Downwind of the Flames: Living with Fire and Smoke in the Mountain West

Sheryl Magzamen, Jeff Pierce

Colorado State University

Estes Valley Land Trust

April 23, 2022

sheryl.magzamen@colostate.edu, jeffrey.pierce@colostate.edu

Colorado State University

Our core team at Colorado State University

Jeff Pierce
Dept. of Atmospheric Science
Aerosol Chemistry and Physics
Theory, Modelling, Remote sensing

Emily Fischer
Dept. of Atmospheric Science
Atmospheric Chemistry
Modelling, Remote sensing, Field work
Diversity, Equity, Inclusion

Sheryl Magzamen
Dept. of Environmental and Radiological Health Science
Environmental Epidemiology
Connect pollution exposures to health outcomes

Bonne Ford
Dept. of Atmospheric Science
Aerosols and remote sensing
Remote sensing, Modelling, Data Analysis

But our collaborative network with smoke is much larger!

Science is a team sport!

Expertise
Atmospheric Science
Engineering
Epidemiology
Biostatistics
Economics
Communication

Courtesy of Emily Fischer

Roadmap

Smoke Trends and Future Projections

Who is Breathing Wildfire Smoke?

– Focus on smoke from local vs. distant fires

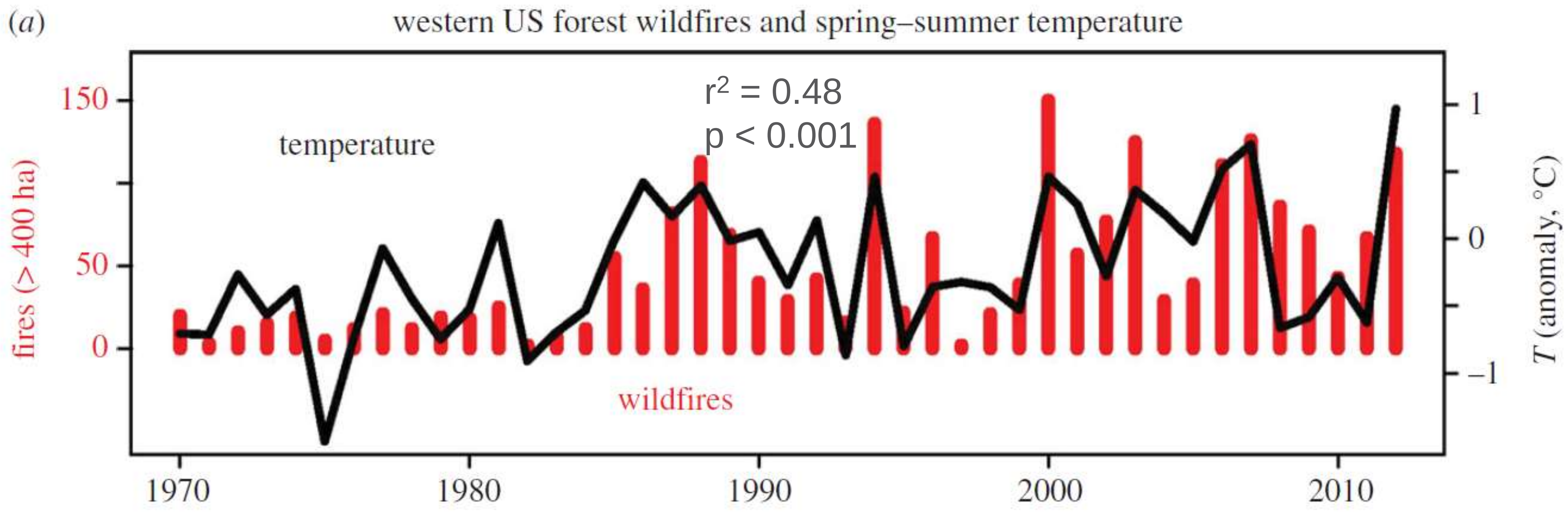
Intro to Epidemiology: Study designs for wildfire smoke health research

Case Studies: Washington 2012, Oregon 2013, and Colorado 2010 – 15, Colorado 2018 - 19:

- Does how we measure matter?
- What health impacts are we seeing?
- Comparing local and long-range smoke on secondary health outcomes
- Can animals help tell the story?

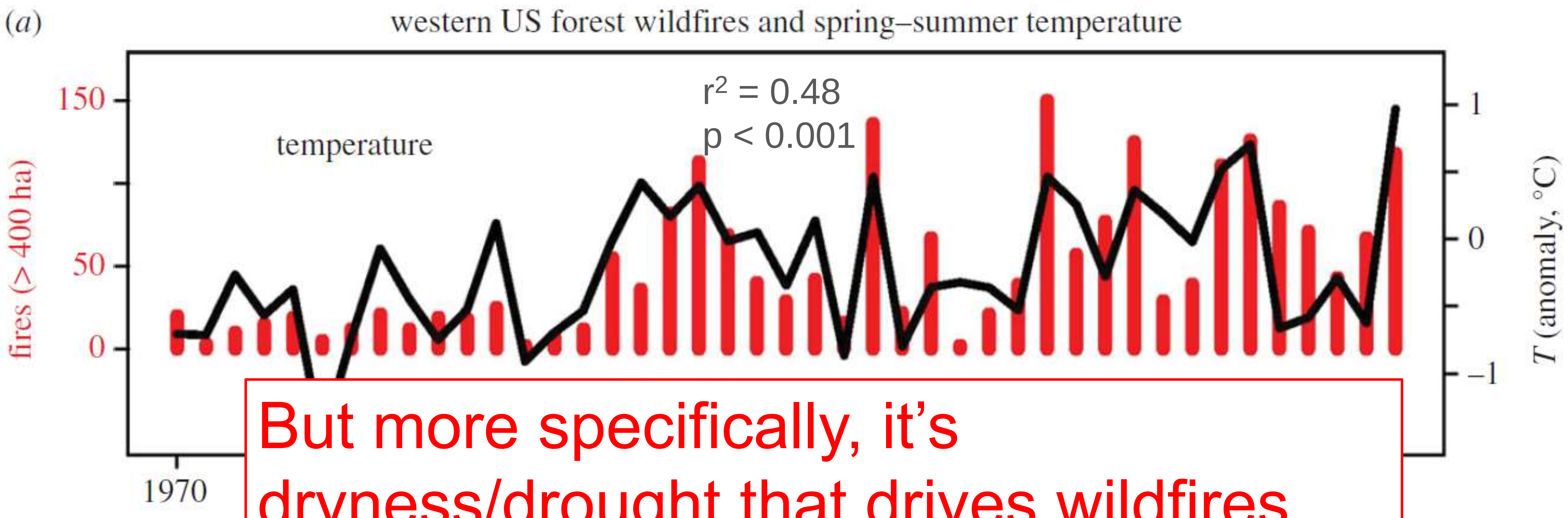
Food for Thought: Where do questions remain and how to stay safe

Large wildfires correlate with spring-summer temperature in the western US



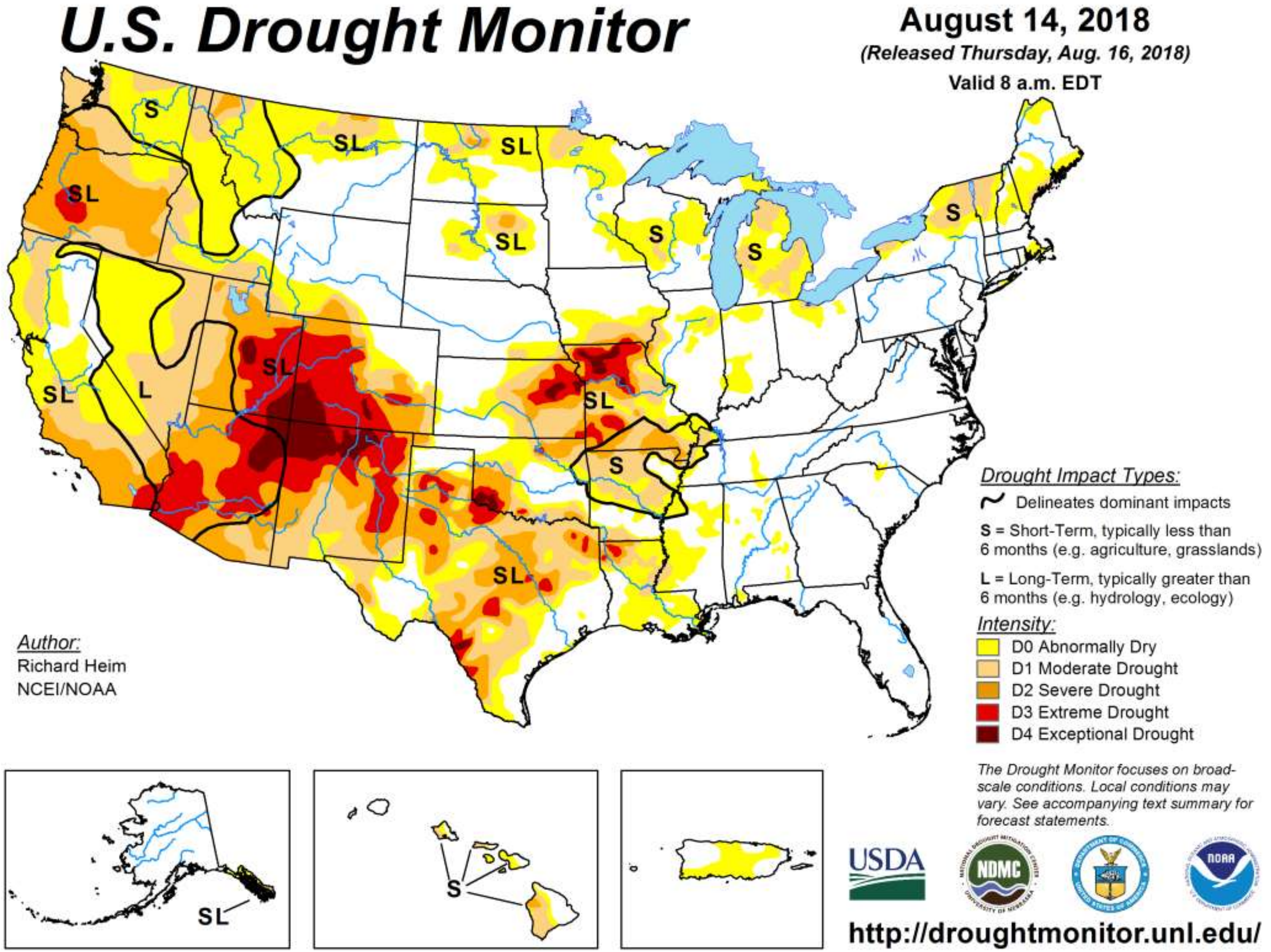
Westerling, Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring, *Phil. Trans. R. Soc. B*, 2016.

Large wildfires correlate with spring-summer temperature in the western US



But more specifically, it's dryness/drought that drives wildfires…

Westerling, Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring, *Phil. Trans. R. Soc. B*, 2016.


U.S. Drought Monitor
August 14, 2018
(Released Thursday, Aug. 16, 2018)
Valid 8 a.m. EDT
S
SL
SL
SL
SL
S
S
S
SL
L
SL
SL
S
SL
Drought Impact Types:
Delineates dominant impacts
S = Short-Term, typically less than 6 months (e.g. agriculture, grasslands)
L = Long-Term, typically greater than 6 months (e.g. hydrology, ecology)
Intensity:
D0 Abnormally Dry
D1 Moderate Drought
D2 Severe Drought
D3 Extreme Drought
D4 Exceptional Drought
Author:
Richard Heim
NCEI/NOAA
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.
SL
S
USDA
NDMC
NOAA
http://droughtmonitor.unl.edu/

Visually, the worst smoke day in August 2018 (8/20)

