Dust in the Great Plains and Northern Rockies: Trends and Influences from Land Use

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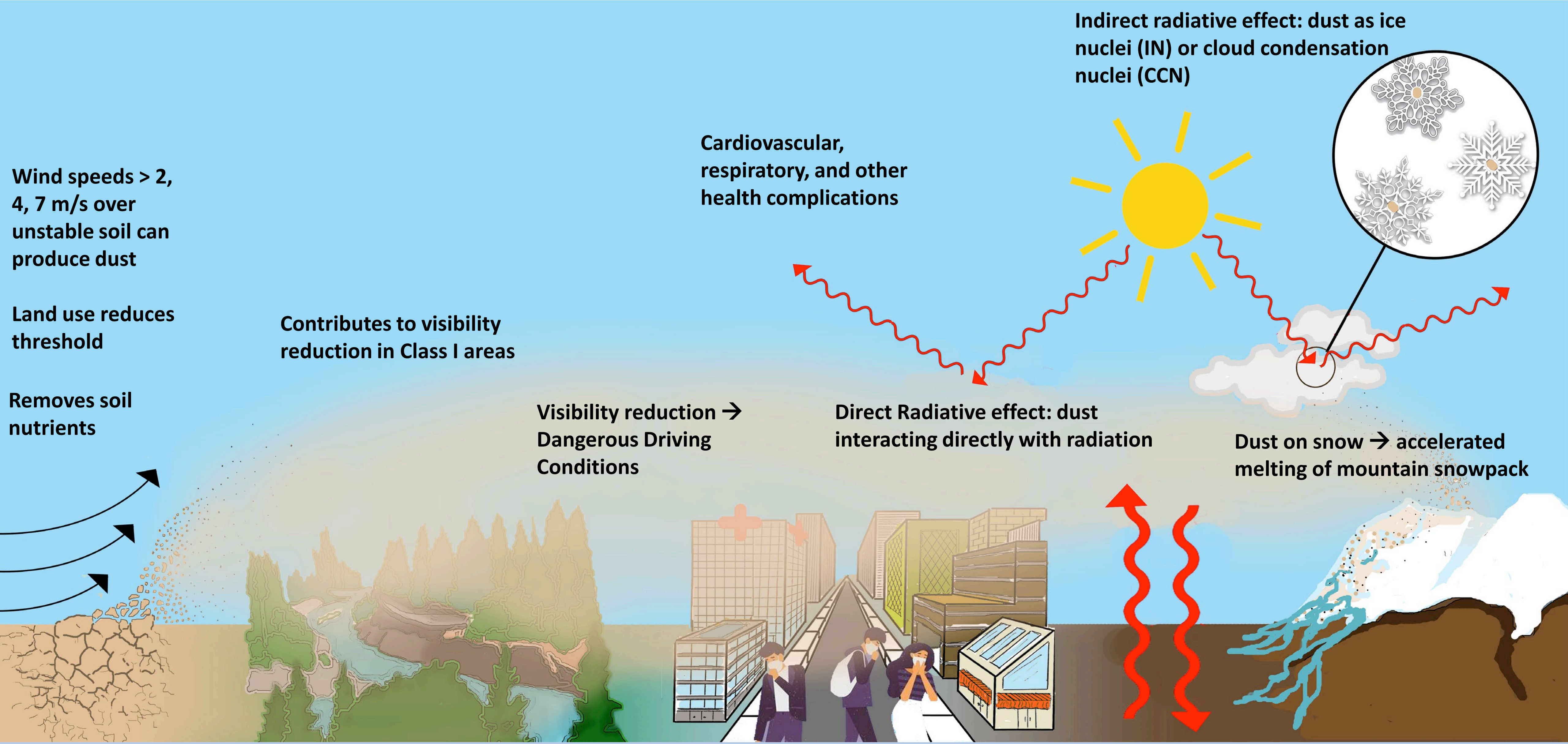
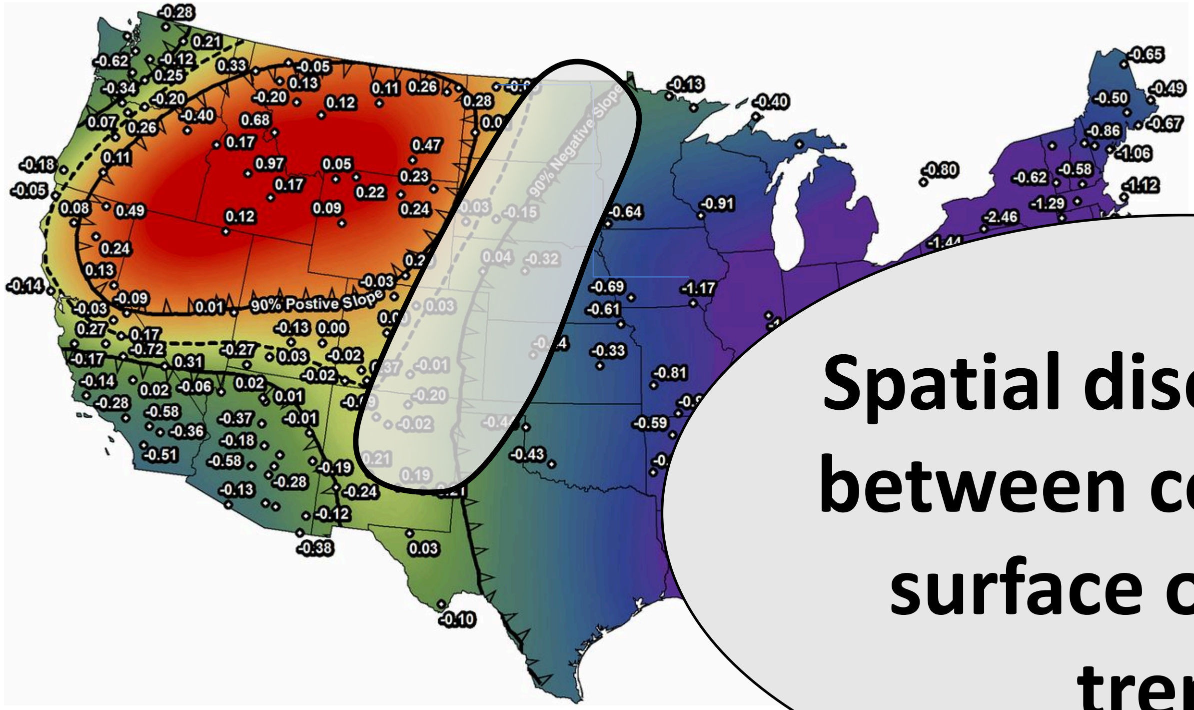
Introduction

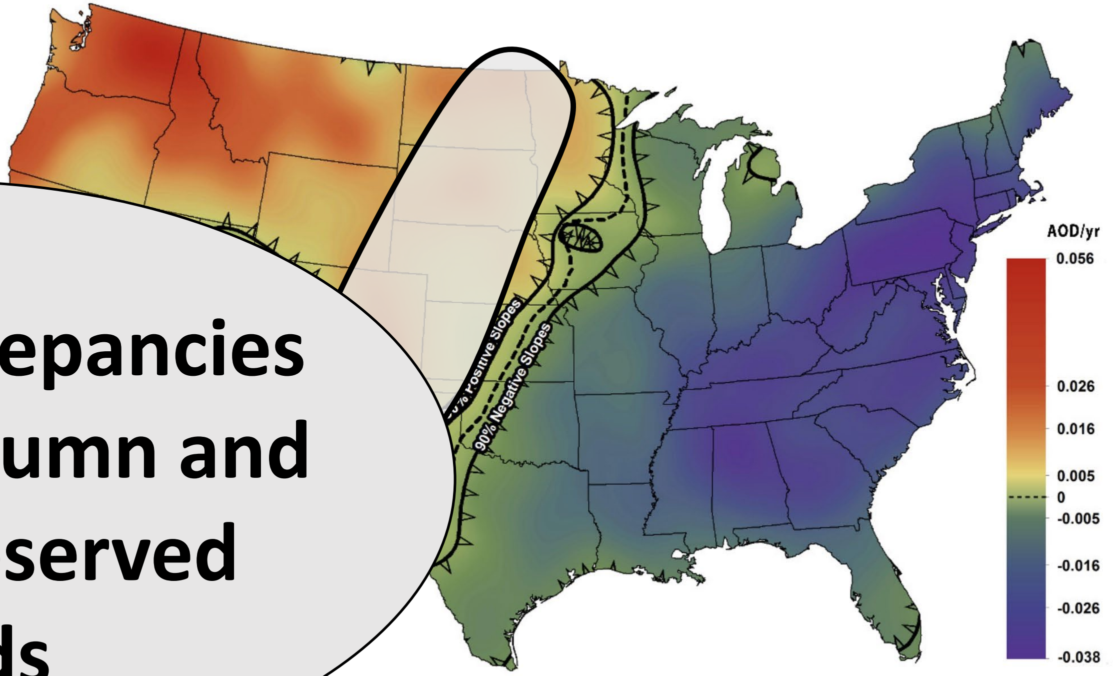


Credit: T. Lambert

98th Percentile Trends in the U.S.



Spatial discrepancies between column and surface observed trends

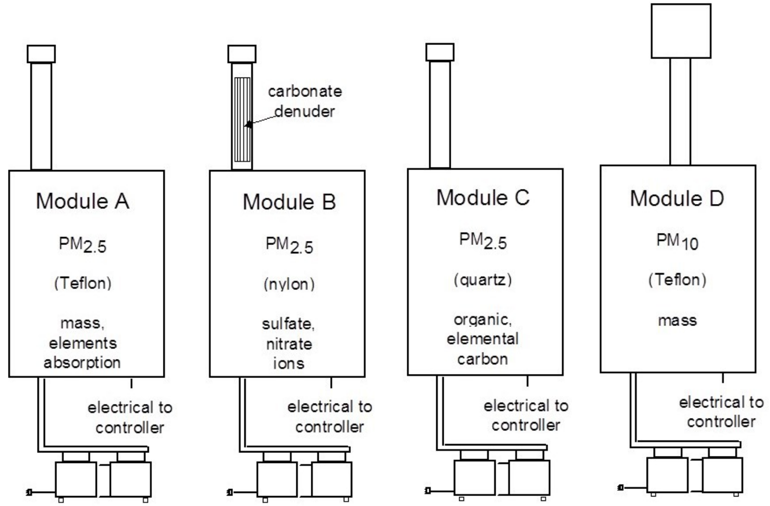


98th percentile $PM_{2.5}$ regression from IMPROVE 1988-2016

98th percentile AOD regression from MODIS AQUA 2002-2017

McClure and Jaffe (2018)

