75, which serves as a proxy for dust observations as justified in section 2. Trend analyses on AOD_{dust}, using the Theil-Sen estimator method (Sen, 1968), reveal a 3–5% increase per year (2000–2018), relative to the median for each 1° × 1° MODIS grid box, over the majority of the Great Plains (Figure 1). Considering these increases over the full time period, a 5% increase per year in AOD_{dust} results in a ~100% change for parts of this region. Nearly all portions of Great Plains states experienced increases in AOD_{dust} during this time period with the exception of eastern Oklahoma, Missouri, and northeastern Minnesota. Increases are most prominent in Iowa, eastern Nebraska, and western North Dakota.

Given that cropland expansion, a known dust source (Li et al., 2013), has increased rapidly in recent years (Lark et al., 2015; Wright, 2015; Wright & Wimberly, 2013), changes in cropland are examined alongside these trend analysis results via the CDL, which classifies cropland for the conterminous United States from 2008–2018. Between 2008 and 2018, cropland coverage increased in nearly all parts of the Great Plains north of 37°N (Figure 2). Some portions saw increases upward of 7.5–10% per year (Figure 2). Again, northeastern Minnesota and portions of Missouri experienced smaller changes and even losses in cropland coverage, spatially consistent with the AOD_{dust} trends in Figure 1. Oklahoma showed between no change to decreases in cropland coverage, inconsistent with increased AOD_{dust} observed in the western portion of the state, potentially a result of increases in oil and gas development in the area. To further investigate how these dust and agriculture trends are related and to consider the role of atmospheric dust transport, the AOD_{dust} trends and cropland coverage change results were spatially correlated over a range of spatial lags (Figure 3). The CDL results cover 2008–2018 (whereas MODIS AOD_{dust} trends cover 2000–2018) and represent a subset of a longer, documented increasing trend in agriculture for the Great Plains (Hicke & Lobell, 2004; Mueller et al., 2016), accelerated further by the biofuel boom beginning in the mid-2000s (Tyner, 2008). The strongest and most statistically significant correlations are found 2° to the west and 1° to the north. This suggests that cropland expansion is contributing to dust loading increases to the northwest of the dust source. These results are somewhat consistent with wind speed and direction climatologies from stations in the Great Plains (Figures S2 and S3). For the majority of these stations, wind