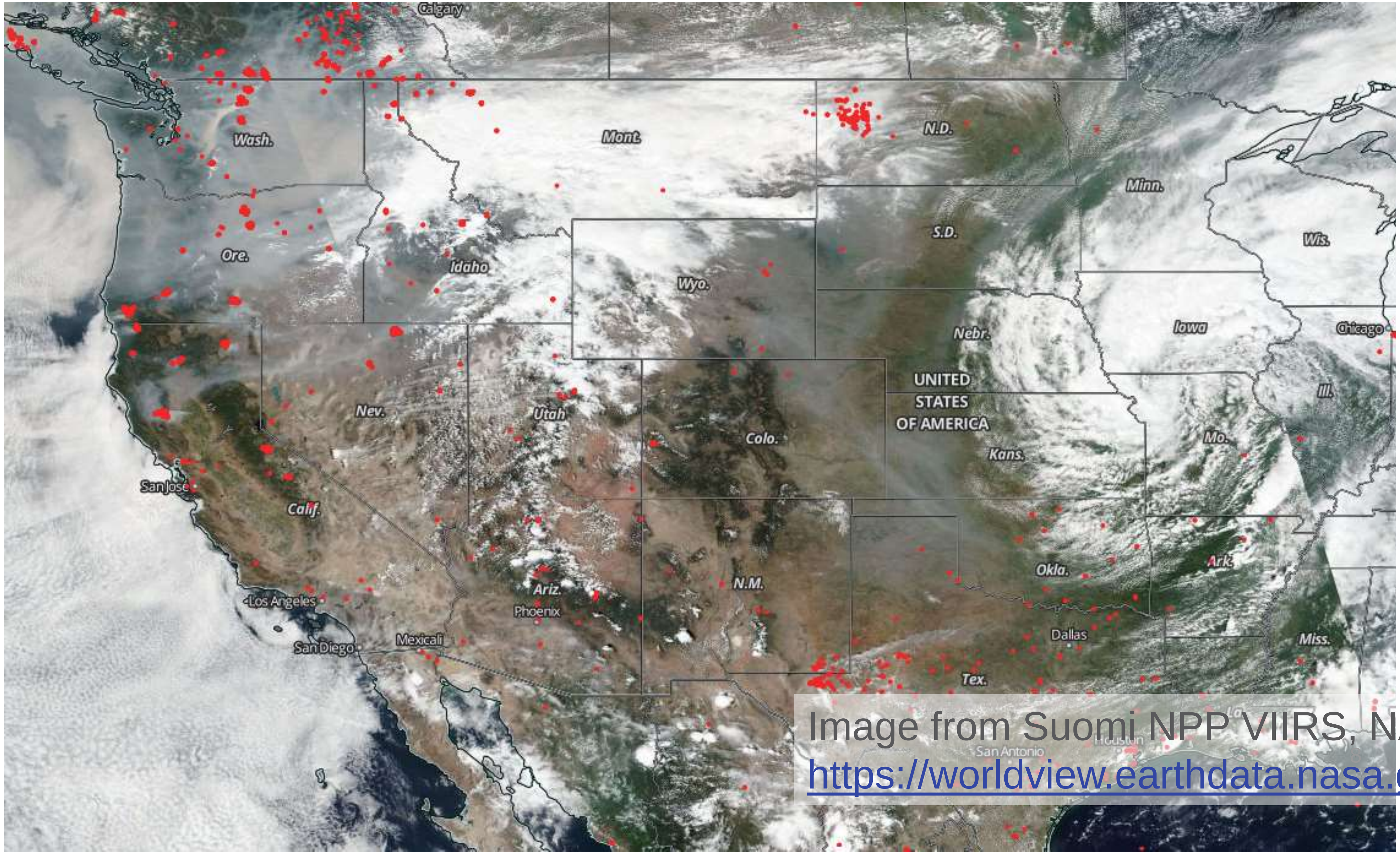


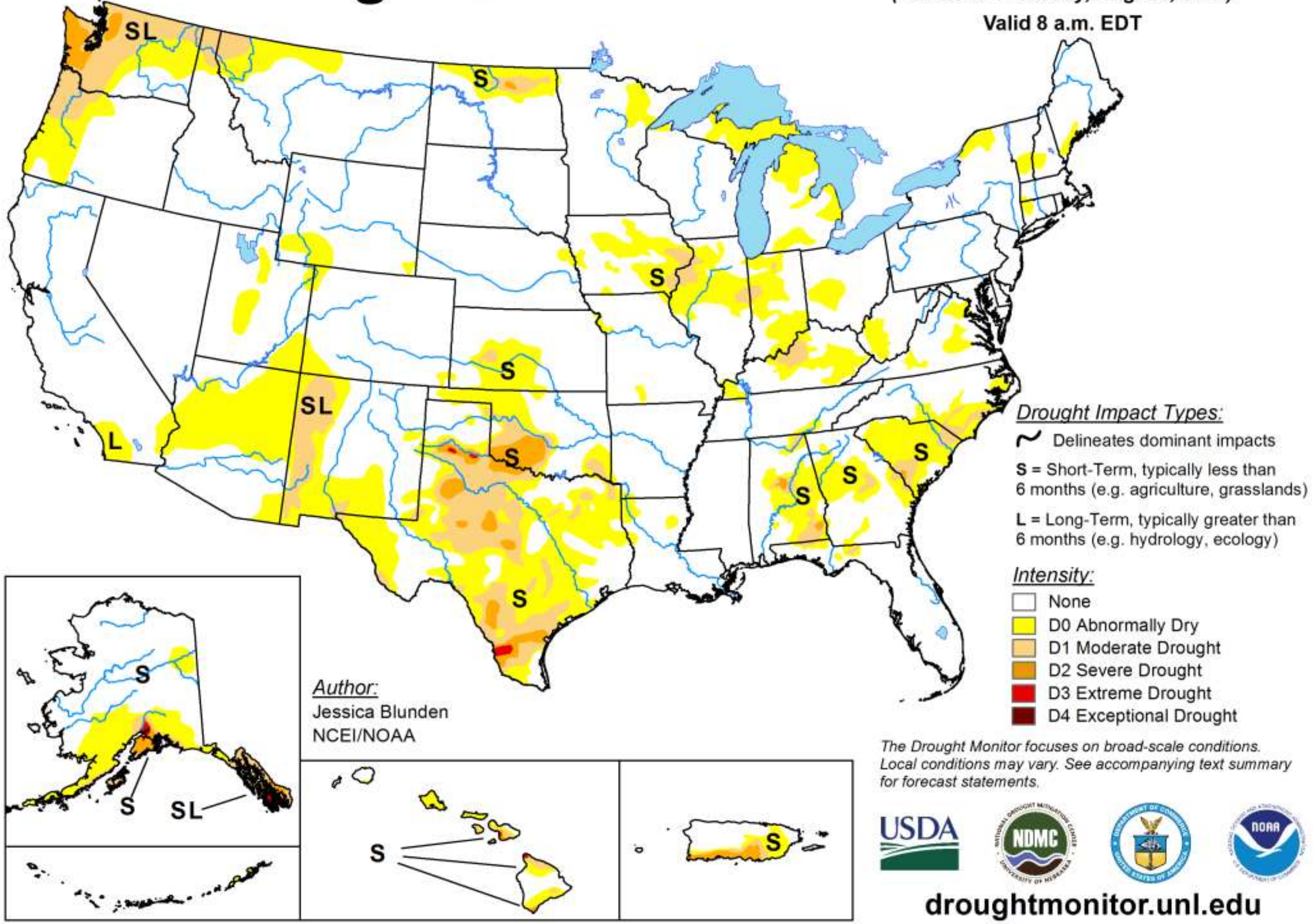
Image from Suomi NPP VIIRS, NASA Worldview:
https://worldview.earthdata.nasa.gov/

U.S. Drought Monitor

August 20, 2019

(Released Thursday, Aug. 22, 2019)

Valid 8 a.m. EDT



Visually, the worst smoke day in August 2019 (8/7)

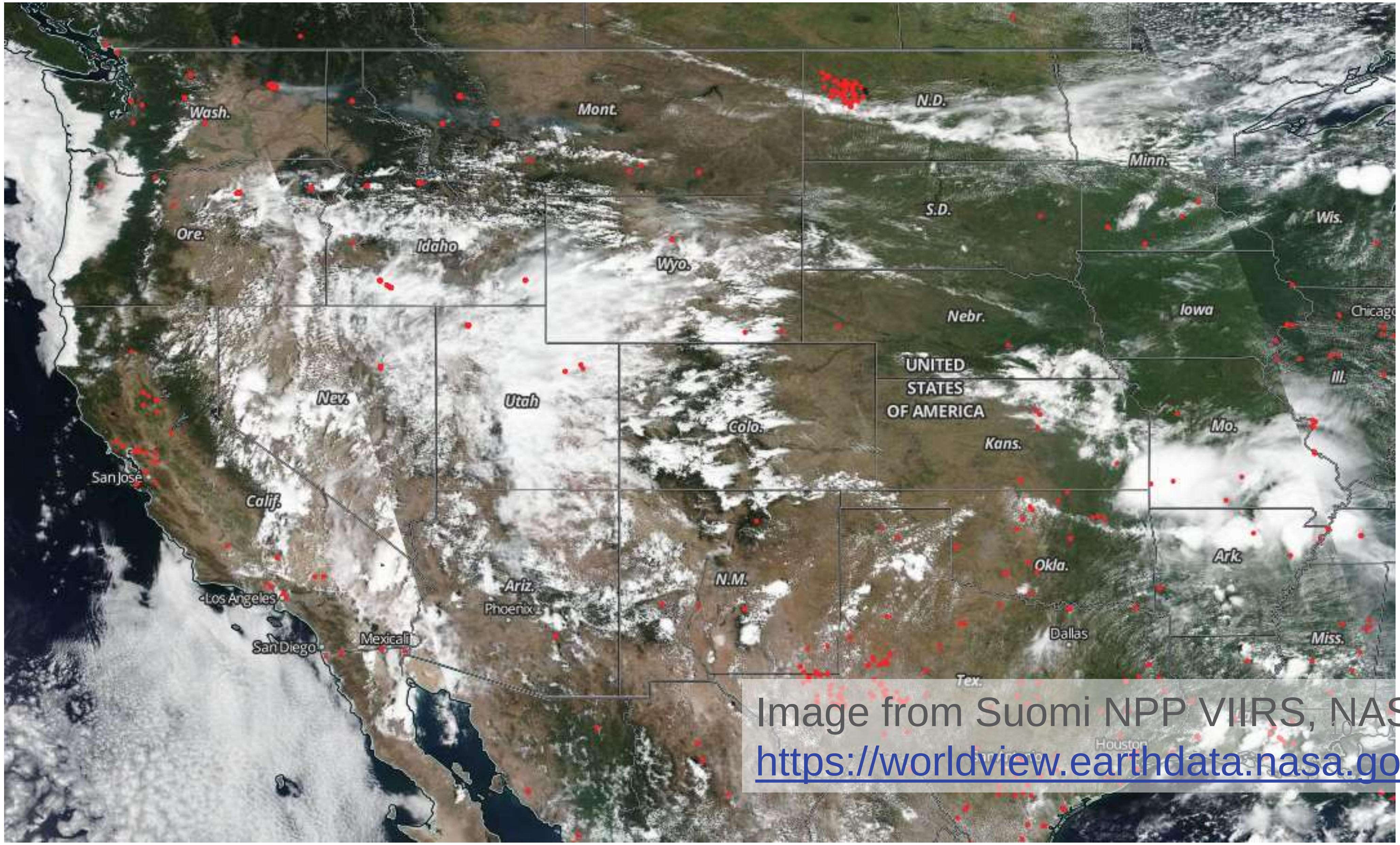


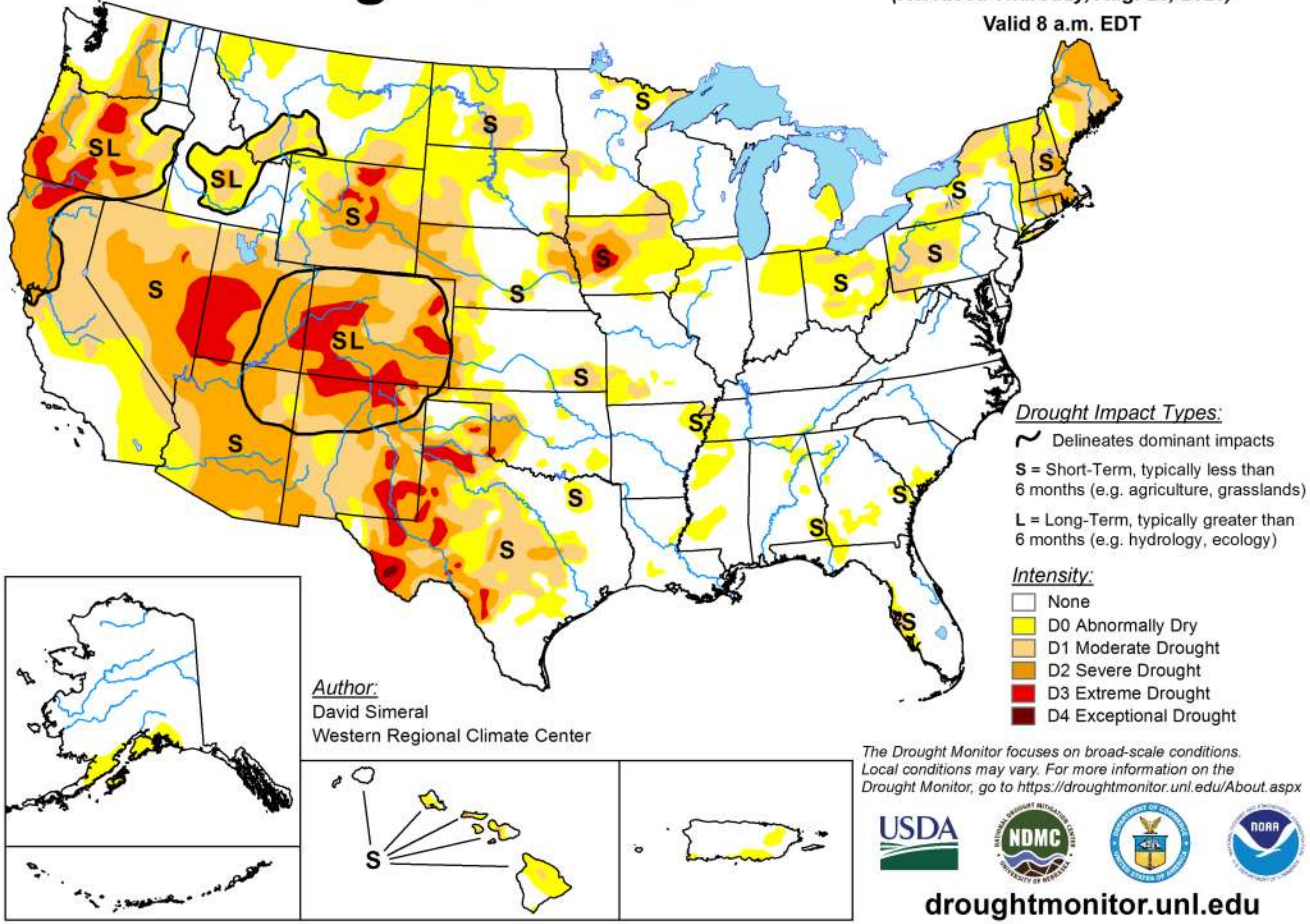
Image from Suomi NPP VIIRS, NASA Worldview: https://worldview.earthdata.nasa.gov/