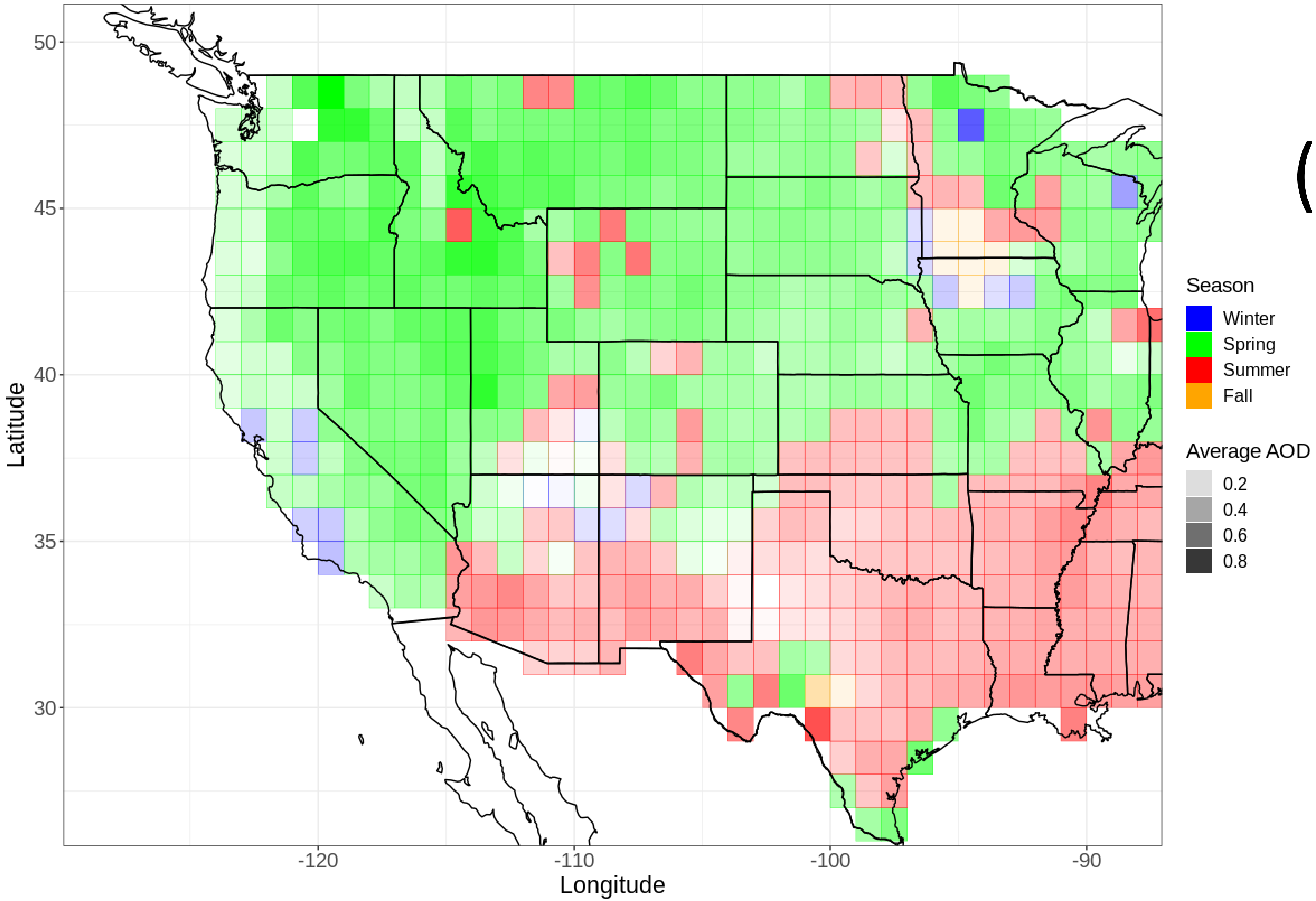
Ground-Based Observations



- Interagency Monitoring of Protected Visual Environments (IMPROVE)
  - 24-hour aerosol samples every three days
  - Speciation and mass measurements of $PM_{2.5}$ and mass measurements of PM_{10}
  - Analyzing dust: $PM_{10\text{-}2.5}$

- Aerosol Robotic Network (AERONET)
  - Cimel sun photometers
  - Measurements every 3 or 15 minutes (model dependent)
  - Spectral Deconvolution Algorithm → fine and coarse AOD
  - Analyzing dust: AOD_{coarse}

MODIS: AOD_{dust} (2000-2018)



- AOD_{dust} - observations when Ångström exponent (AE) < 0.75
- Color represents season when maximum average AOD_{dust} occurs
- Shading indicates magnitude of average annual AOD_{dust}

Analysis and Limitations

- Data is non-parametric – using Sen's slope to get regression coefficient
- Quantile regression applied to IMPROVE and AERONET data (0.9^{th} quantile)

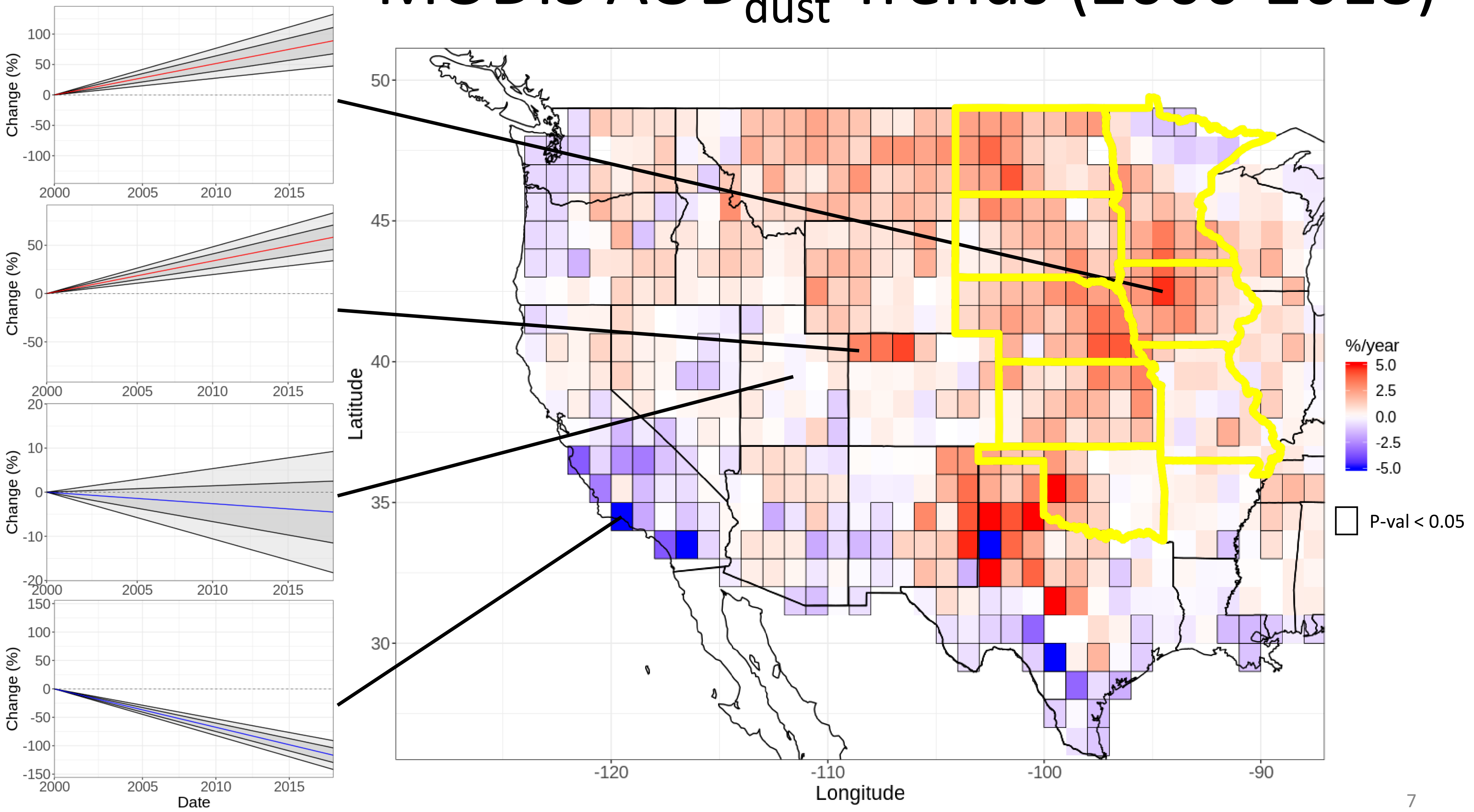
- Data from IMPROVE and AERONET vary in temporal coverage between networks and from site to site

- Temporal resolution is different between datasets: AERONET (15 min), IMPROVE (3 days), MODIS (~2 days)

- Meteorology, hydrology, and climate have important influences on soil stability and dust emissions which are not fully considered here

Trend Analysis

MODIS AOD_{dust} Trends (2000-2018)

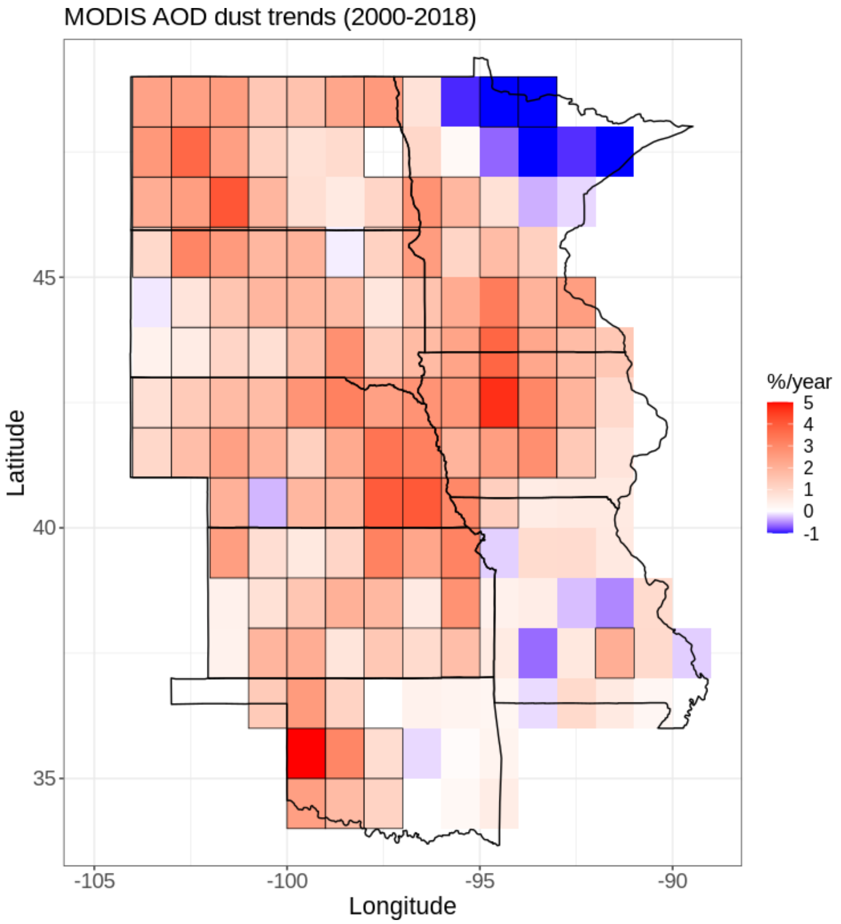


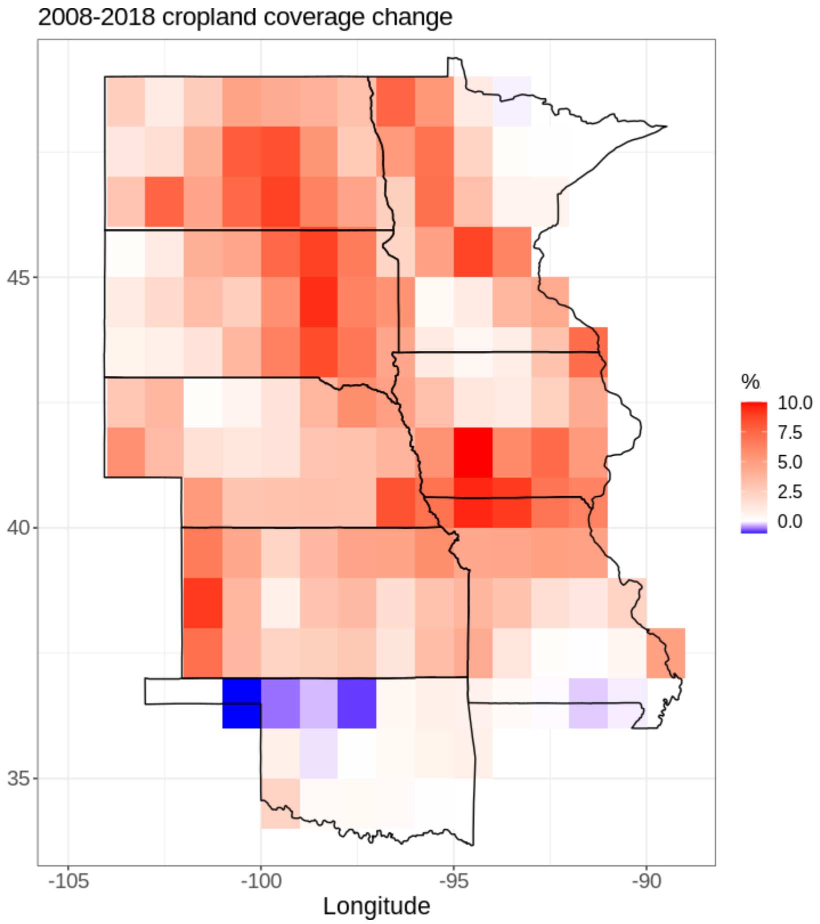
Land Use Change - Agriculture

http://insideenergy.org/2015/05/27/more-money-fewer-grasslands-corn-ethanols-impact-on-rural-america/