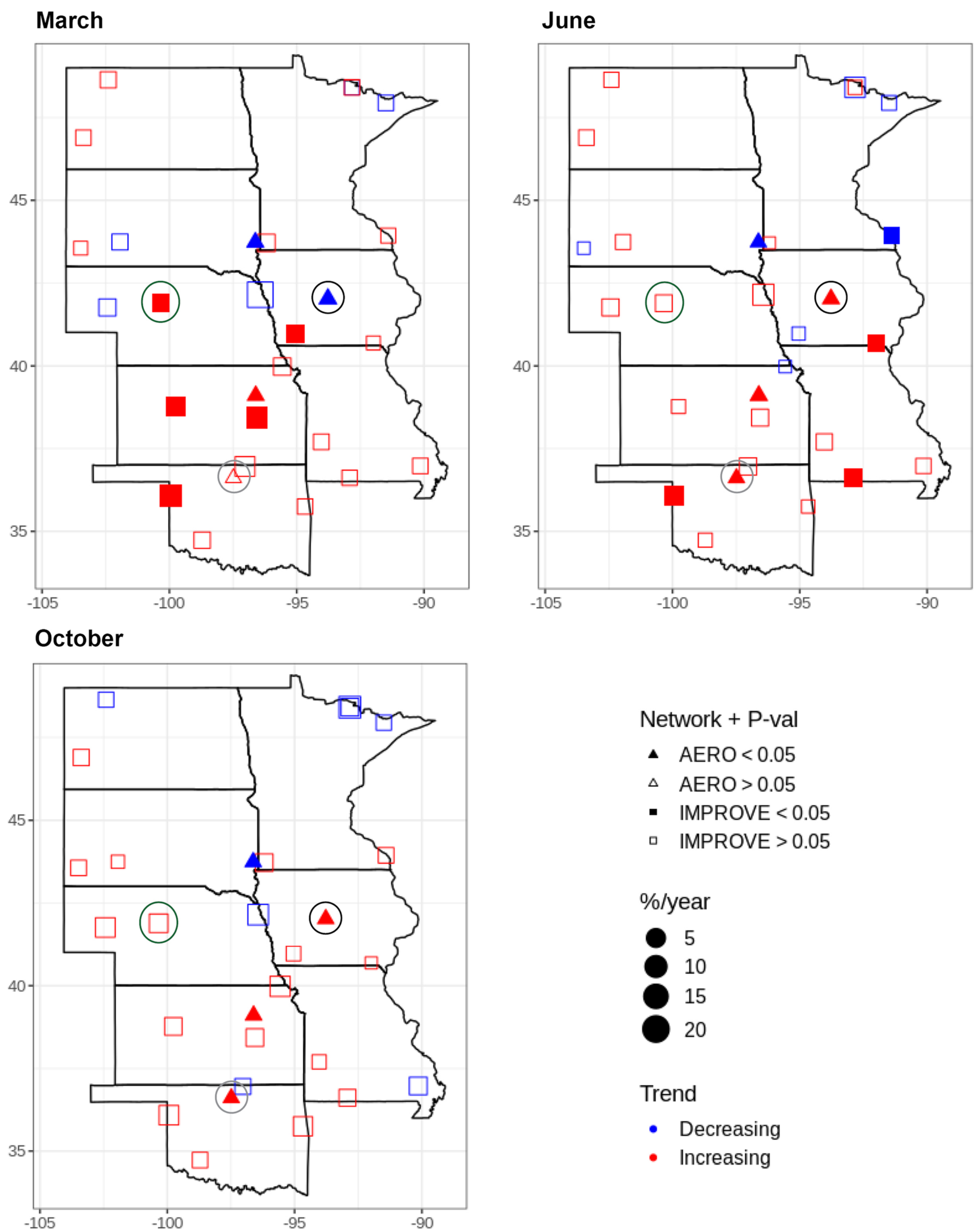

Figure 4. Monthly trends in 90th percentile AERONET AOD_{coarse} (1995–2018) and IMPROVE $PM_{10-2.5}$ (1988–2018) for March, June, and October (left to right). Filled shapes indicate statistical significance (*p* value <0.05).

observations above 5.5 m/s (a midrange windspeed for surface dust emissions) are southerly most of the time. Winds with a southeasterly component also make up the second or third most frequently observed wind direction at the majority of Great Plains stations. Seasonally, southerly winds for moderate to strong wind events (>5.5 m/s) are most frequent in the summer, while the easterly component is featured most frequently in the spring. These seasonal peaks in wind direction frequencies occur during corn and soy planting seasons as well as the growing seasons for most crops in the region. Furthermore, these wind climatologies are consistent with the lagged correlations in Figure 3.

Monthly trends in the 90th percentile for surface-based coarse mode (IMPROVE $PM_{10-2.5}$ and AERONET AOD_{coarse}) aerosol observations both at the surface and in the column show that positive trends are mainly observed during months associated with planting and harvesting seasons of the predominate crops in the region (Figure 4). Soybean harvest in particular leads to dusty conditions because they are left to dry to about 14% moisture content before harvesting (Roy & Thorne, 2003). Clearing for corn planting typically occurs in March, soybean planting in June, and corn and soybean harvest, in addition to winter wheat planting, typically occur in October (USDA-NASS, 1997, 2020). During these three months, positive trends, often ranging from 10–15%, are observed in the coarse mode particularly in the southern Great Plains. For example, the Ames AERONET site in Iowa (indicated by black circle) is an interesting case study in that its trend is negative in March and positive in June and October. An explanation lies in the crop type in this region. In their analysis of cropland expansion between 2008 and 2012, Lark et al. (2015) found that soybeans were the predominant breakout crop, or the crop type that expanded most substantially during the time period, in Iowa. Since soybean crops are planted and harvested in June and October, respectively, it would follow that a positive trend signal would appear during those months, rather than in March. Additionally, the AERONET Cart site (indicated by gray circle) in Oklahoma observes statistically significant positive trends in June and October, with lower statistical significance produced for the trend in March. This is perhaps explained by winter wheat, the predominant breakout crop from northern Texas through Oklahoma and Kansas (Lark et al., 2015), which has its planting and harvesting seasons around October and June, respectively. Lastly, the IMPROVE site located in Nebraska National Forest (indicated by green circle), observes a highly statistically significant positive trend in March, with lower statistical significance in June and October. Corn was the predominant breakout crop in Nebraska from 2008–2012 (Lark et al., 2015) and may correspond to the strong March signal at this Nebraska site with surface clearing for corn planting beginning around March (Wardlow & Egbert, 2008).