U.S. Drought Monitor

August 18, 2020

(Released Thursday, Aug. 20, 2020)

Valid 8 a.m. EDT



Visually, the worst smoke day in August 2020 (8/21)

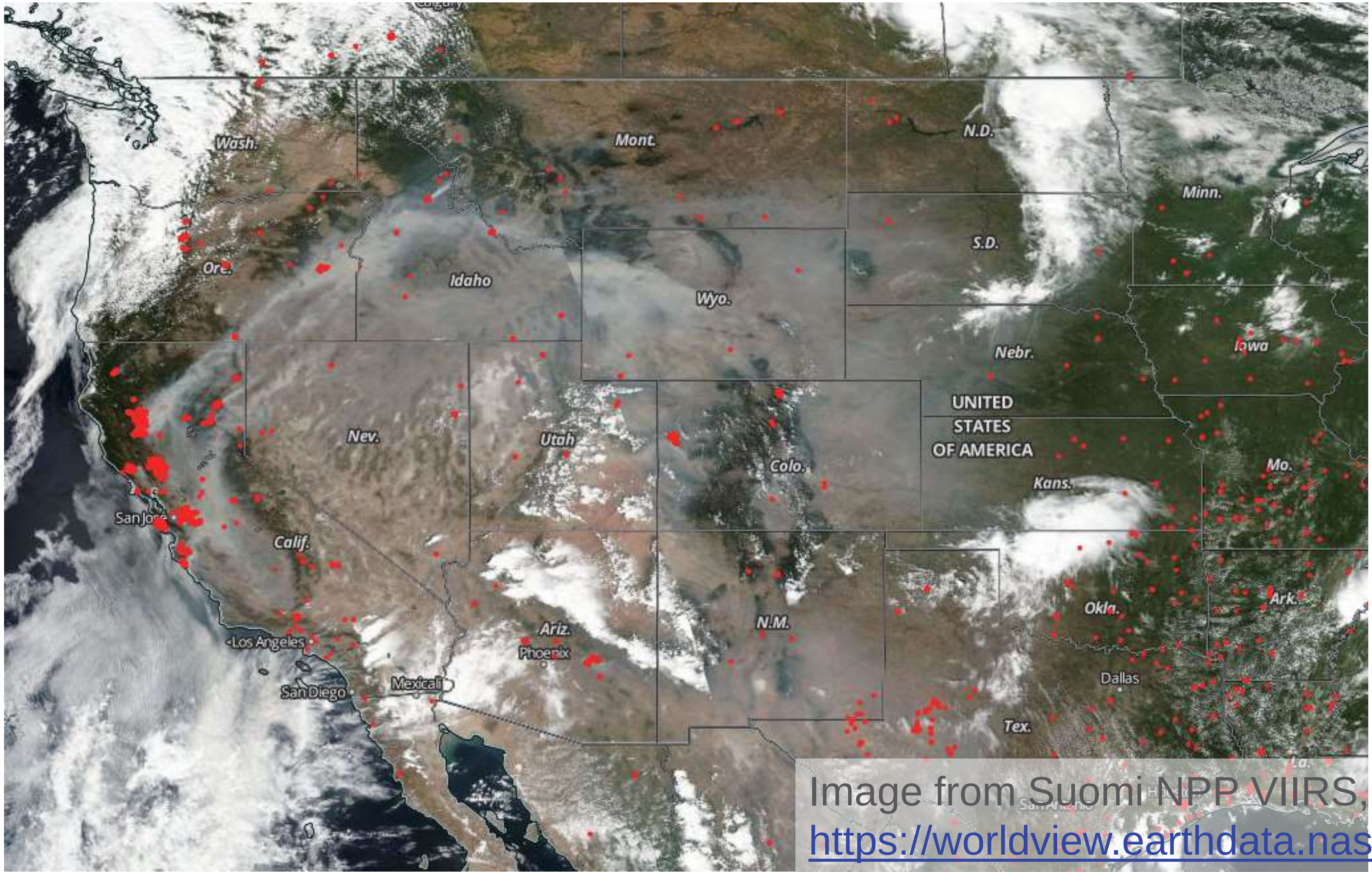


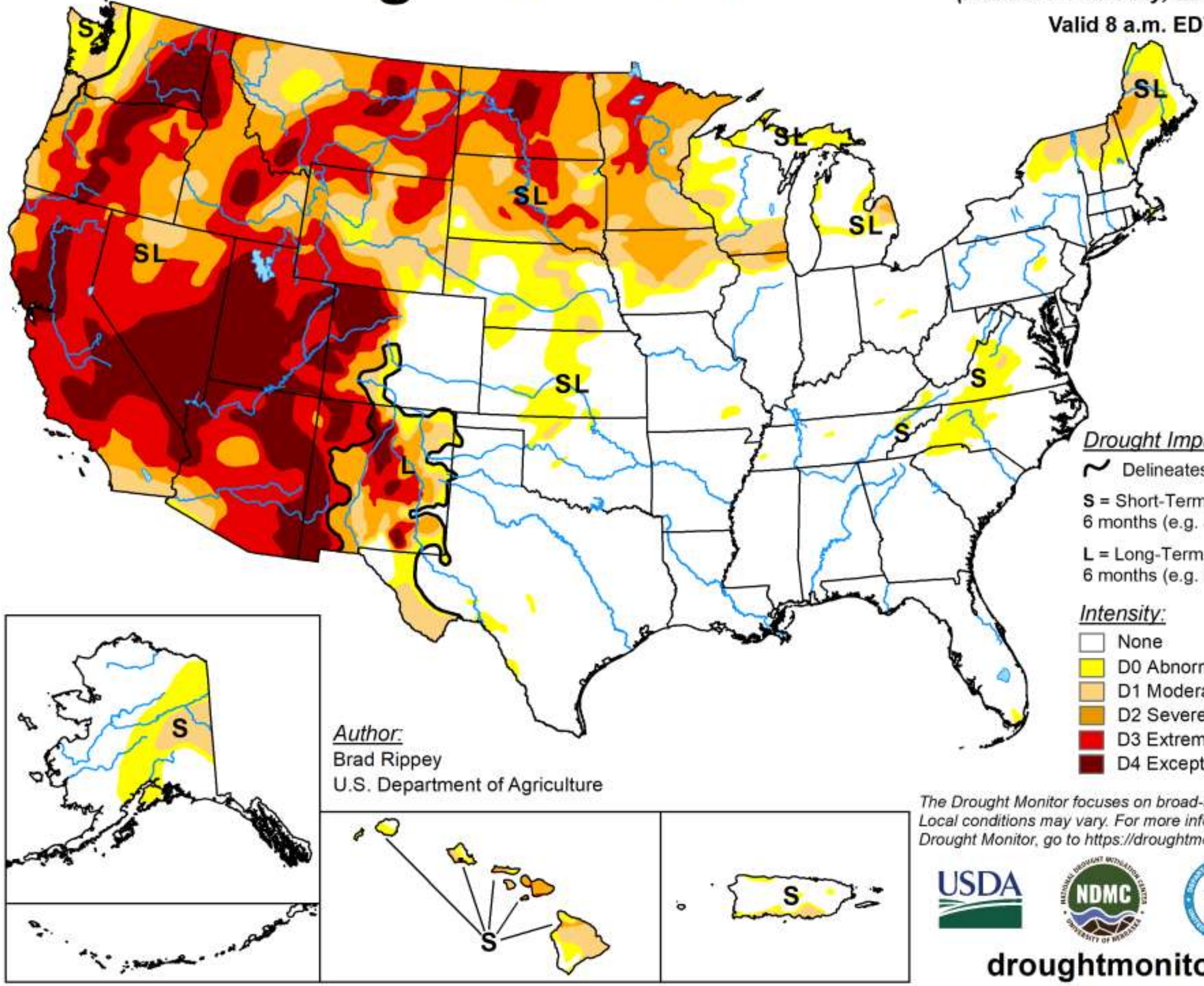
Image from Suomi NPP VIIRS, NASA Worldview: https://worldview.earthdata.nasa.gov/

U.S. Drought Monitor

July 20, 2021

(Released Thursday, Jul. 22, 2021)

Valid 8 a.m. EDT



Drought Impact Types:

~ Delineates dominant impacts

S = Short-Term, typically less than 6 months (e.g. agriculture, grasslands)

L = Long-Term, typically greater than 6 months (e.g. hydrology, ecology)

Intensity:

- None
- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

Author:

Brad Rippey

U.S. Department of Agriculture

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. For more information on the Drought Monitor, go to https://droughtmonitor.unl.edu/About.aspx

droughtmonitor.unl.edu

Visually, the worst smoke day in July 2021 (7/21)