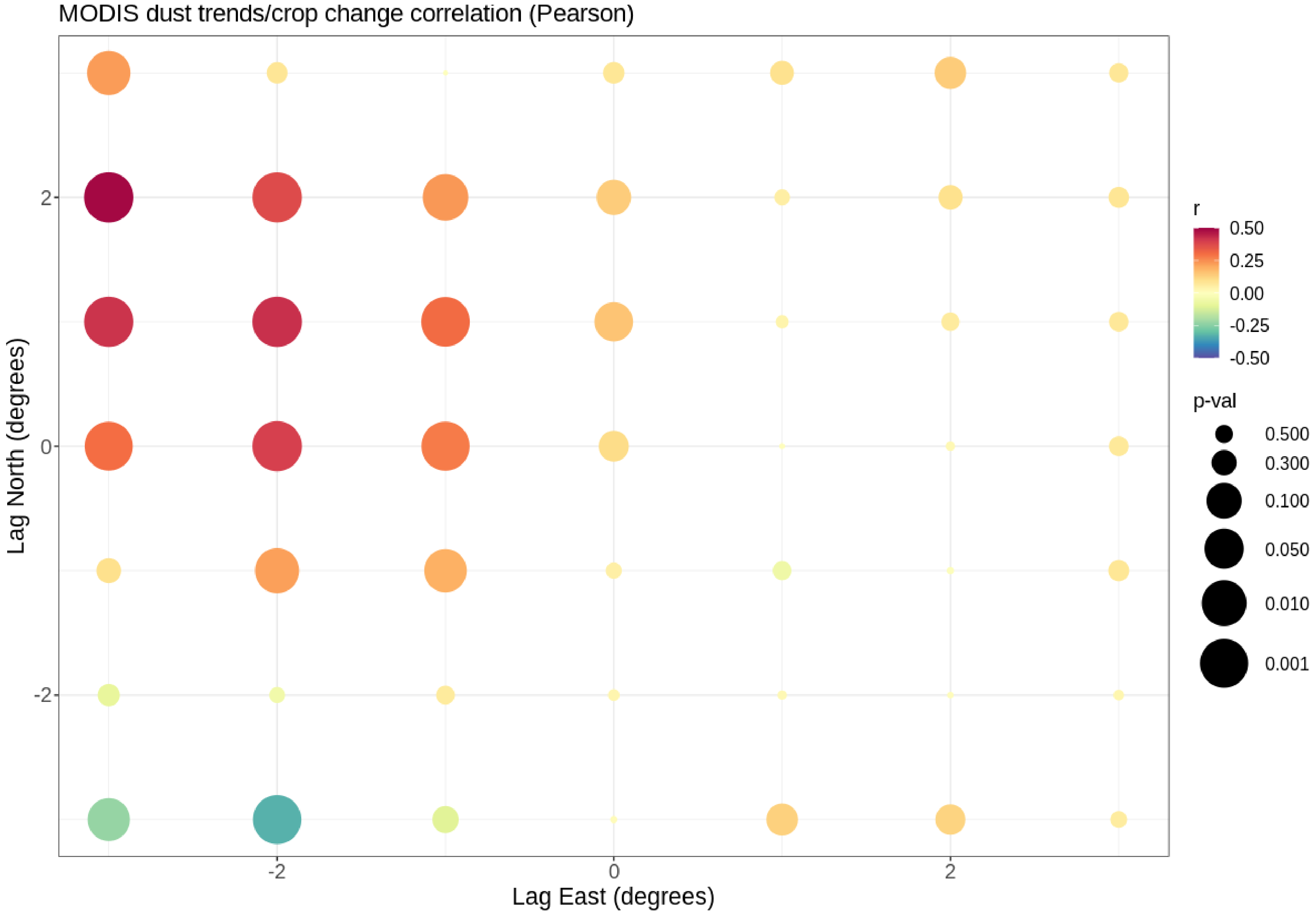
- Rapid grassland to cropland conversion in the Great Plains spurred by biofuel boom (late 2000s) (e.g. Lark et al., 2015; Wright, 2015)
- 530,000 ha decline in grassland in ND, SD, NE, MN, IA (2006-2011) (Wright and Wimberly, 2013)
- Desertification - Human land degradation contributed to dust storms and amplified drought during 1930s Dust Bowl (Cook et al., 2009)
- Employed the Cropland Data Layer – cropland classification product from USDA