Alternate land use changes should also be considered when interpreting the results of this study, such as oil and gas development, which is a prominent feature in western North Dakota and Oklahoma. For example, in North Dakota, recent energy development is associated with increased $PM_{10-2.5}$ emissions (Gebhart et al., 2018). Oil and gas development in western North Dakota may explain higher observed statistical significance of positive AOD_{dust} trends in the area. In Oklahoma, where cropland expansion is not observed, increases in dust may also be influenced by oil and gas development throughout the state. Among AERONET sites, Oklahoma's Cart site exhibits the smallest variance in monthly trends. Among IMPROVE sites, the smallest variance occurs for sites in North Dakota. These relatively small variances in monthly trends may be partially explained by more consistent dust emissions from oil and gas development in those states in comparison to more seasonal emissions due to crop planting and harvesting.

4. Conclusions and Discussion

This study identifies dust loading trends in the Great Plains region over the recent decades to elucidate the influence of cropland expansion on those trends. Trend analysis of MODIS AOD_{dust}, or AOD for observations with AE < 0.75, and coarse mode AERONET AOD and IMPROVE PM observations reveals spatially consistent increases of 5% per year across the Great Plains (2000–2018). At the same time, agriculture has expanded rapidly over the last decade with cropland surface coverage increasing by 5–10% in portions of the Great Plains states and a large portion of expansion occurring on lands previously classified as unsuitable for cultivation (Lark et al., 2015). These cropland increases are spatially correlated with MODIS AOD_{dust} trends measured to the west northwest (Figure 3). Furthermore, positive monthly trends in 90th percentile AERONET AOD_{coarse} and IMPROVE $PM_{10-2.5}$ coincide with planting and harvesting seasons for predominate crops in the area. These results depict an increasingly dusty Great Plains via direct contribution from agriculture downwind to the west northwest.

These results foreshadow a future where desertification becomes an increasing risk in the Great Plains in the event of increased drought severity or frequency due to climate change. This risk has economic and human health impacts, just as with the 1930s Dust Bowl. Dust's human health effects include meningococcal meningitis (Goudie, 2014), Valley fever (Tong et al., 2017), and a variety of respiratory and cardiovascular illnesses

(Host et al., 2008; Hefflin et al., 1994; Miri et al., 2008). An increase in dust emissions, and therefore increased human exposure to emissions, may enhance the potency and frequency of these human health impacts. For example, under Representative Concentration Pathways 8.5 (RCP8.5) for 22 climate models, fine dust in the Southwest, which includes the southern Great Plains, is expected to increase by 0.22–0.43 $\mu g\ m^{-3}$, contributing to a 300% increase in annual hospitalizations due to cardiovascular and respiratory illnesses in 2076–2095 relative to 1996–2015 (Achakulwisut et al., 2018). Additional contributions of dust emissions from unrestrained agricultural expansion would further exacerbate any dust-induced health effects related to climate change.