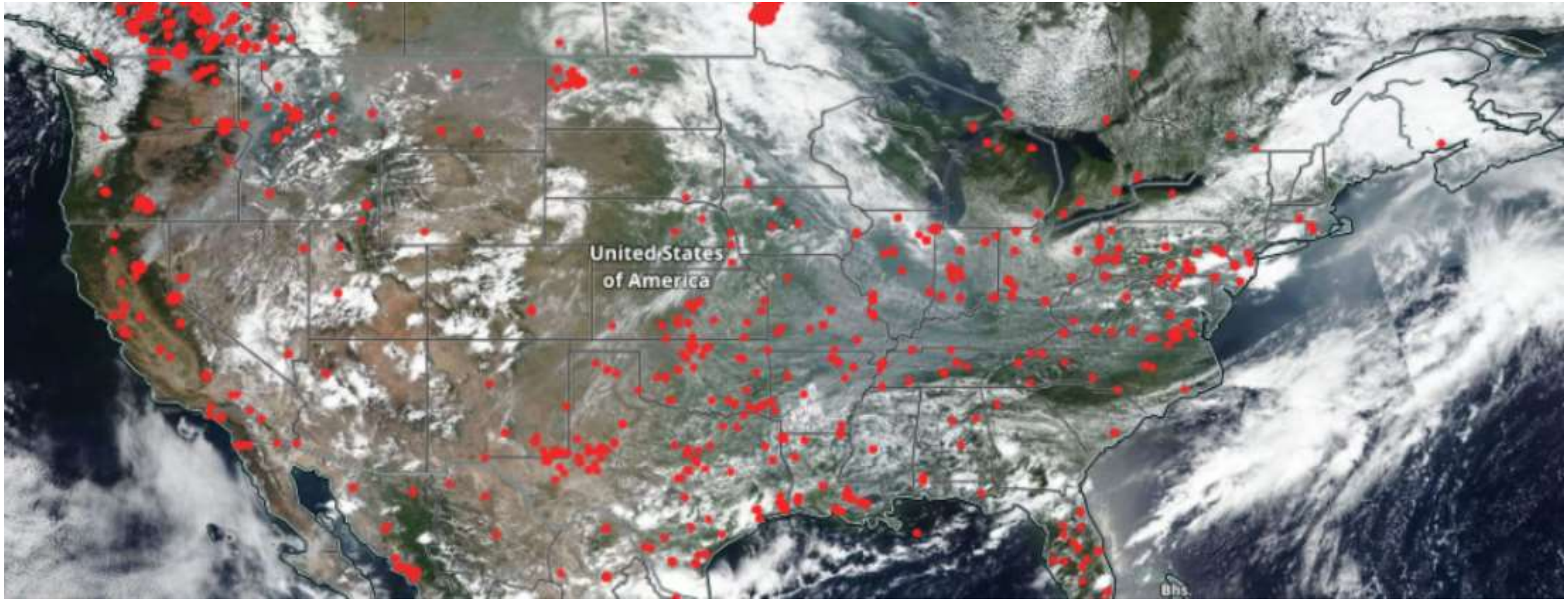
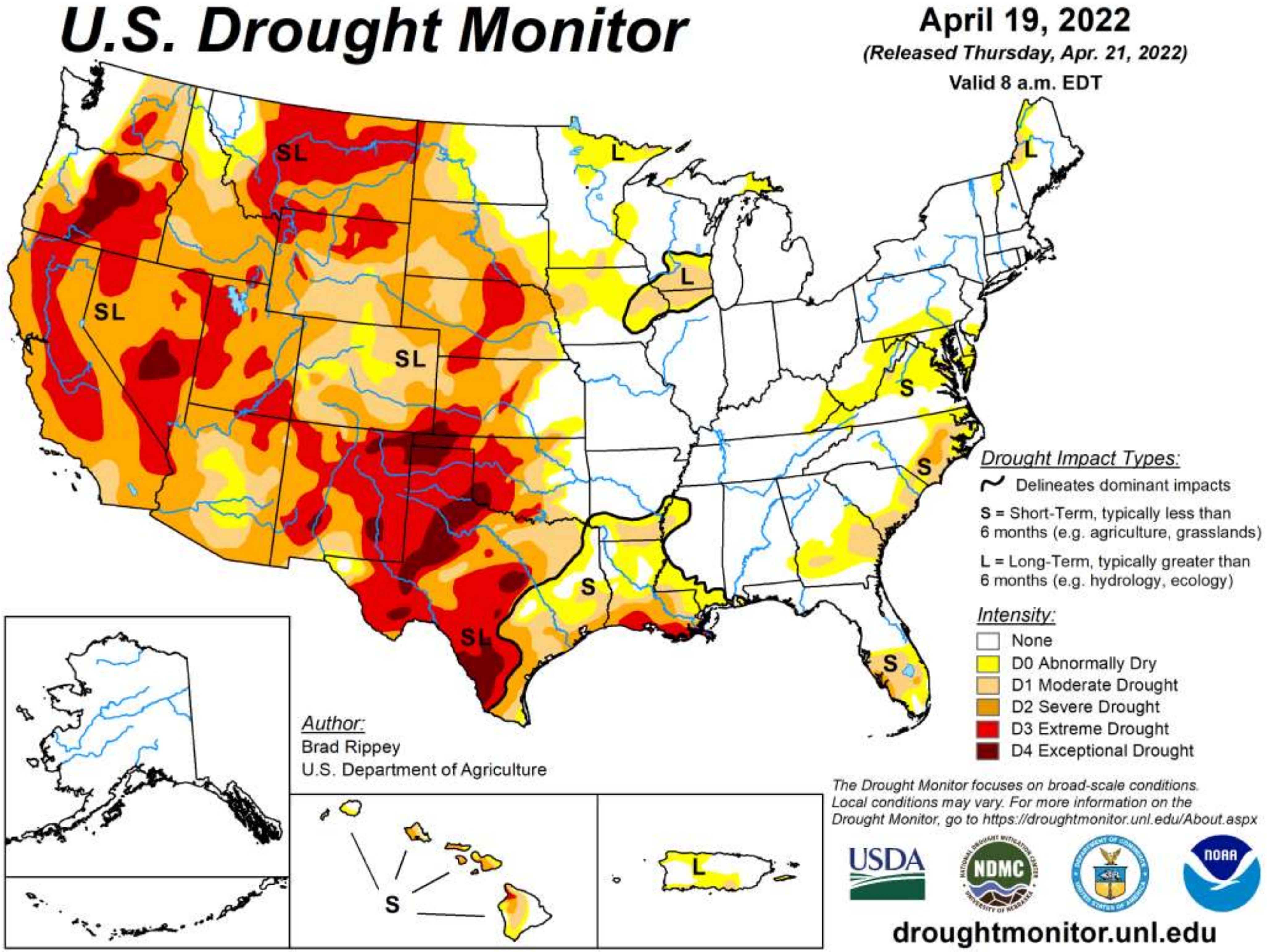
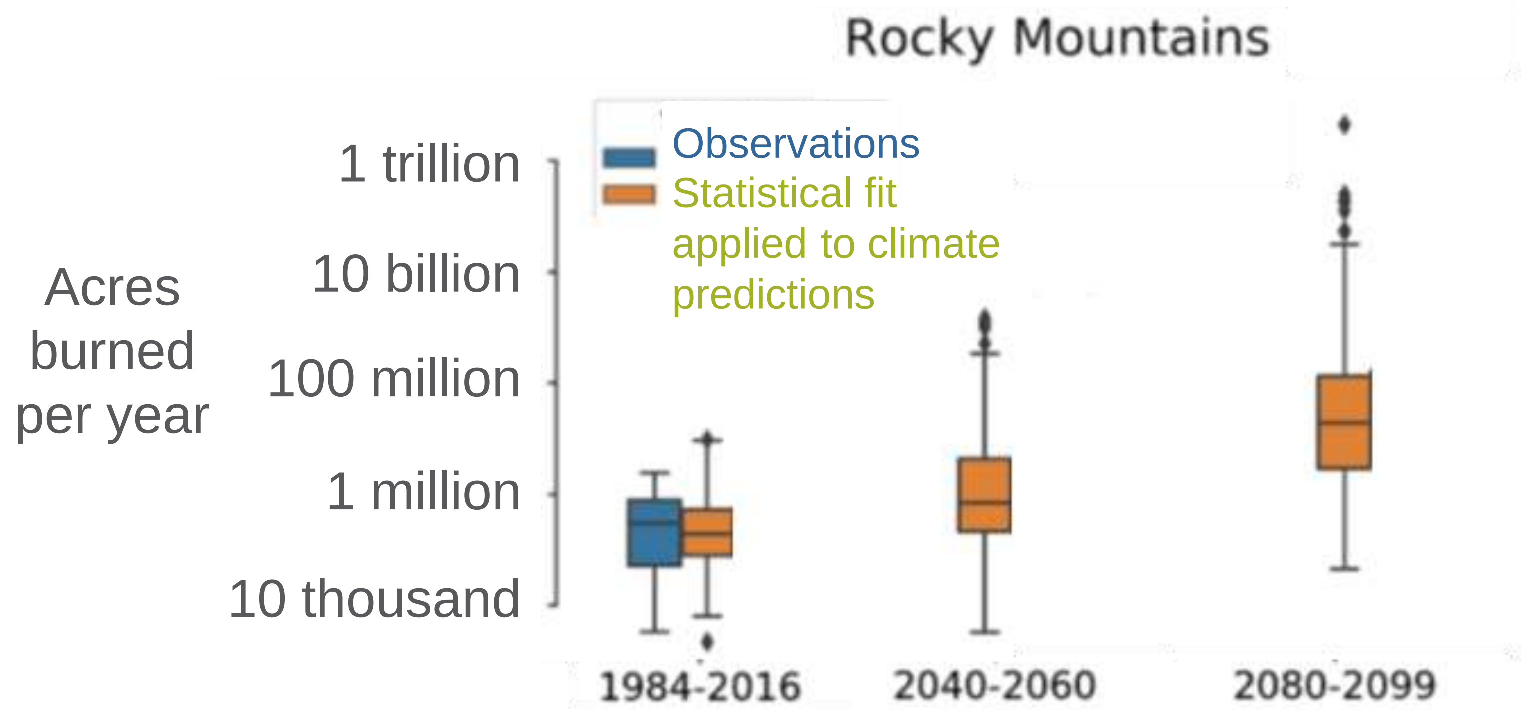
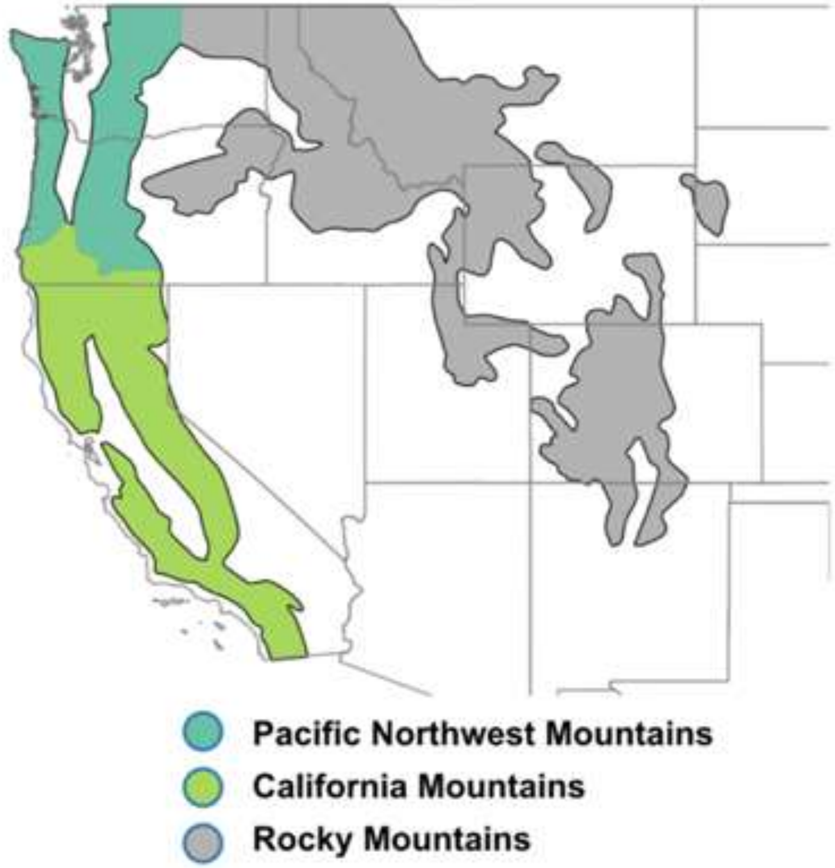


Image from Suomi NPP VIIRS, NASA Worldview:
https://worldview.earthdata.nasa.gov/


U.S. Drought Monitor
April 19, 2022
(Released Thursday, Apr. 21, 2022)
Valid 8 a.m. EDT
SL
L
L
L
SL
SL
S
S
S
SL
S
S
S
L
Drought Impact Types:
Delineates dominant impacts
S = Short-Term, typically less than 6 months (e.g. agriculture, grasslands)
L = Long-Term, typically greater than 6 months (e.g. hydrology, ecology)
Intensity:
None
D0 Abnormally Dry
D1 Moderate Drought
D2 Severe Drought
D3 Extreme Drought
D4 Exceptional Drought
Author:
Brad Rippey
U.S. Department of Agriculture
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. For more information on the Drought Monitor, go to https://droughtmonitor.unl.edu/About.aspx
USDA
NDMC
droughtmonitor.unl.edu

Based on present-day predictors of fire, burn area should increase in the Rockies across 15 climate models





Earth's Future

Research Article | Open Access

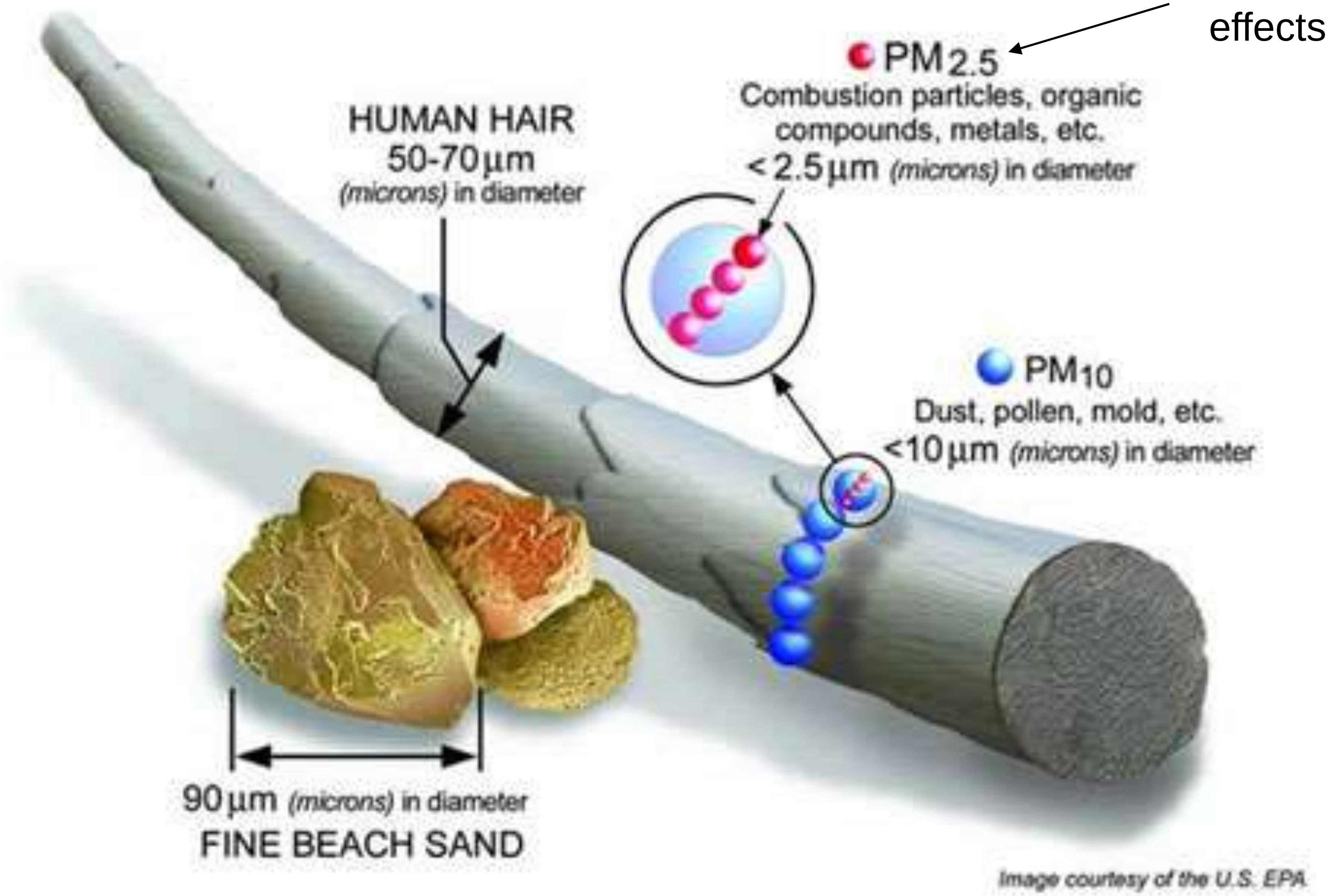
Past variance and future projections of the environmental conditions driving western U.S. summertime wildfire burn area