MODIS AOD$_{dust}$ Trends/Cropland Change





Agriculture

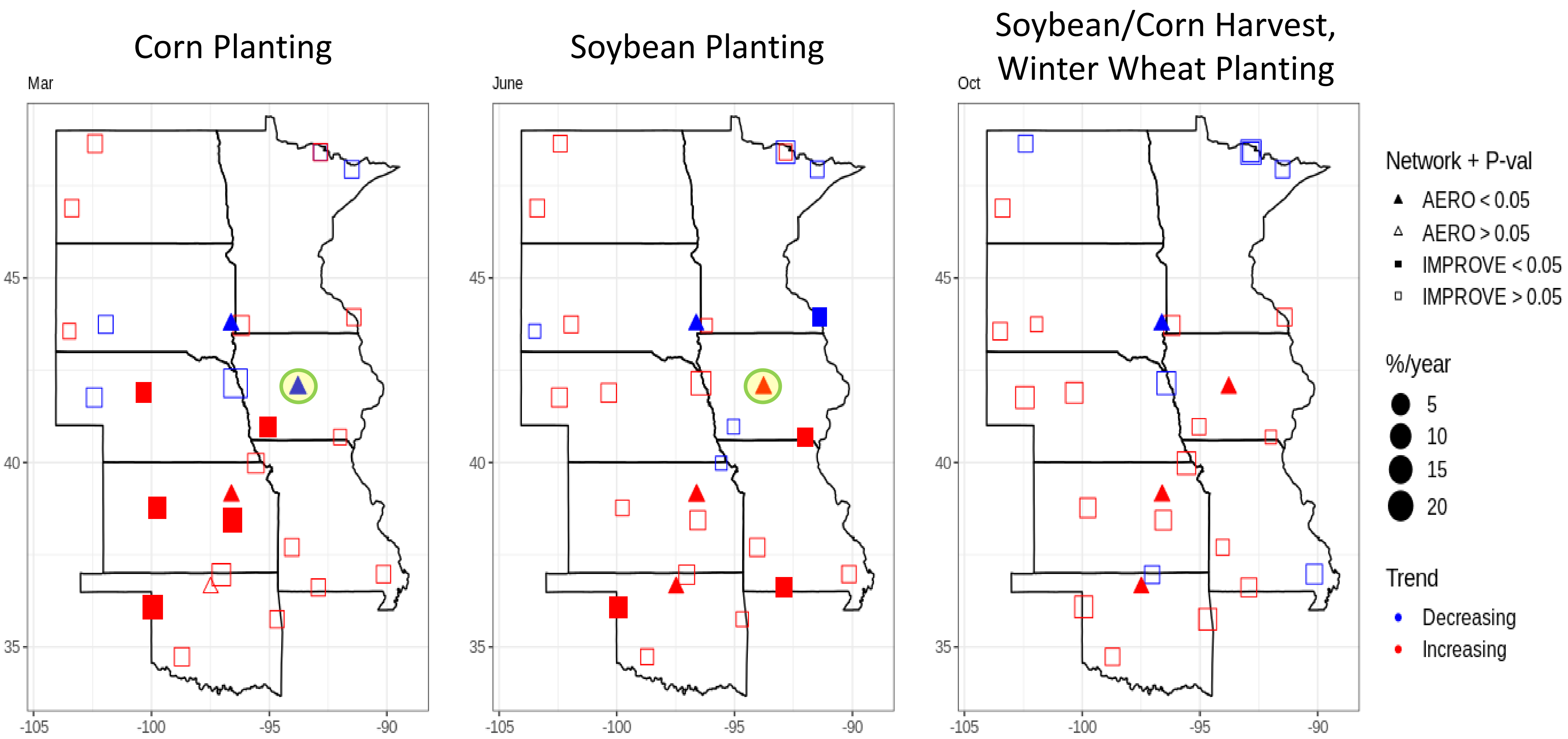


Lag Correlation

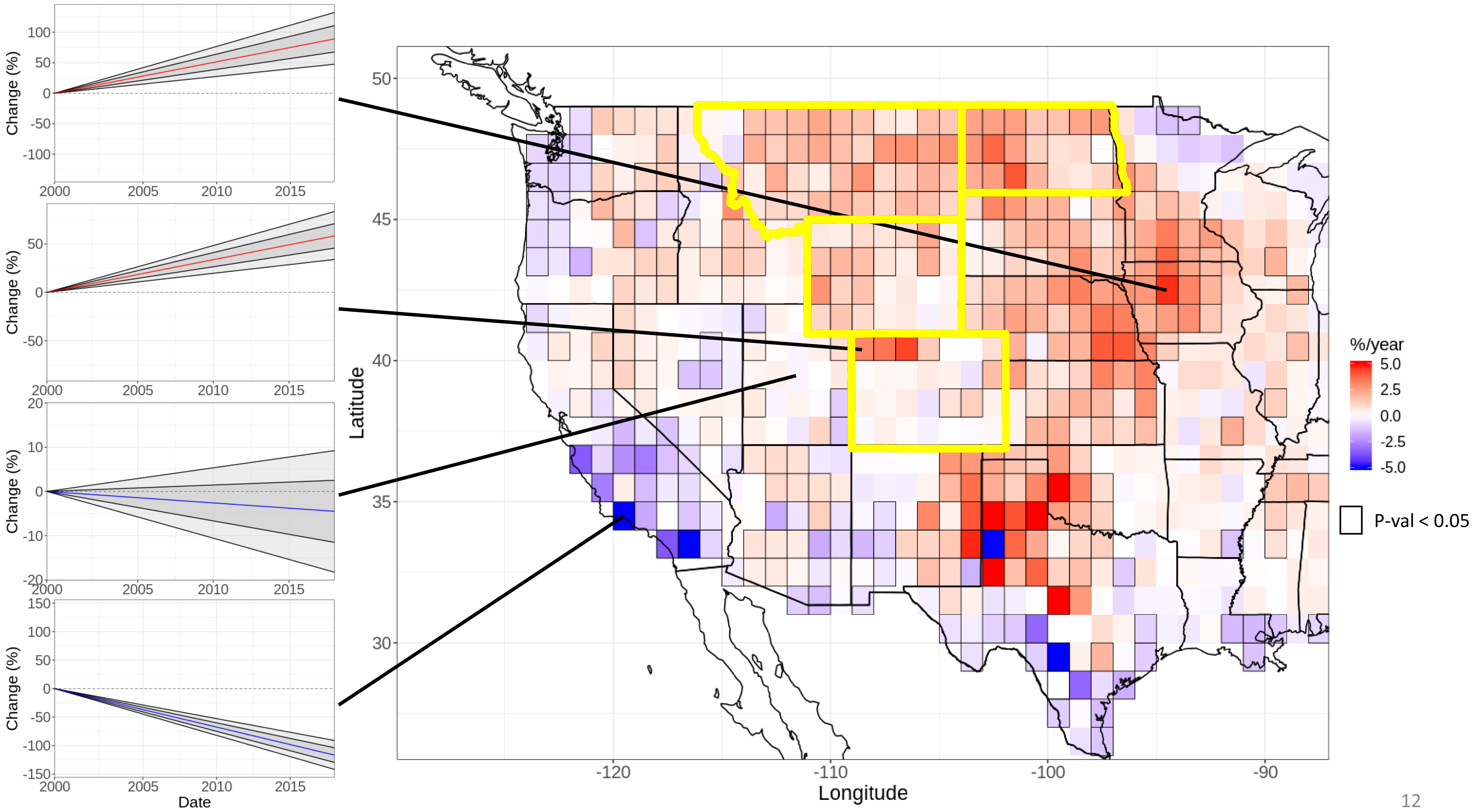
Displacing MODIS AOD_{dust} trends to the northwest maximizes correlation and statistical significance

Suggests downwind influences from agricultural expansion on dust to the northwest

Monthly 0.9th Quantile trends



Oil & Gas



Change (%)
Date
2000
2005
2010
2015
Latitude
Longitude
%/year
5.0
2.5
0.0
-2.5
-5.0
P-val < 0.05
-120
-110
-100
-90
50
45
40
35
30

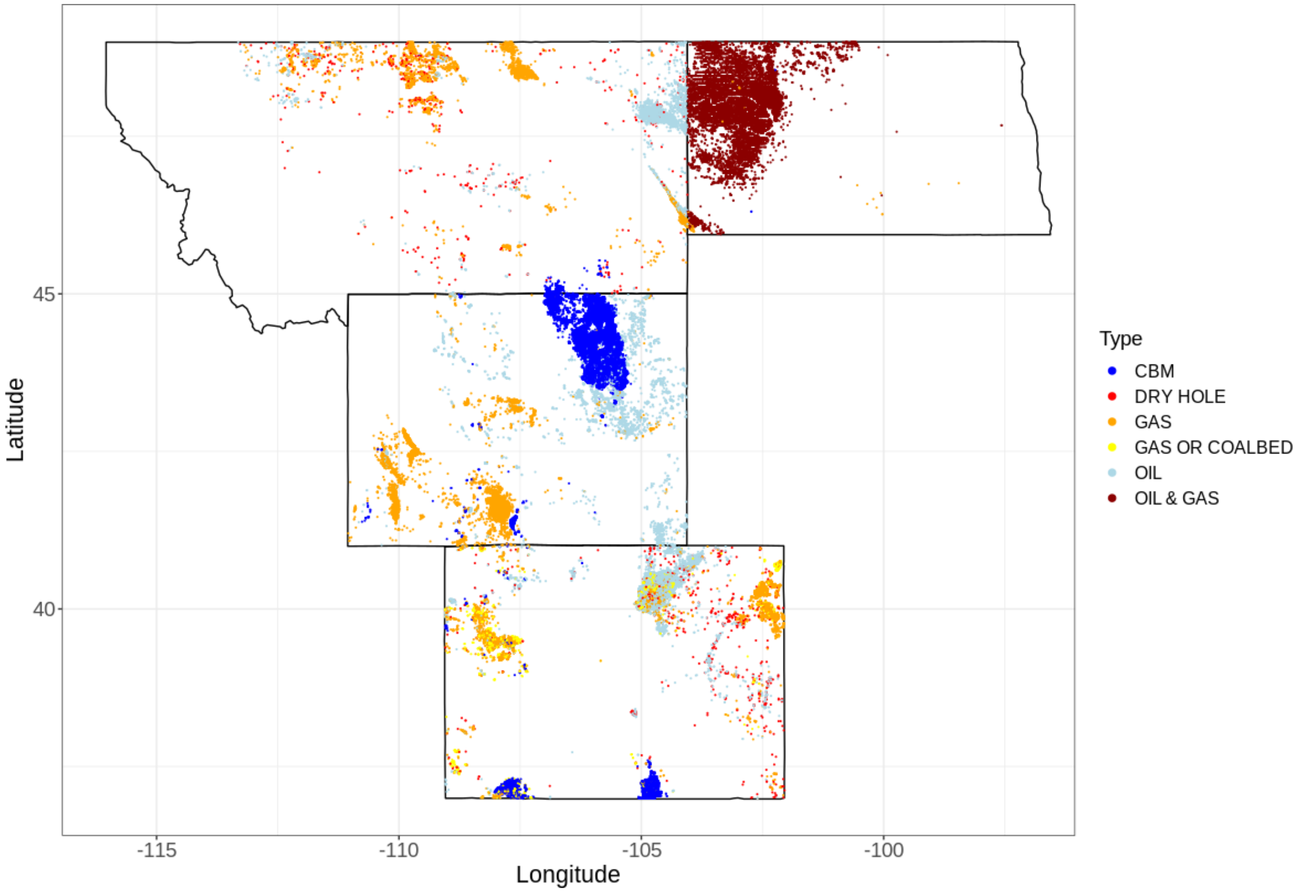
Land Use Change – Oil and Gas Development

Well pads in Permian Basin, Texas
https://www.bloomberg.com/news/articles/2018-10-16/the-permian-oil-boom-is-showing-signs-of-overheating

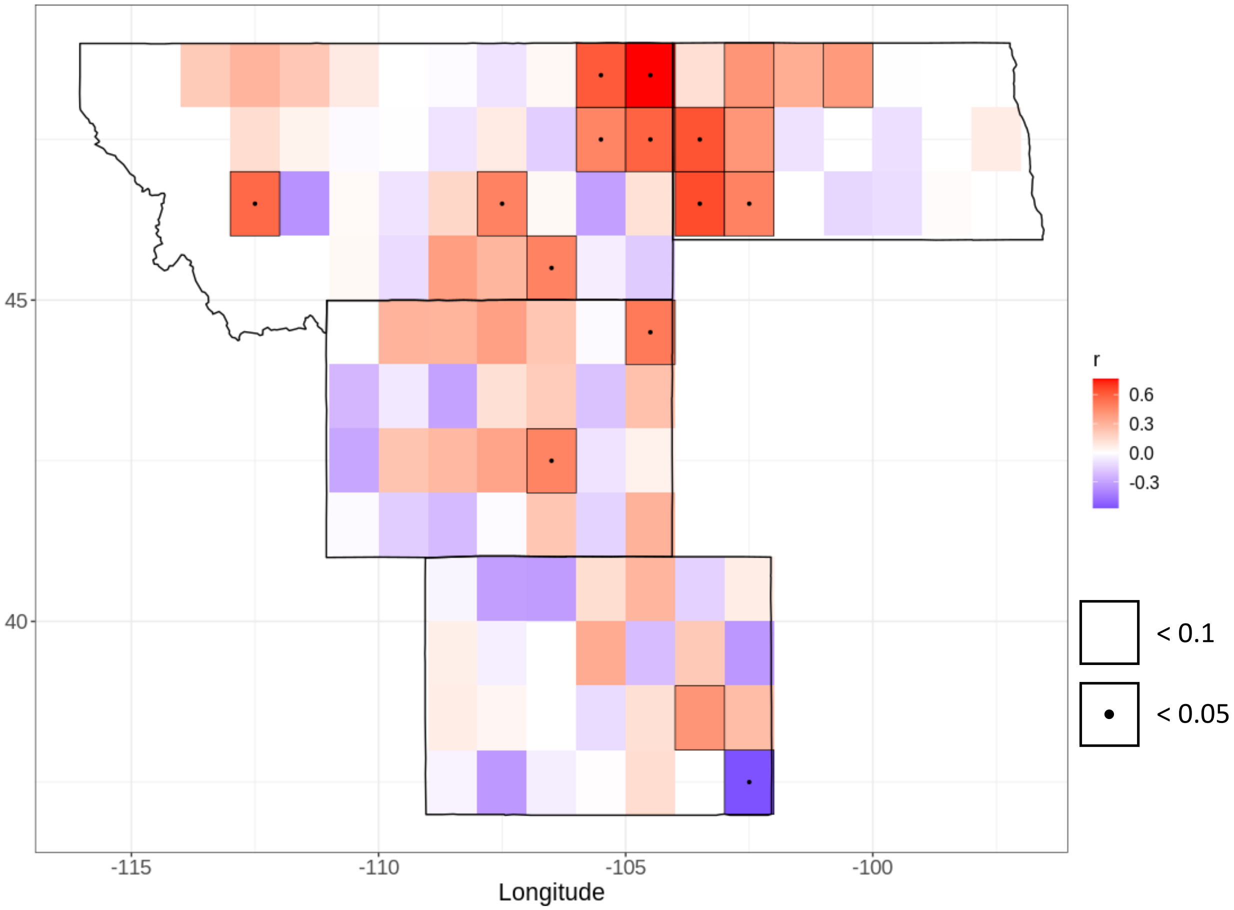
- Construction and maintenance increases soil wind erosion susceptibility (Buto et al., 2010)
  - Several acre well pad
  - Single lane road for each pad
- Between 2000-2012, 4.5 Tg of carbon or 10 Tg of dry biomass removed in the Central Plains (Allred et al. 2015)
- Reclamation process is not well defined or enforced (e.g. Bugden et al., 2016; Warner and Shapiro, 2013)
- Employed oil and gas well data from enverus.com

MODIS/Oil and Gas Correlation

Well Construction (2000-2018)



Annual MODIS AOD_{dust}/well construction frequency correlations (2000-2018)



Summary and Discussion

- Dust loading has increased substantially during the last two to three decades over the Great Plains and Rockies regions (~5%/year for MODIS AOD_{dust})
  - High dust loading events have increased in the Great Plains and are associated with crop planting and harvest seasons
- Temporal and spatial correlations indicate potential contribution of recent energy development and agricultural expansion to dust emissions
- Increased dust emissions due to these land use practices directly impacts health, visibility, water resources, radiative forcing, and environmental policy
- De-incentivization policies, comprehensive and enforced reclamation efforts, and improvements to existing policies could mitigate these risks

Acknowledgments

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- Special thanks to Gannet Hallar for her contribution to this work and her fantastic mentorship