While this paper focuses on the influence of land use change on dust loading in the Great Plains, other variables can contribute to dust emissions, including wind speed, precipitation, and soil moisture. In fact, recent research found that IMPROVE fine dust concentrations in the Great Plains from 1990–2015 were largely explained by surface and atmospheric stability (Pu & Ginoux, 2018). As another consideration, the Palmer Drought Severity Index (PDSI) for the Great Plains reveals high year-to-year variability in drought characteristics between 2000 and 2018 (NOAA NCEI, 2020). The influence of wet and dry episodes on dust loading should be investigated in future work. Furthermore, longer-term perturbations such as extended periods of anomalous sea surface temperatures related to the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) have been shown to play a significant role in multiyear droughts and wet periods in the Great Plains, including the 1930s Dust Bowl (Cook et al., 2009; Nigam et al., 2011). The AMO has been in the warm phase since the mid-1990s (Trenberth et al., 2019), which is typically associated with drought in the Great Plains and may have influenced trends identified in this study. An analysis that considers decadal and multidecadal oscillations, in addition to other meteorological and climatological characteristics, should be considered in future work focused on understanding the extent which land use change influences dust loading in the Great Plains. In light of recent research that suggests an increasing tendency toward megadroughts and greater decadal precipitation swings due to anthropogenic warming (Williams et al., 2020), this is especially relevant. These drought tendencies elucidate the need for improved agricultural practices aimed at minimizing risk of a new Dust Bowl in the Great Plains.

Solutions to avoid desertification and health risks discussed thus far exist in the form of agricultural and biofuel policy changes. For example, the Renewable Fuels Standard (RFS2), which is intended to limit the conversion of land to feedstock for renewable biofuels, has lacked enforcement as this form of land conversion has largely gone unrestricted (Lark et al., 2015). This presents an opportunity to reform enforcement strategies and improve record keeping to increase the efficacy of RFS2 and other similar preexisting policies (Lark et al., 2015; Wright et al., 2017). Lark et al. (2015) also point to the “Sodsaver” provision in the 2014 U.S. Farm Bill, which seeks to deincentivize grassland to cropland conversion by reducing crop insurance subsidies on these lands in Montana, Nebraska, Iowa, Minnesota, and the Dakotas. However, these six states only represent 36% of grassland to cropland conversion at this time, and the provision does not cover conversion from other ecosystems such as forests. In this case, Lark et al. suggest a more comprehensive and nationwide provision would enhance preservation of grasslands and other natural ecosystems, thereby keeping soils undisturbed and less susceptible to soil erosion. The Conservation Reserve Program (CRP), a U.S. land retirement program, also presents an opportunity for potentially mitigating environmental policy reform. Between 2010 and 2013, across 12 midwestern states, roughly 360,000 ha of CRP grassland were converted back to cropland (Morefield et al., 2016). Increased restrictions on amount and type of CRP land available for cropland conversion may help to secure soils in the Great Plains. Globally, many researchers point to climate-smart agriculture and sustainable land management practices that could prevent and mitigate desertification (Smith et al., 2020), particularly in the case of drought and precipitation changes due to climate change. Among the most effective strategies are crop diversification and improved water management through water harvesting and reducing runoff (Schwilch et al., 2014). However, these are just two examples among a wide-ranging collection of agricultural practices aimed at desertification mitigation solutions. Action and participation from all forms of stakeholders, including farmers, researchers, legislators, and concerned citizens, is required for proper design and implementation of the strategies mentioned above (Lipper et al., 2014).

These results also demonstrate the importance of expanding measurements in sensitive and rapidly changing landscapes. Aerosol monitoring systems are lacking in spatial coverage in the Great Plains states relative to the rest of the United States. Only 23 IMPROVE sites and four AERONET sites have seven or more years of coarse mode observations within the study region. Spatial density of monitoring sites is much higher elsewhere in the United States. Expansion of monitoring in these and other existing networks would provide evidence and data to inform current and future policy decisions regarding agricultural activity. In addition to increased aerosol monitoring observations, modeling land use changes, like agriculture, and their influence on dust loading in the future has the potential to contribute greatly to effectual policy and legislative responses to threats of drought and desertification due to climate change. While results of future land use change impacts on dust loading exist in the literature, such as the projected influence of deforestation on dust in Amazonia (Betts et al., 2008), modeling efforts regarding dust in the Great Plains region and agricultural land use change are currently absent.

Data Availability Statement

Ground-based AOD measurements were obtained from AERONET (at https://aeronet.gsfc.nasa.gov/). Ground-based in situ measurements are available through IMPROVE (at http://views.cira.colostate.edu/fed/QueryWizard/Default.aspx). Users will need to register for an account to access the data. MOD08_D3 data are available for bulk download (at https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/61/MOD08_D3/?process=ftpAsHttp&path=allData%2f61%2fMOD08_D3), and the national CDL product can be found online (at https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php).

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