Steven J. Brey, Elizabeth A. Barnes, Jeffrey R. Pierce, Abigail L. S. Swann, Emily V. Fischer

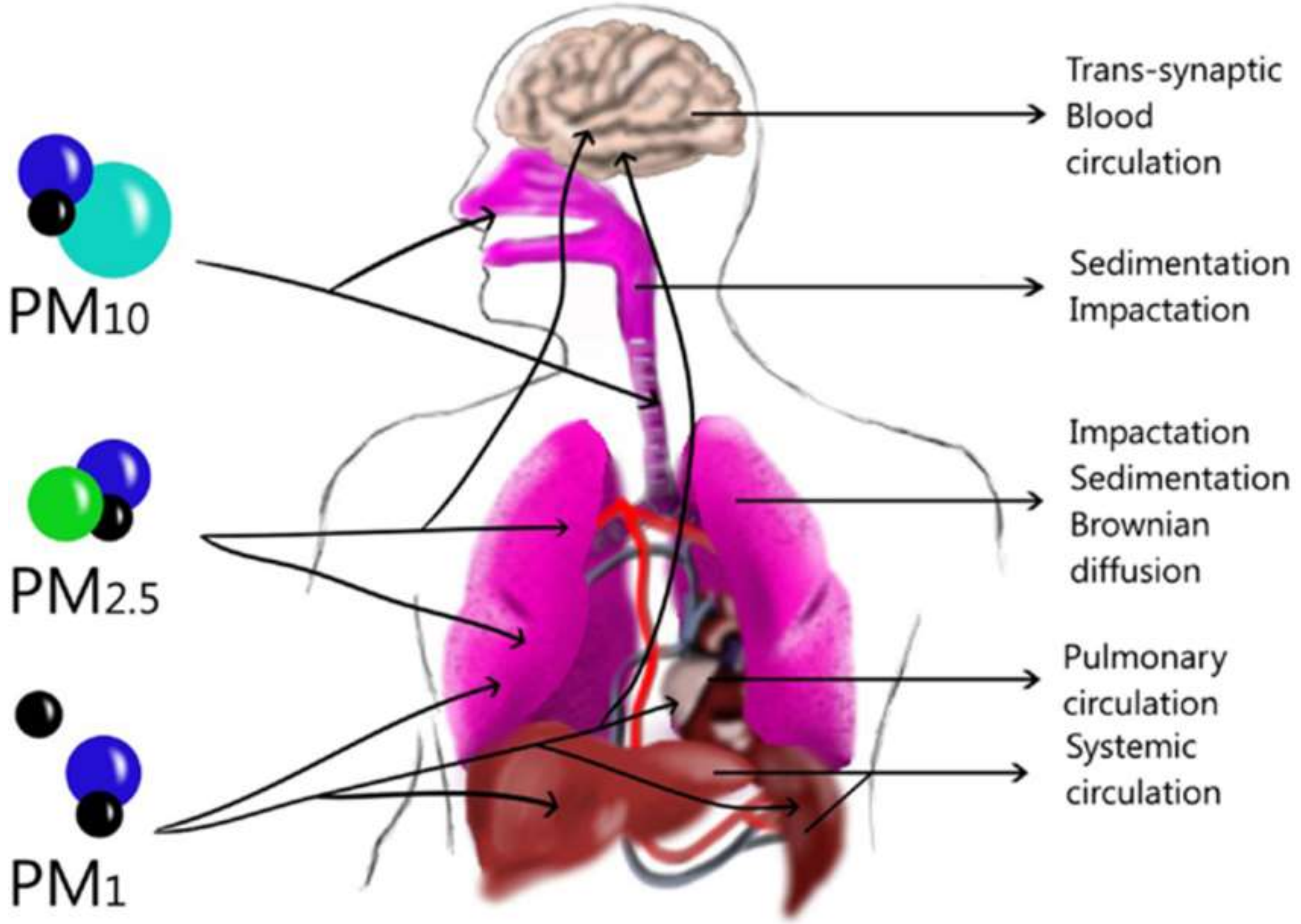
First published: 17 July 2020 | https://doi.org/10.1029/2020EF001645

Fine particulate matter (aerosols): $PM_{2.5}$

Aerosol health effects tied to $PM_{2.5}$

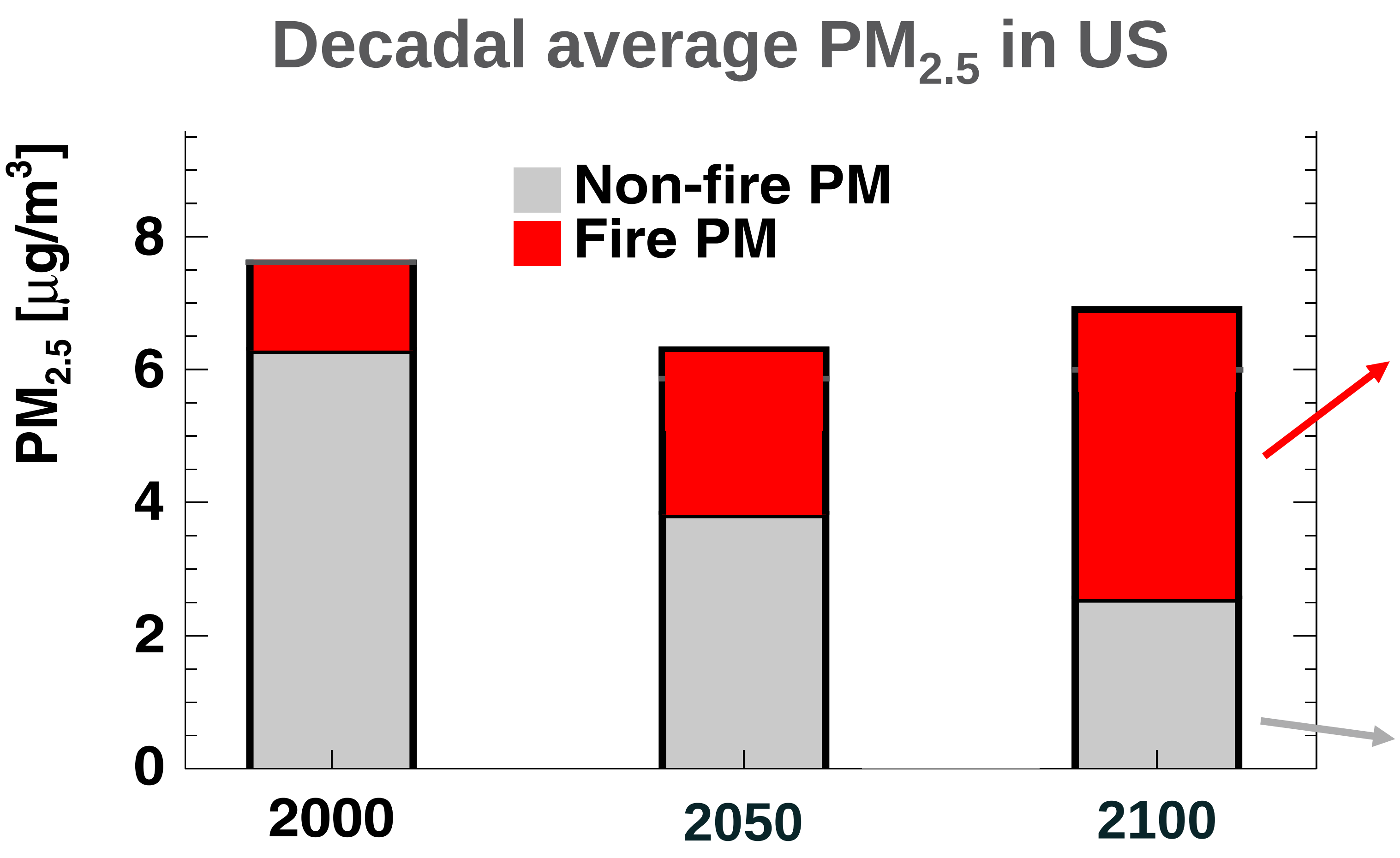


$PM_{2.5}$ deposits predominately in the lower airways



Falcon-Rodriguez et al., Frontiers of Immunology, 2016.

Using an Earth System Model, we predict smoke to offset improvements in anthropogenic emissions in the future



Bonne Ford, Maria Val Martin, Sarah E. Zelasky, Emily V. Fischer, Susan C. Anenberg, Colette L. Heald, Jeffrey R. Pierce: Future Fire Impacts on Smoke Concentrations, Visibility, and Health in the Contiguous United States, *GeoHealth*, 2018.

How do we understand how much smoke people are breathing?

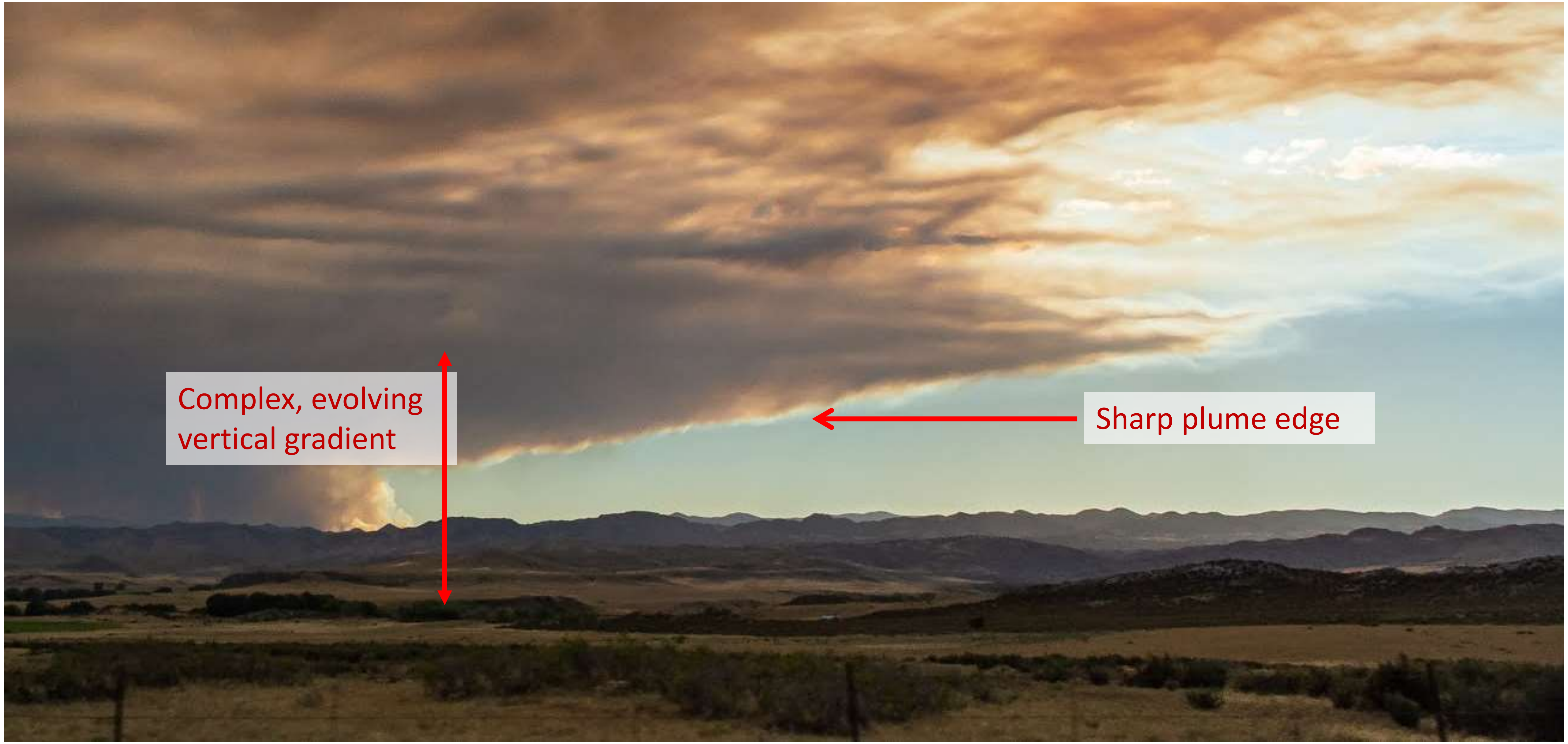
Quantifying exposure to wildfire smoke is a big challenge.

Taken by Ali Akherati, driving from Laramie to Fort Collins, CO 8/16

Quantifying exposure to wildfire smoke is a big challenge.