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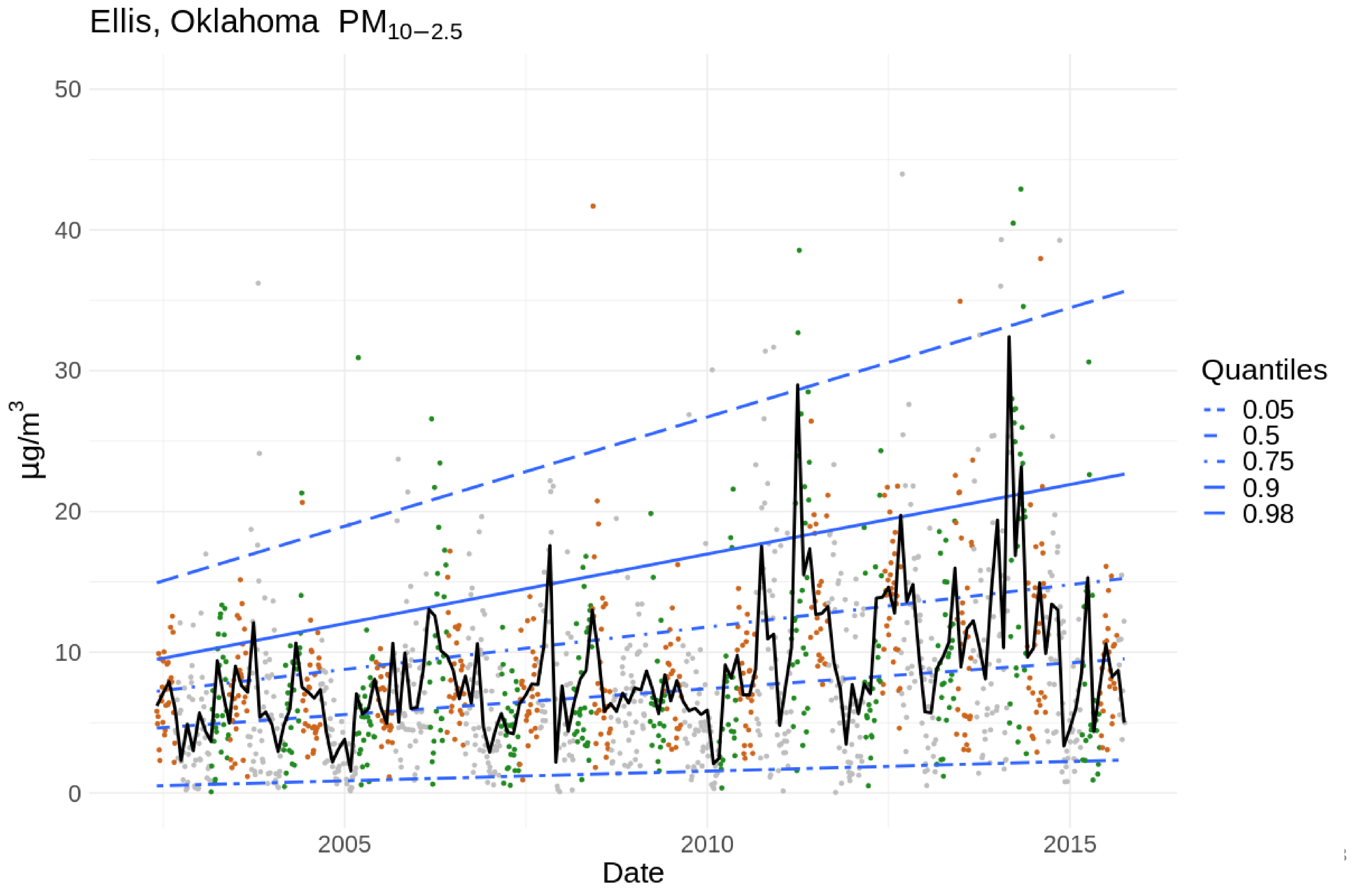
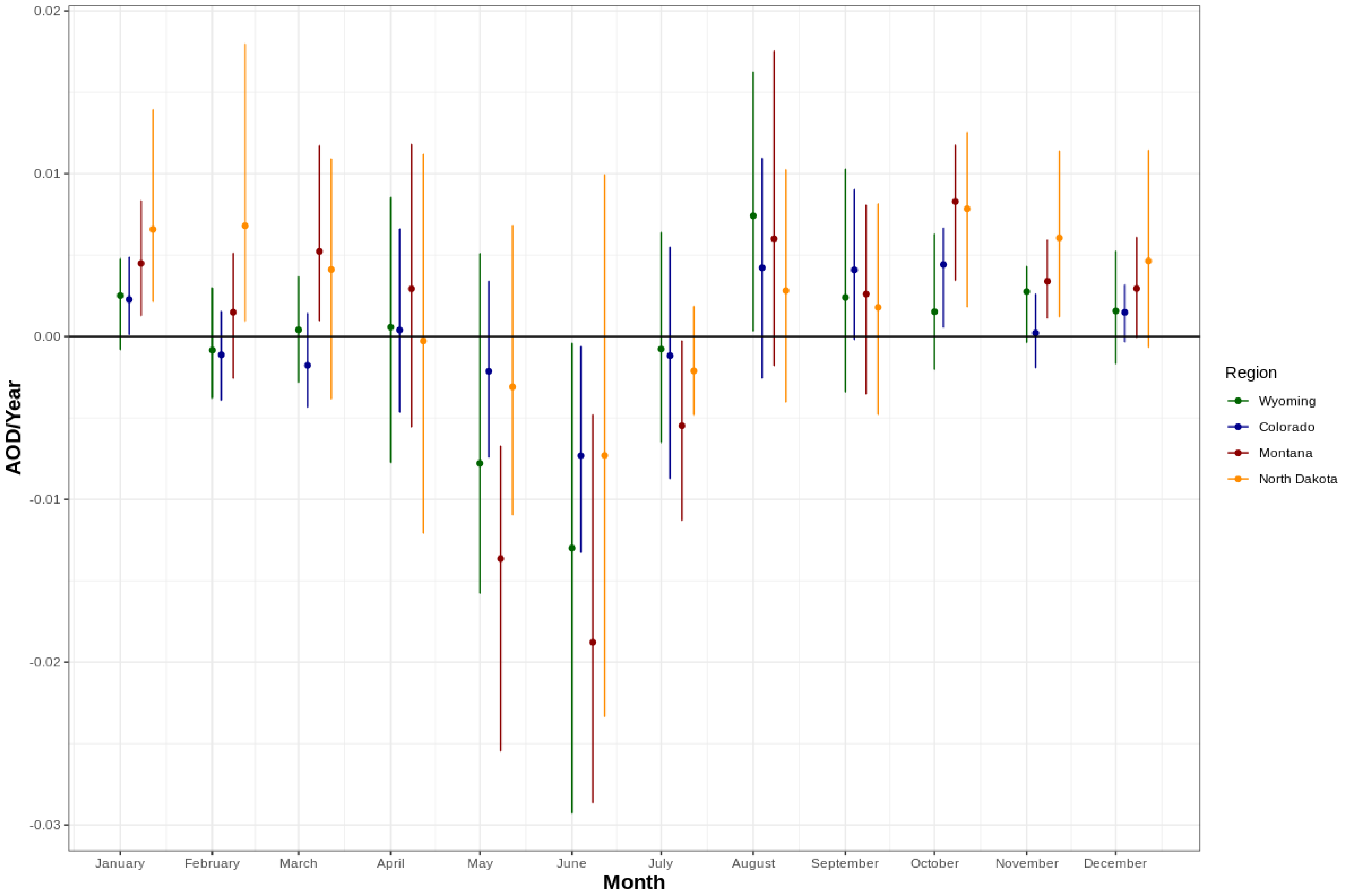
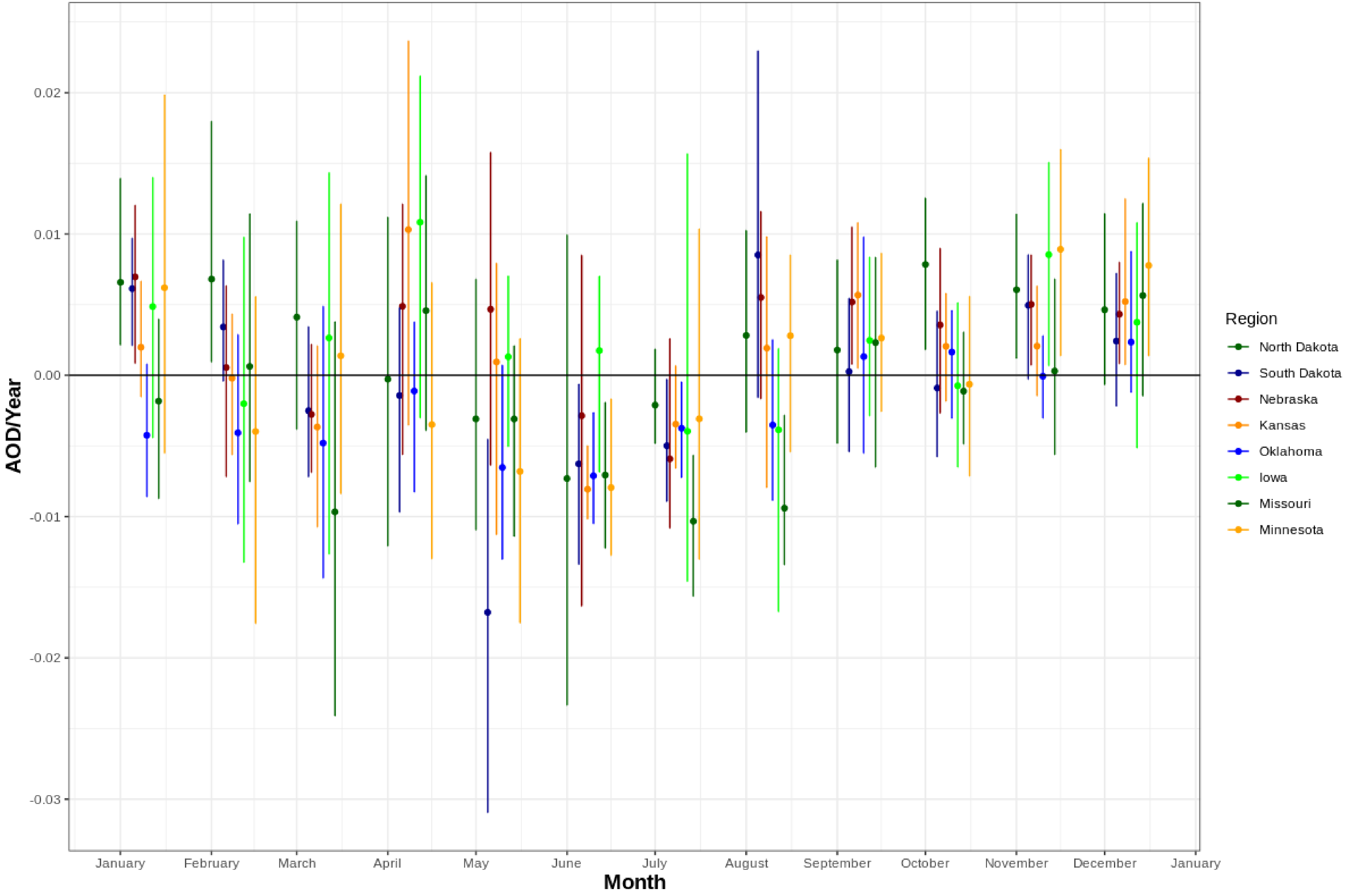
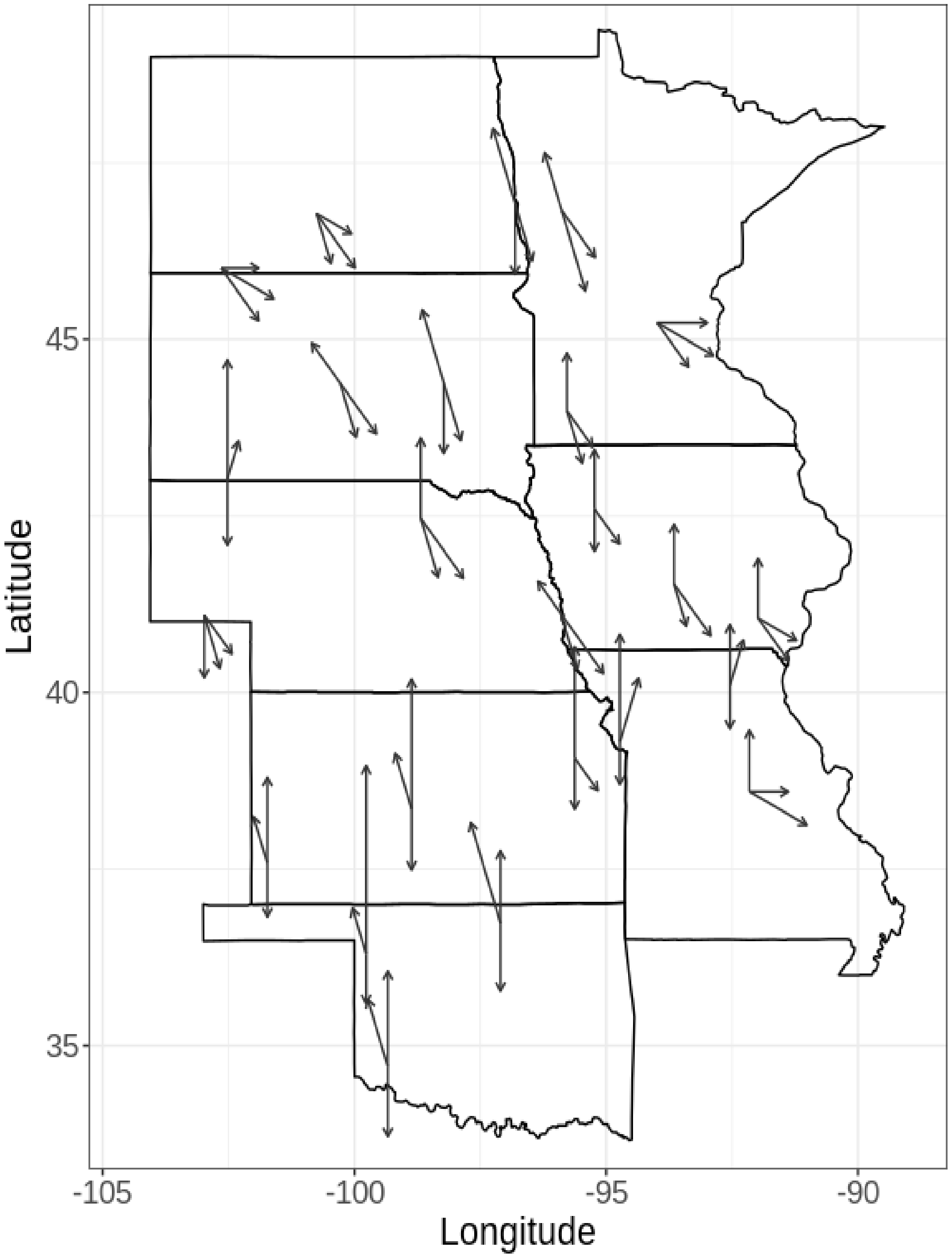