Taken by Ali Akherati, driving from Laramie to Fort Collins, CO 8/16

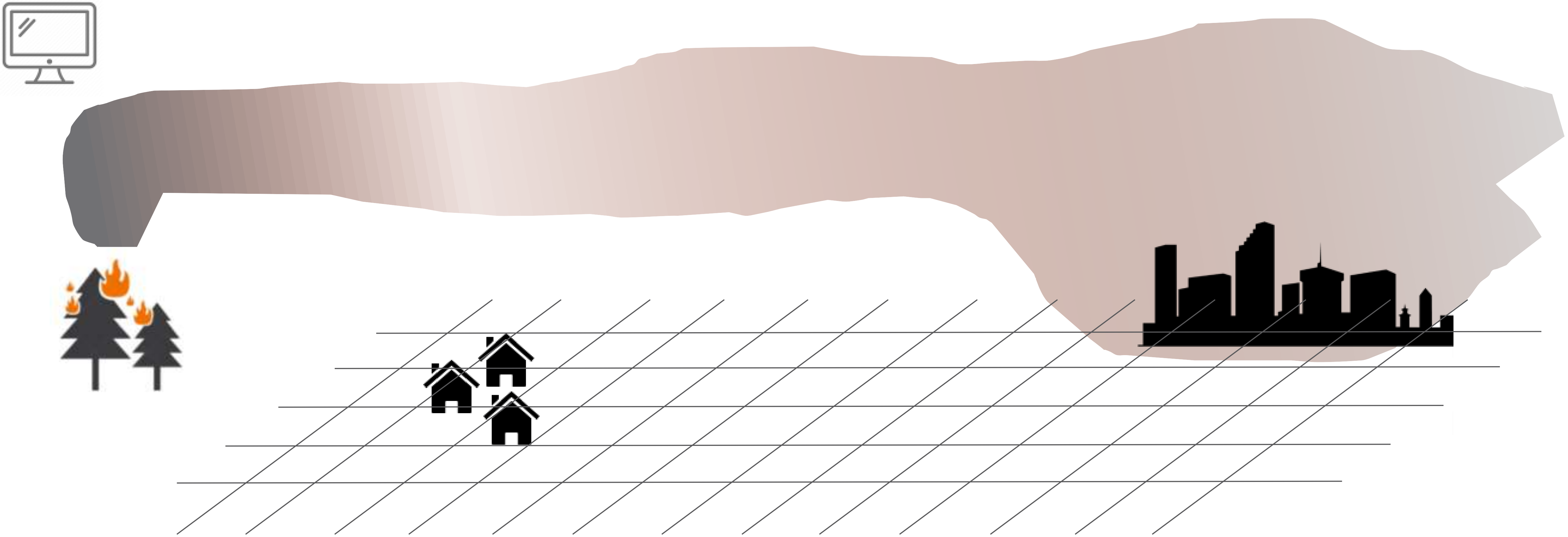
Quantifying exposure to wildfire smoke is a big challenge.



Taken by Ali Akherati, driving from Laramie to Fort Collins, CO 8/16

Three imperfect methods to estimate smoke exposure

Chemical Transport Models – Still struggle with many things, including: injection height, total emissions and their speciation; new fires, etc.

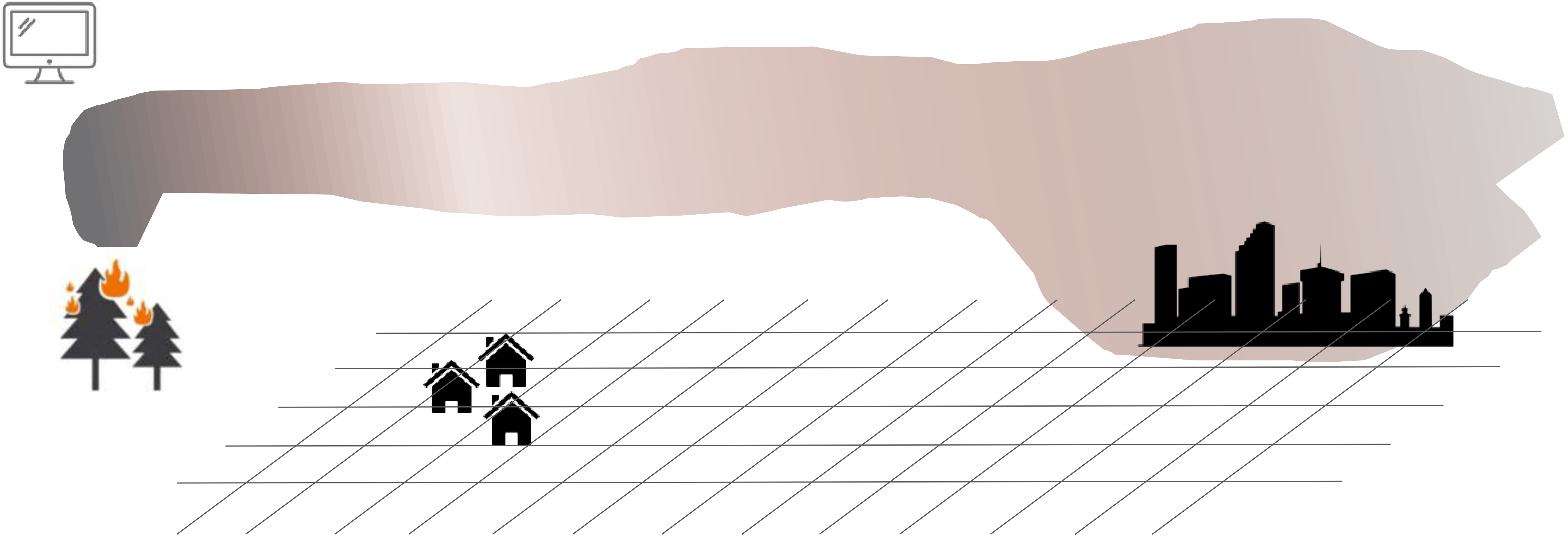


Slide courtesy of Emily Fischer

Three imperfect methods to estimate smoke exposure

Chemical Transport Models – Still struggle with many things, including: injection height, total emissions and their speciation; new fires, etc.

Satellites – Can detect the plumes spatial extent, but usually can't tell us about surface impacts.

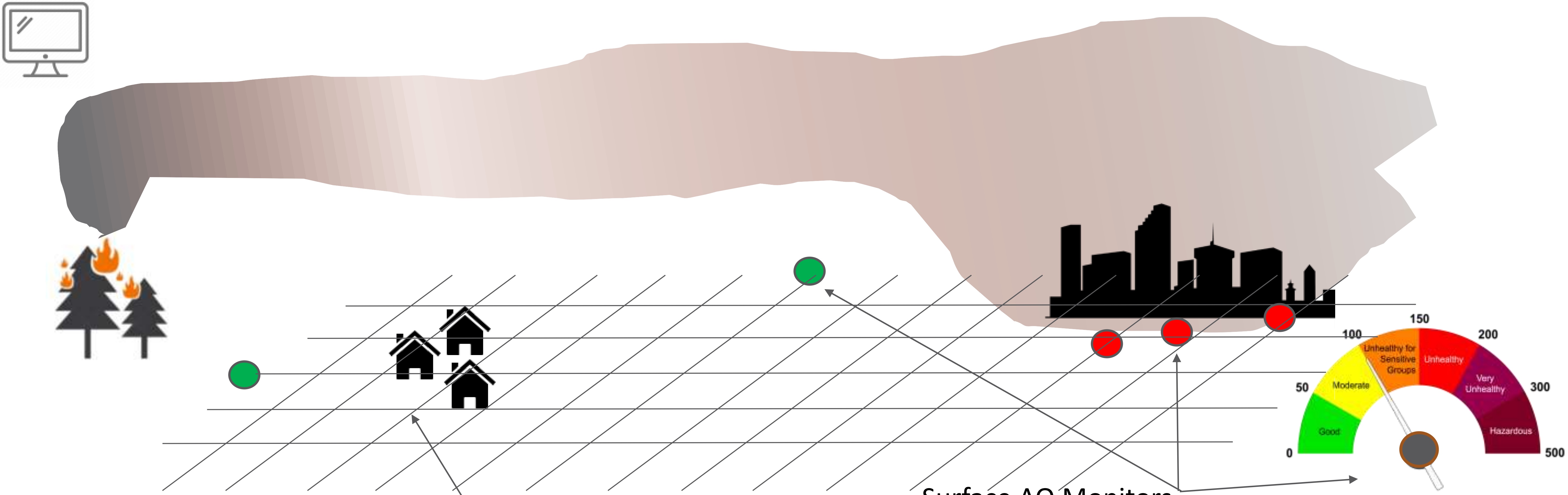


Slide courtesy of Emily Fischer

Three imperfect methods to estimate smoke exposure

Chemical Transport Models – Still struggle with many things, including: injection height, total emissions and their speciation; new fires, etc.

Satellites – Can detect the plumes spatial extent, but usually can't tell us about surface impacts.



We need to know AQ everywhere where people live, work and play - not just near the monitors!

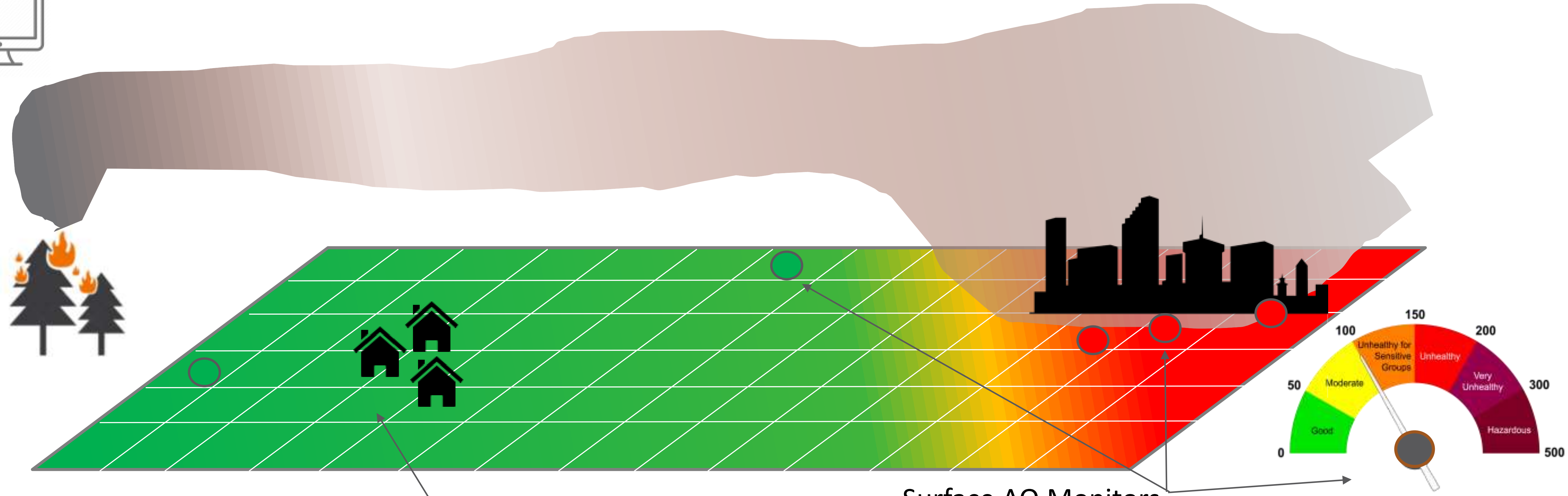
Surface AQ Monitors (note these are sparse)

Slide courtesy of Emily Fischer

Three imperfect methods to estimate smoke exposure

Chemical Transport Models – Still struggle with many things, including: injection height, total emissions and their speciation; new fires, etc.

Satellites – Can detect the plumes spatial extent, but usually can't tell us about surface impacts.



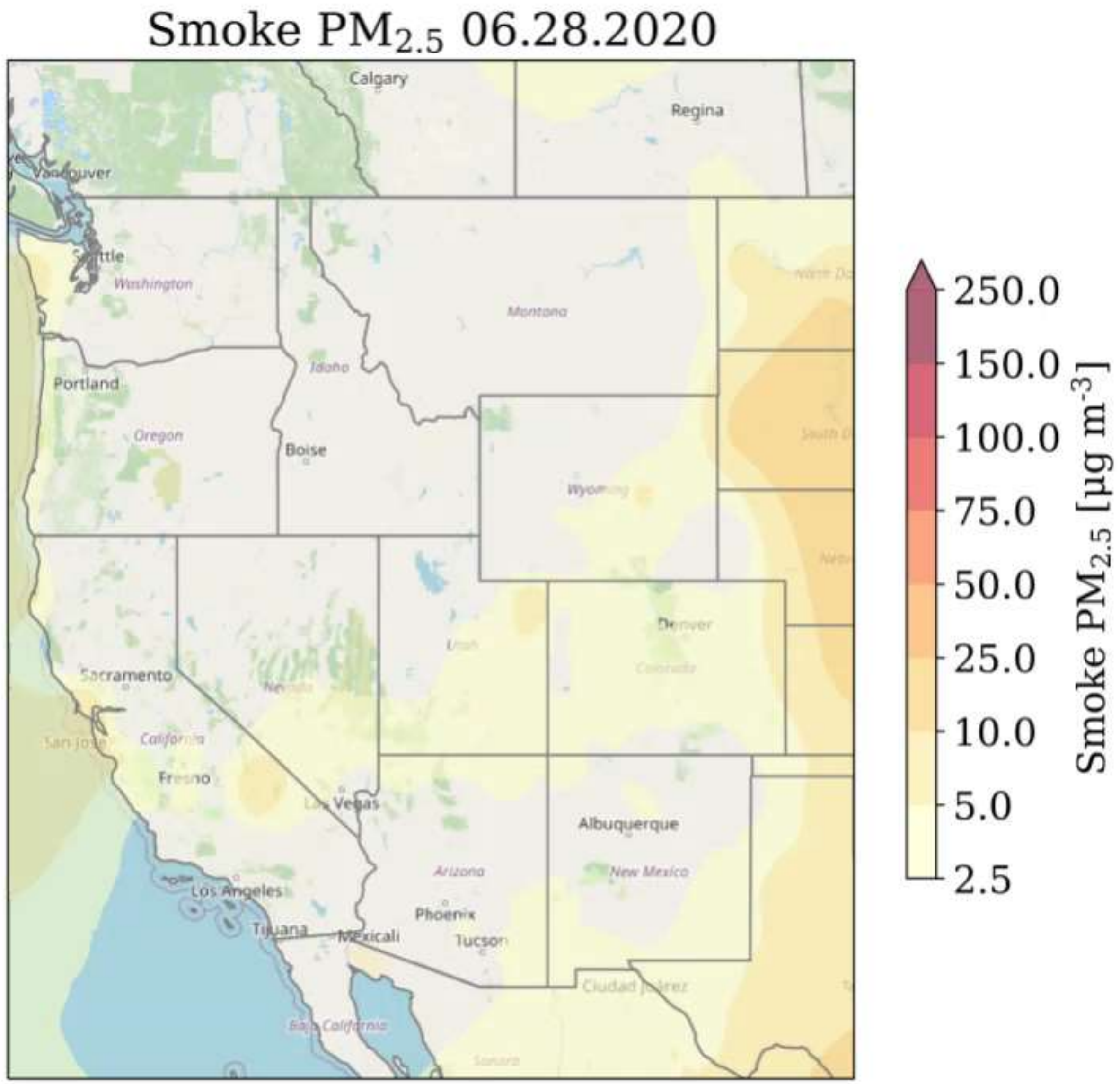
Surface AQ Monitors (note these are sparse)

We need to know AQ everywhere where people live, work and play - not just near the monitors!

Slide courtesy of Emily Fischer

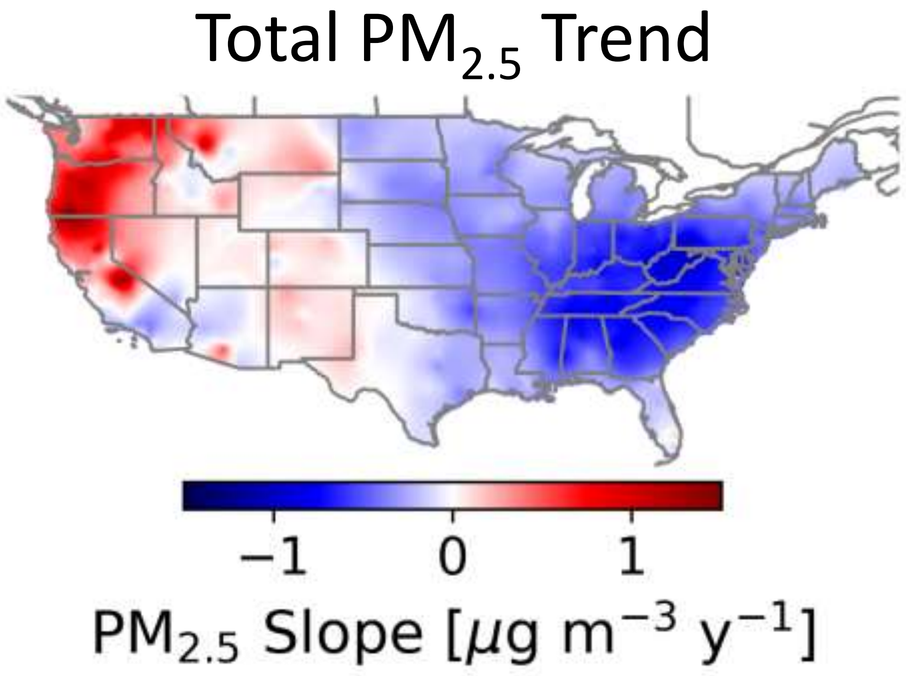
Our daily $PM_{2.5}$ smoke maps:

Combine surface monitor and satellite information



Summertime particulate matter is getting worse in the western US.

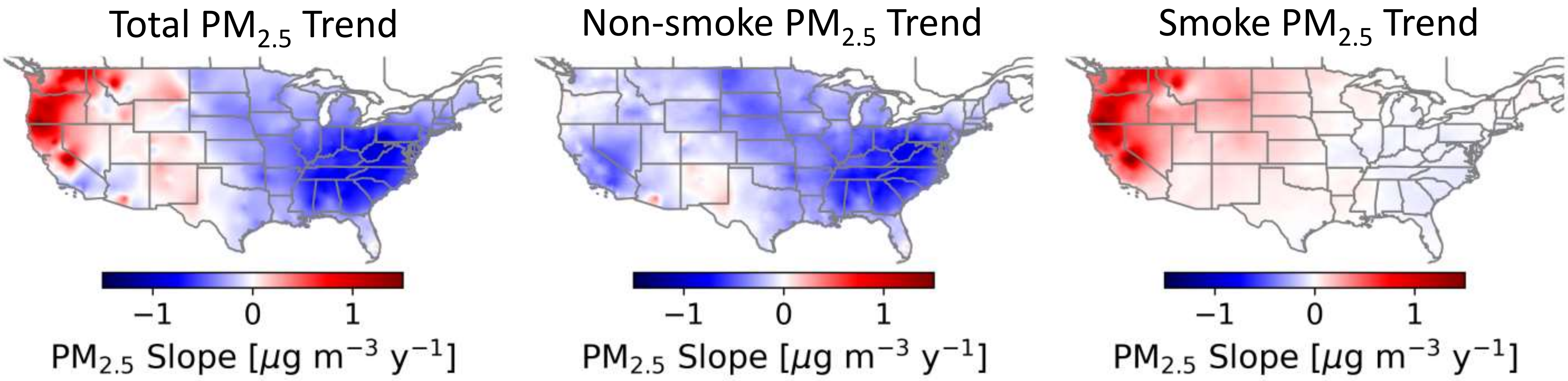
2006 – 2020 trends in summer $PM_{2.5}$



Katelyn O'Dell, Bonne Ford, Emily V. Fischer, and Jeffrey R. Pierce. (2019). Contribution of wildland-fire smoke to US $PM_{2.5}$ and its influence on recent trends. ES&T. doi: 10.1021/acs.est.8b05430.

Summertime particulate matter is getting worse in the western US.
It's the smoke!

2006 – 2020 trends in summer $PM_{2.5}$



Katelyn O'Dell, Bonne Ford, Emily V. Fischer, and Jeffrey R. Pierce. (2019). Contribution of wildland-fire smoke to US $PM_{2.5}$ and its influence on recent trends. ES&T. doi: 10.1021/acs.est.8b05430.

Challenges in identifying smoke

- Currently not available in real time.
  - Working on real-time product with City of Fort Collins!
- Challenging to estimate in mountainous and remote regions.
  - Smoke concentrations greatly affected by topography.

Overnight downslope flow
August 15, 6:30 AM MDT

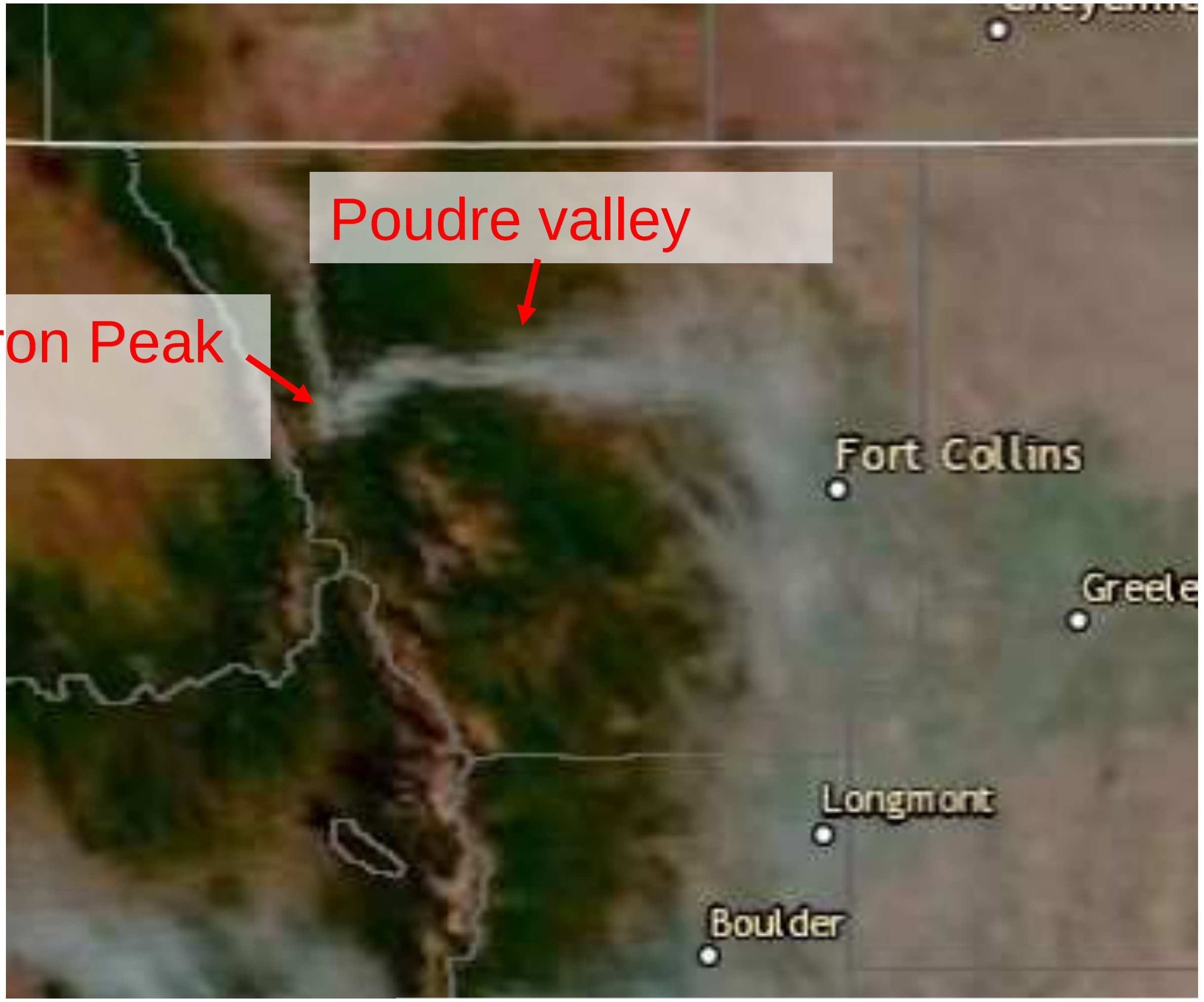
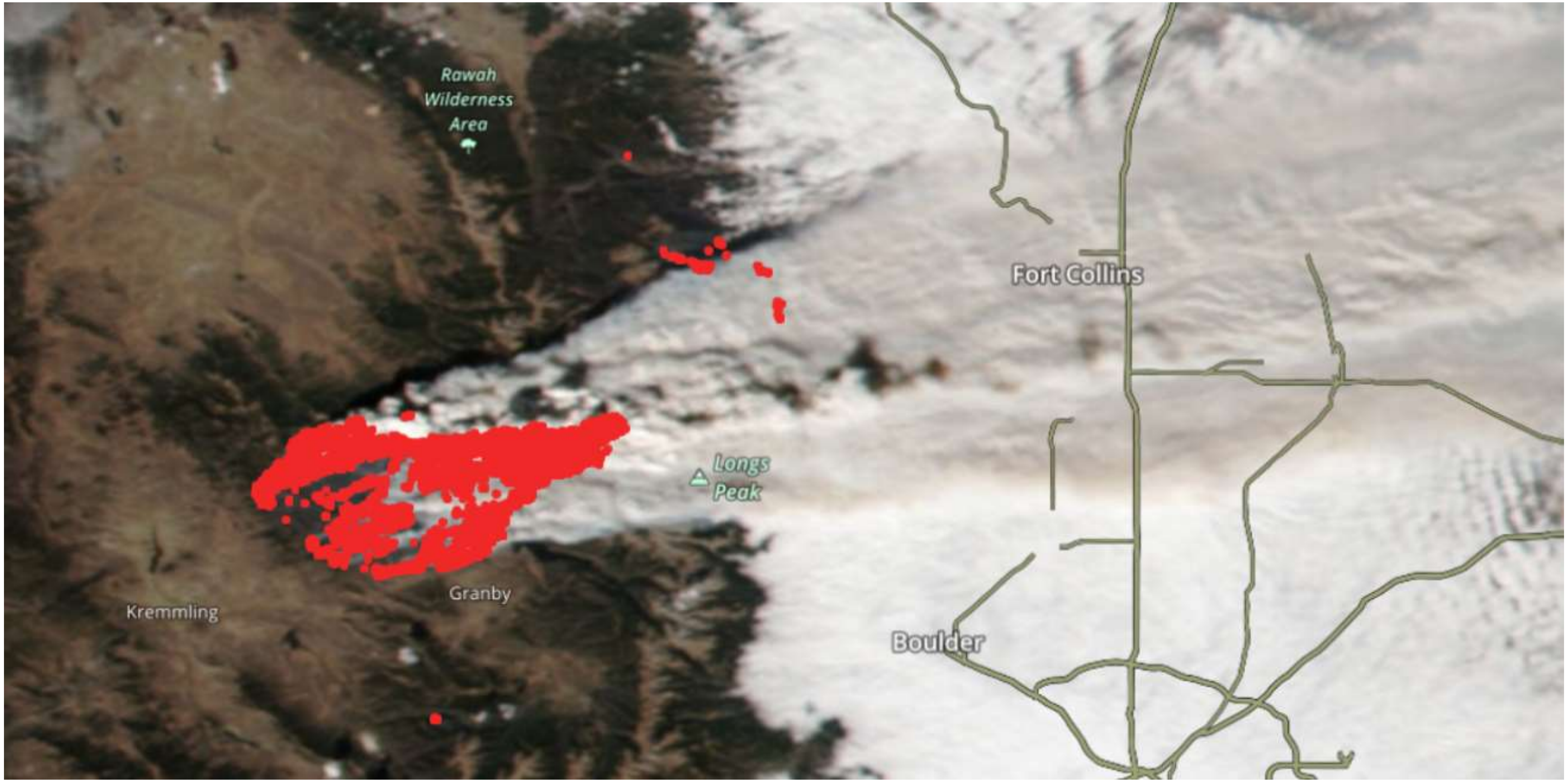