Ellis, Oklahoma PM10−2.5
50
40
30
20
10
0
μg/m3
2005
2010
2015
Date
Quantiles
0.05
0.5
0.75
0.9
0.98

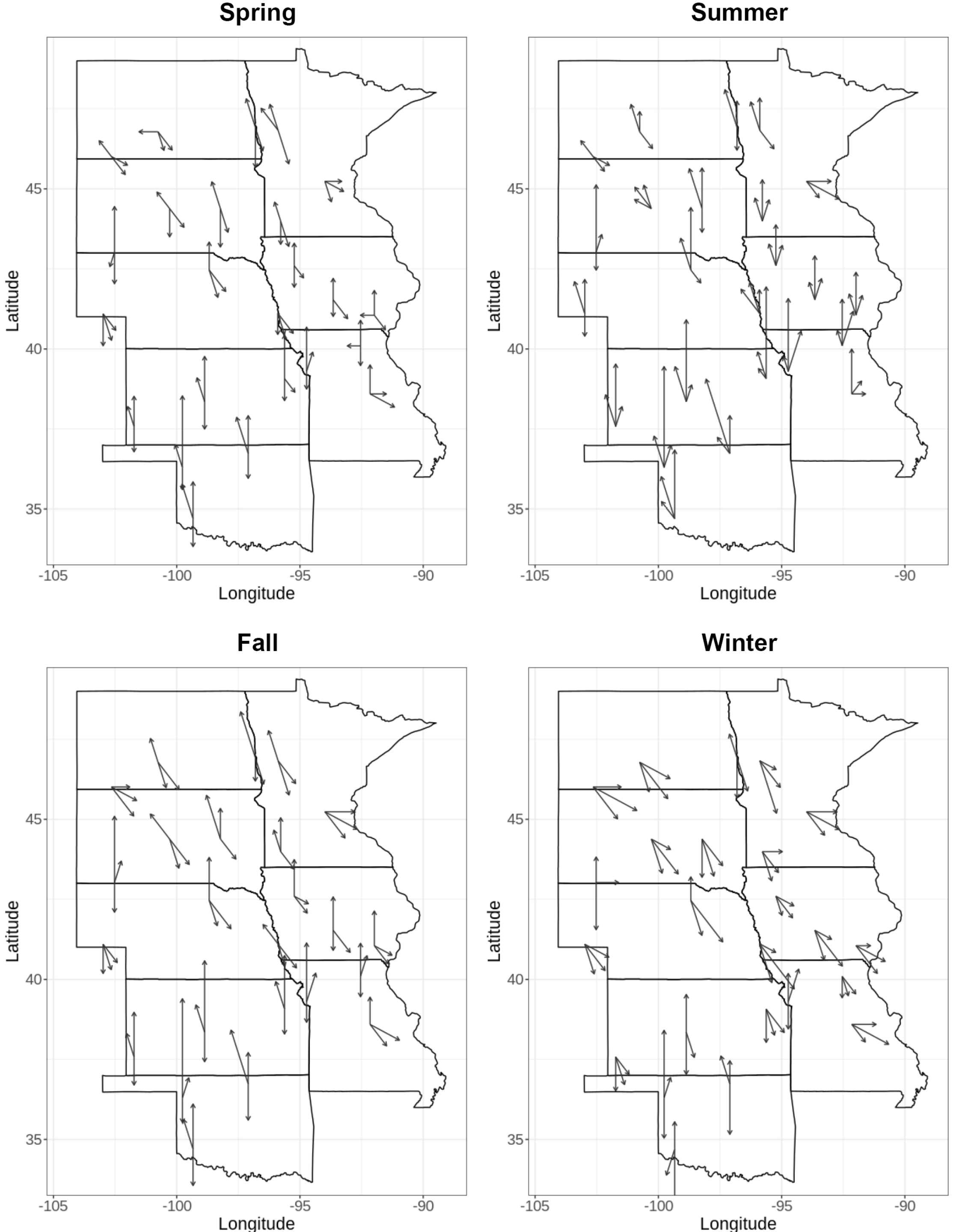

0.02
0.01
0.00
-0.01
-0.02
-0.03
AOD/Year
January
February
March
April
May
June
July
August
September
October
November
December
Month
Region
Wyoming
Colorado
Montana
North Dakota



AOD/Year
0.02
0.01
0.00
-0.01
-0.02
-0.03
January
February
March
April
May
June
July
August
September
October
November
December
January
Month
Region
North Dakota
South Dakota
Nebraska
Kansas
Oklahoma
Iowa
Missouri
Minnesota



Latitude
45
40
35
-105
-100
-95
-90
Longitude

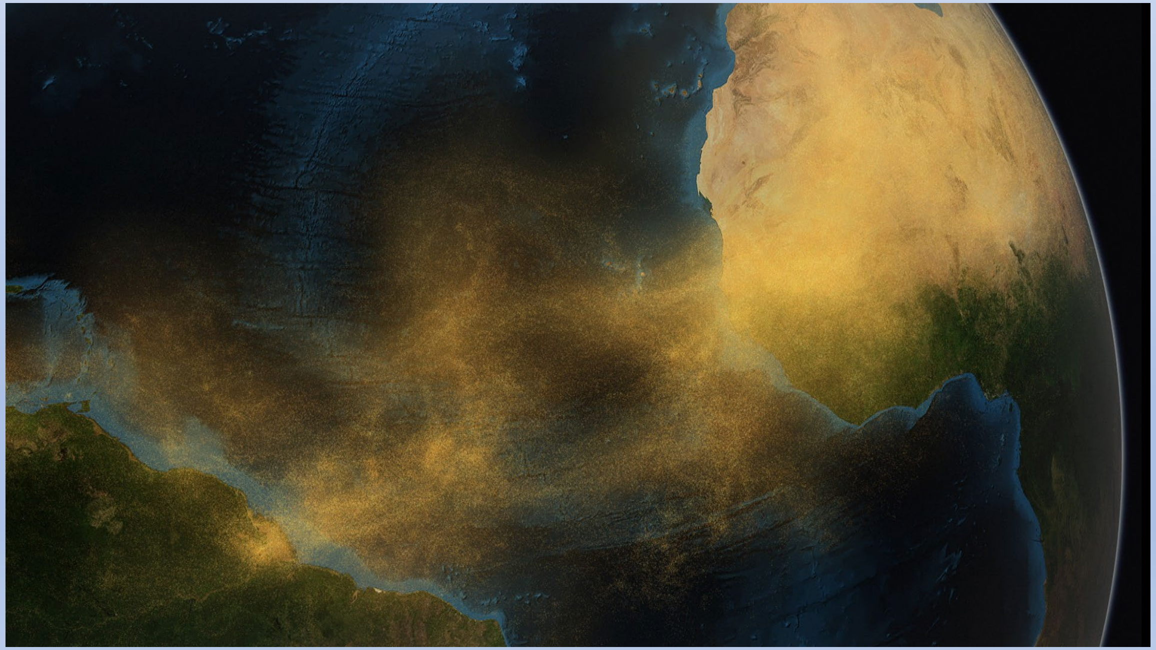

Spring
Summer
Fall
Winter
Latitude
Longitude
45
40
35
-105
-100
-95
-90

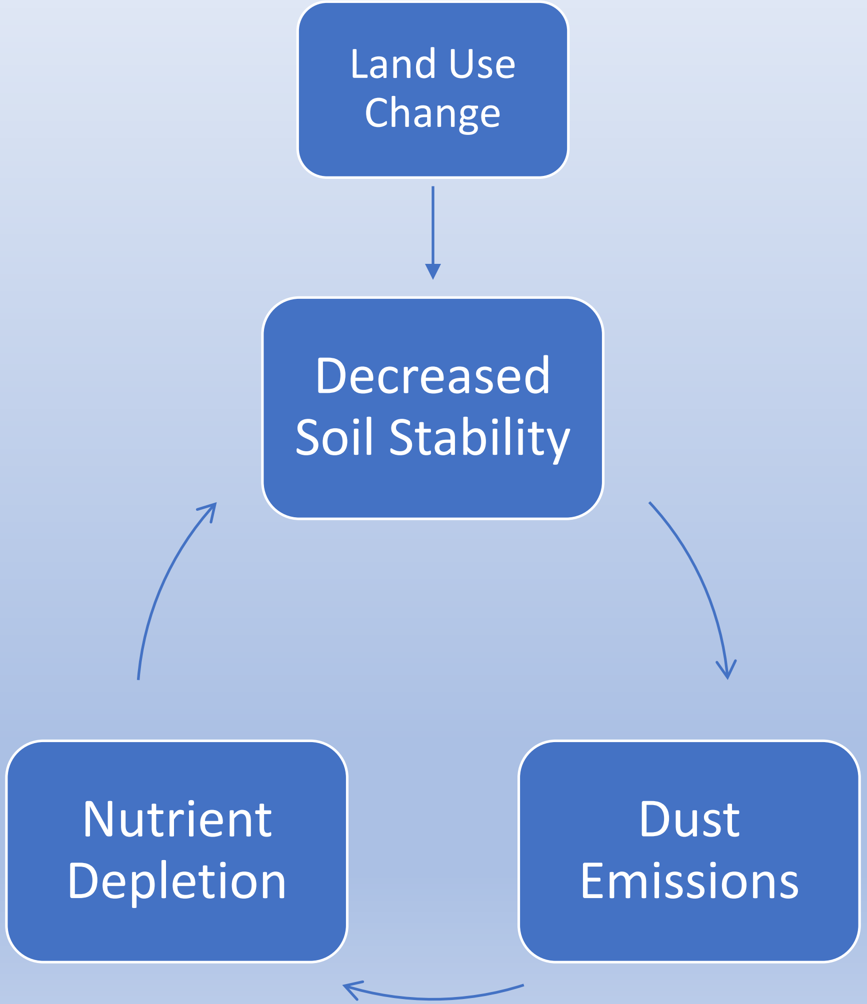
Dust Impacts

- Wind speeds > 2, 4, 7 m/s (Stout, 2001; Whicker et al., 2002; Belnap et al., 2009) produce dust
- Land use reduces threshold (e.g. Belnap and Gillette, 1998)
- Contributes to visibility reduction in Class I areas (Kavouras et al., 2009) – opposes efforts to reduce haze following the Regional Haze Rule
- Dangerous Driving Conditions (e.g. Ashley et al., 2014)
- Cardiovascular and respiratory complications (e.g. Malig and Ostro, 2009; Zanobetti and Schwartz, 2009, Brunekreef and Forsberg 2005; Sandstrom and Forsberg, 2008)
- Direct Radiative effect: dust interacting directly with radiation (e.g. Boucher et al., 2013)
- Indirect radiative effect: dust as ice nuclei (IN) or cloud condensation nuclei (CCN) changes how clouds interact with radiation (e.g. Koehler et al., 2009)
- Dust on snow ⍰ accelerated melting of mountain snowpack (e.g. Painter et al., 2012)

Dust and Desertification

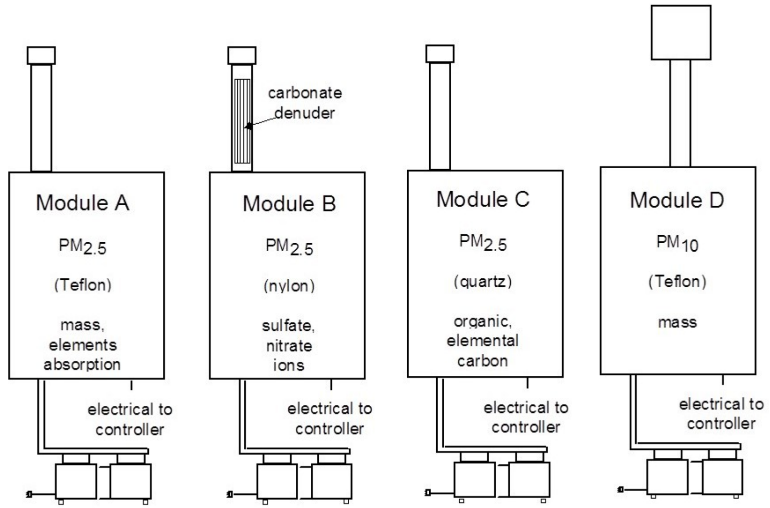
- The dust giveth and the dust taketh away
  - Dust from the Sahara and Sahel enriches soils in the Amazon in addition to biomass burning (e.g. Swap et al., 1992; Barkley et al., 2019)





https://www.nasa.gov/content/goddard/nasa-satellite-reveals-how-much-saharan-dust-feeds-amazon-s-plants

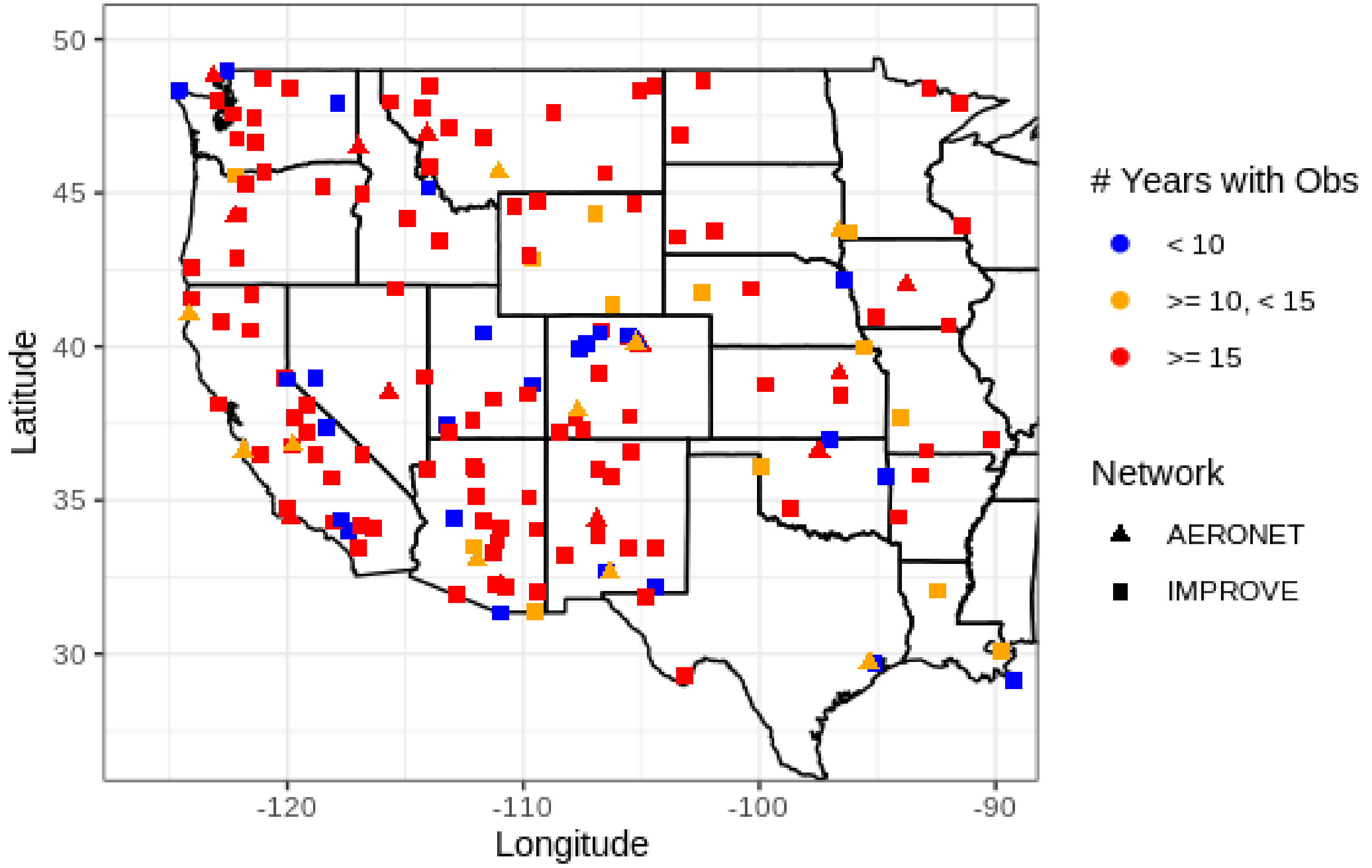
Ground-Based Observations



- Interagency Monitoring of Protected Visual Environments (IMPROVE)
  - 24-hour aerosol samples every three days
  - Analyzing dust: $PM_{10-2.5}$

- Aerosol Robotic Network
  - Cimel sun photometers
  - Measurements every 3 or 15 minutes (model dependent)
  - Spectral Deconvolution Algorithm → fine and coarse AOD
  - Analyzing dust: AOD_{coarse}

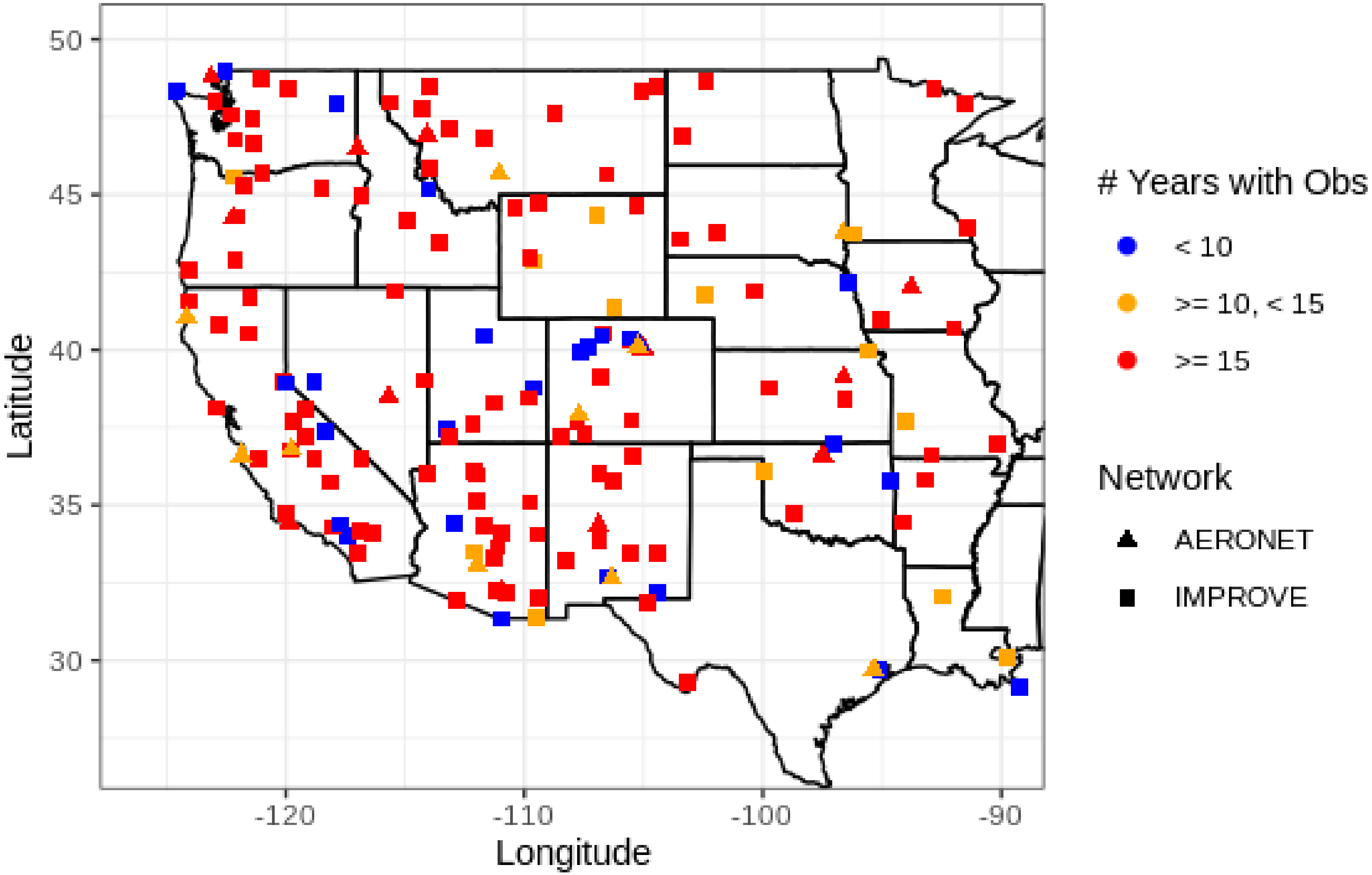
Data Availability



- 23 AERONET sites
- 147 IMPROVE sites
- 170 sites combined with at least 7 years of observations

Ground-Based Observations

170 sites combined with at least 7 years of observations



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  - 147 IMPROVE sites

Moderate Resolution Imaging Spectroradiometer (MODIS)

- 36 bands from 0.4 to 14 µm
- Global coverage every ~2 days depending on latitude
- Collection 6, version 4.4 global daily atmosphere product
  - Dark target over land algorithm produces AOD values
- AOD observations subset by Ångström exponent (AE)
  - AE – inversely proportional to particle size
- Analyzing dust: Observations with AE < 0.75 (AOD_{dust})

$$\frac{\tau_\lambda}{\tau_{\lambda_0}} = \left(\frac{\lambda}{\lambda_0}\right)^{-\alpha}$$

$$\alpha = -\frac{\log\left(\frac{\tau_{\lambda_1}}{\tau_{\lambda_2}}\right)}{\log\left(\frac{\lambda_1}{\lambda_2}\right)}$$

Trend Analysis

- Data is non-parametric – using Sen's slope to get regression coefficient
  - Sen's slope – median of slopes for all possible pairs of points (Theil, 1950; Sen, 1968)
  - P-value based on Kendall's tau (Kendall, 1938)
  - Confidence intervals based on Gilbert's method (Gilbert, 1987)
  - For Rockies region where oil and gas is expanding – expected increase in background dust due to ongoing construction and maintenance

- Quantile regression applied to IMPROVE and AERONET data
  - xy-pair bootstrap method → confidence intervals and p-value
  - For Great Plains analysis where agriculture is expanding – expected increases in intermittent dust events during and around planting and harvesting seasons

Limitations

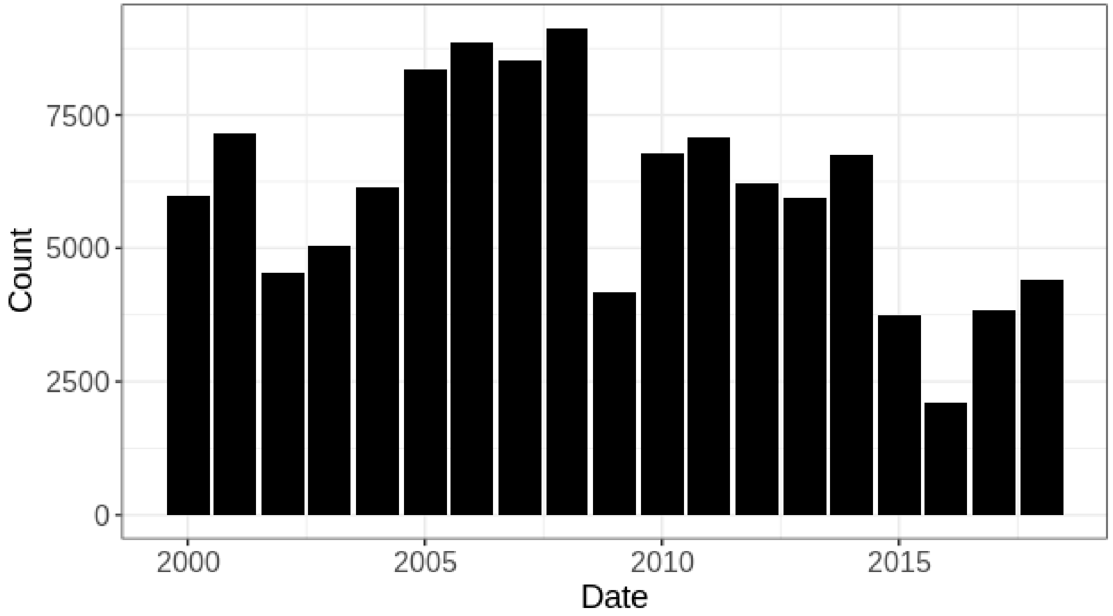
- Data from IMPROVE and AERONET vary in temporal coverage between networks and from site to site
- IMPROVE makes surface in-situ observations while AERONET and MODIS provide remotely sensed column measurements
- Temporal resolution is different between datasets: AERONET (15 min), IMPROVE (3 days), MODIS (~2 days)
- Meteorology, hydrology, and climate have important influences on soil stability and dust emissions which are not fully considered here

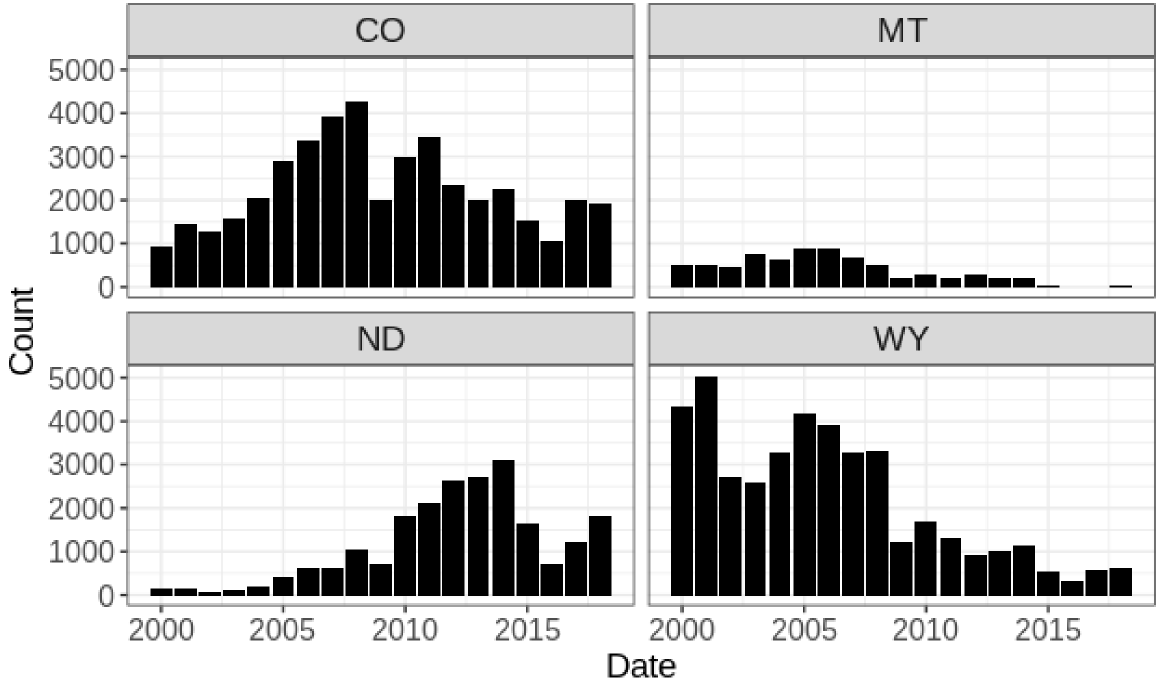
Cropland Data Layer (CDL)

- Produced by United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS)
- 30m cropland classification product – employs Landsat and MODIS imagery among other datasets
- Available 2008-2018
- All features classified as either crop or non-crop to analyze change

Oil and Gas Well Data

- Oil and gas well data obtained from Enverus (https://www.enverus.com)
  - An energy data, insights, and software company founded in 1999 originally named Drillinginfo
- Information includes: well name and #, lease name, operator name, elevation, coordinates, production type, well status, spud date, and more
- Wells with status listed as cancelled, expired permit, permitted, unknown, or confidential removed from analysis
- Well data subset by year using the spud date field for 2000-2018





Wells Drilled Per Year

- CO peak in 2008
- WY decrease since 2001
- ND increase since 2000
- 2000-2009: ~6800 wells constructed per year
- 2010-2018: ~5200 wells constructed per year

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Agricultural Expansion: Discussion

- Rapid cropland expansion is spatially correlated with MODIS AOD_{dust} trends downwind to the northwest
- Positive monthly trends in AERONET AOD_{coarse} and IMPROVE $PM_{10-2.5}$ coincide with planting and harvesting seasons for predominate crops
- Considering high uncertainty in future drought estimates for the region, rapid agricultural expansion could present a threat for potential land degradation and desertification similar to the 1930s Dust Bowl
  - Climate models estimate 50-200% increase in summertime drought risk in Great Plains in response to a warming of 1-4°C (Swain and Hayhoe, 2015)
- Policy changes → reduced desertification risk
  - Improve and expand existing policies (e.g. “Sodsaver” provision reduces crop insurance subsidies in only 6 states)
  - Expand aerosol measurement networks
  - Land surface development restrictions (e.g. sensitive landscapes cannot be developed)

Agricultural Expansion

- Trends have influenced regions' compliance with National Ambient Air Quality Standards (NAAQS) for PM_{10}
  - Kansas – 0 exceedances (2000-2009), 1 exceedance every 3 years (2010-2018)
  - South Dakota – 0 (2000-2009), 1 every 2 years (2010-2018)

Oil and Gas Development: Discussion

- MODIS AOD_{dust} increased ~5%/year in Rockies and Northern Great Plains states (2000-2018) and AOD_{dust} observations are temporally correlated with well construction in Montana and North Dakota
- Increased dust emissions due to oil and gas development directly impacts **health**, visibility, **water resources**, and radiative forcing
- **Health**: 1200 to 4600 premature deaths associated with dust emissions from shale gas development in Appalachian basin (2004-2016) (Mayfield et al., 2019)
- **Water Resources**: Dust deposition increased by 81% in parts of the Rockies (1993-2014) combining with decreased snowfall to accelerate snowmelt by 7-18 days (Clow et al., 2016)
- Policy Changes → reduced dust emissions:
  - Construction strategies (e.g. gravel paved roads)
  - Land surface development restrictions (e.g. sensitive landscapes cannot be developed)
  - Consistent, expansive, enforced, and specific reclamation requirements

Summary

- Dust loading has increased substantially during the last two to three decades over the Great Plains and Northern Rockies
    - High dust loading events have increased in intensity over the similar regions
- These trends have likely been influenced by rapid oil and gas development and agricultural expansion
- Oil and gas development and agricultural expansion present dangers to human health and water resources in addition to increasing risk of desertification in the Northern Rockies and Great Plains
- De-incentivization policies, comprehensive and enforced reclamation efforts, and improvements to existing policies could mitigate these risks