Image from GOES-16, NOAA AerosolWatch: https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/

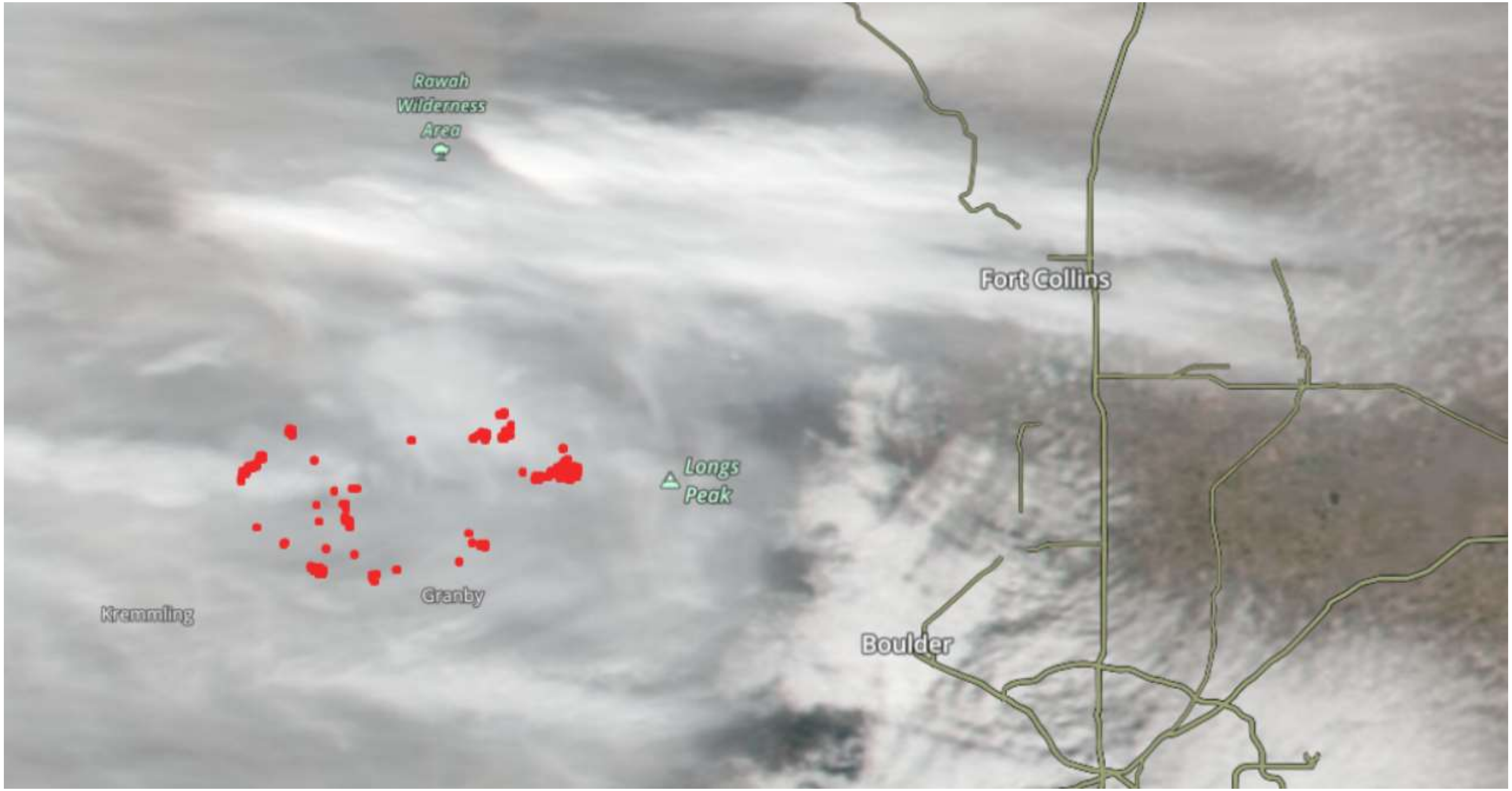
Challenges in identifying smoke

- Currently not available in real time.
  - Working on real-time product with City of Fort Collins!
- Challenging to estimate in mountainous and remote regions.
  - Smoke concentrations greatly affected by topography.
  - Satellites alone struggle to tell us about smoke at the surface.

October 22, 2020: Most of the smoke aloft?



October 23, 2020: High clouds obscure picture



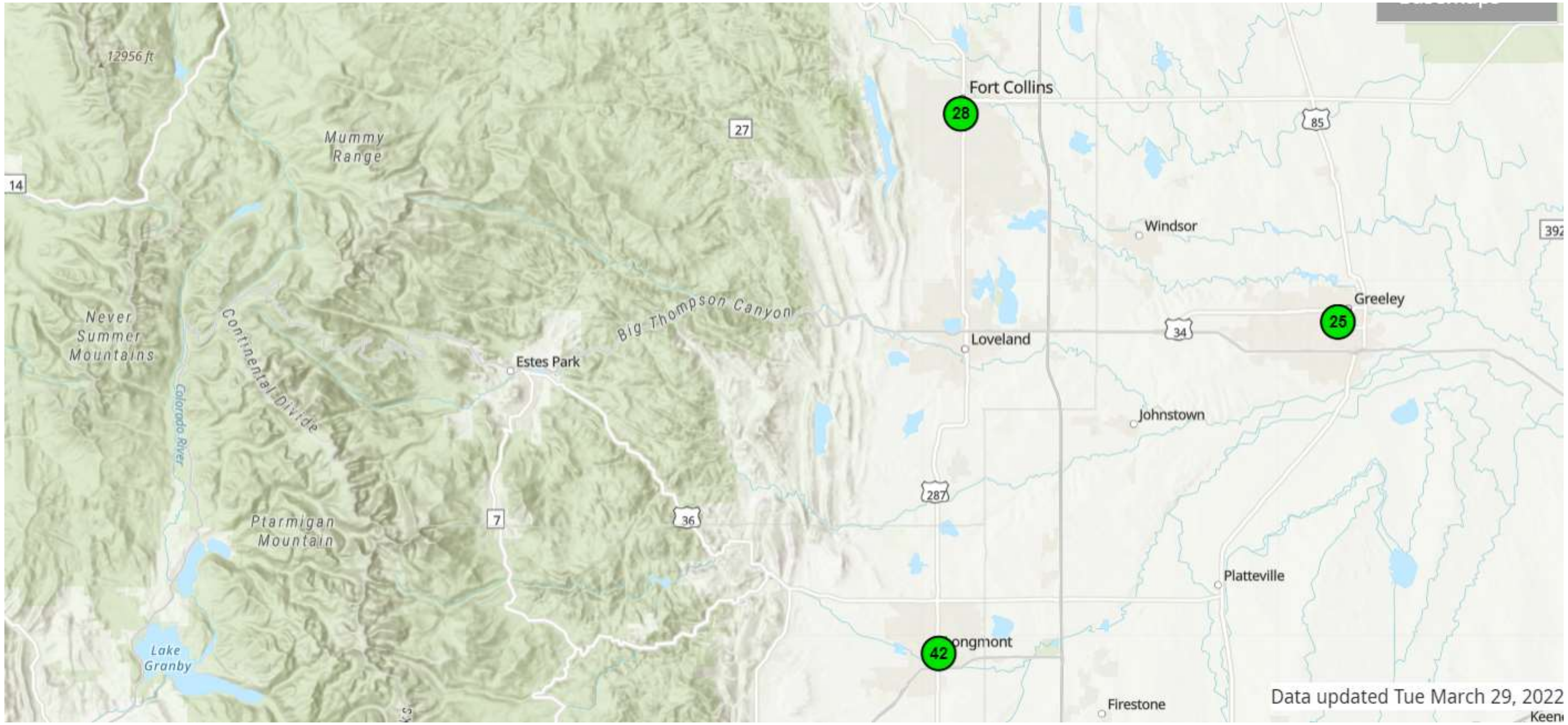
Challenges in identifying smoke

- Currently not available in real time.
  - Working on real-time product with City of Fort Collins!
- Challenging to estimate in mountainous and remote regions.
  - Smoke concentrations greatly affected by topography.
  - Satellites alone struggle to tell us about smoke at the surface.
    - No info at night.

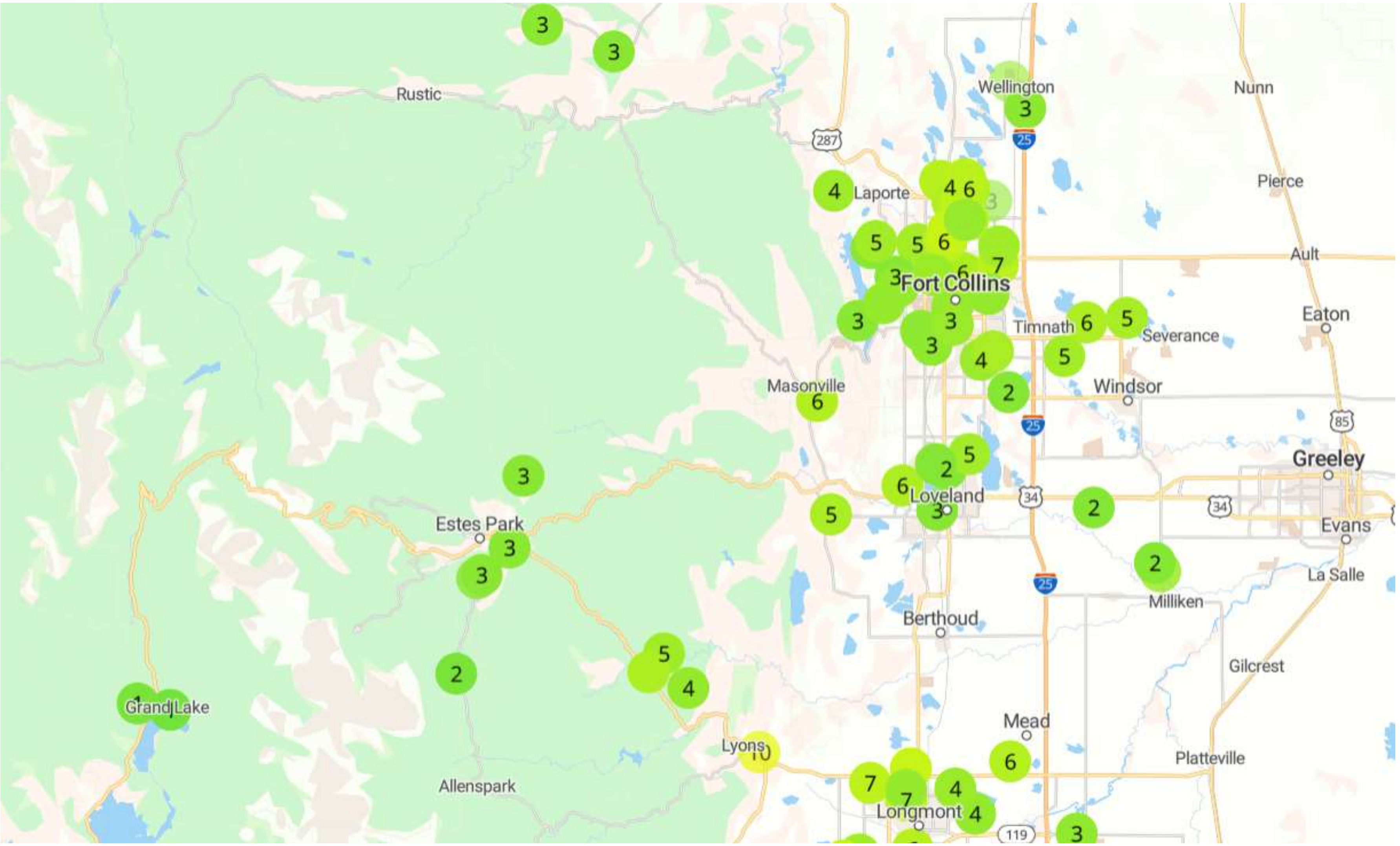
Challenges in identifying smoke

- Currently not available in real time.
  - Working on real-time product with City of Fort Collins!
- Challenging to estimate in mountainous and remote regions.
  - Smoke concentrations greatly affected by topography.
  - Satellites alone struggle to tell us about smoke at the surface.
    - No info at night.
  - Few regulatory $PM_{2.5}$ monitors.

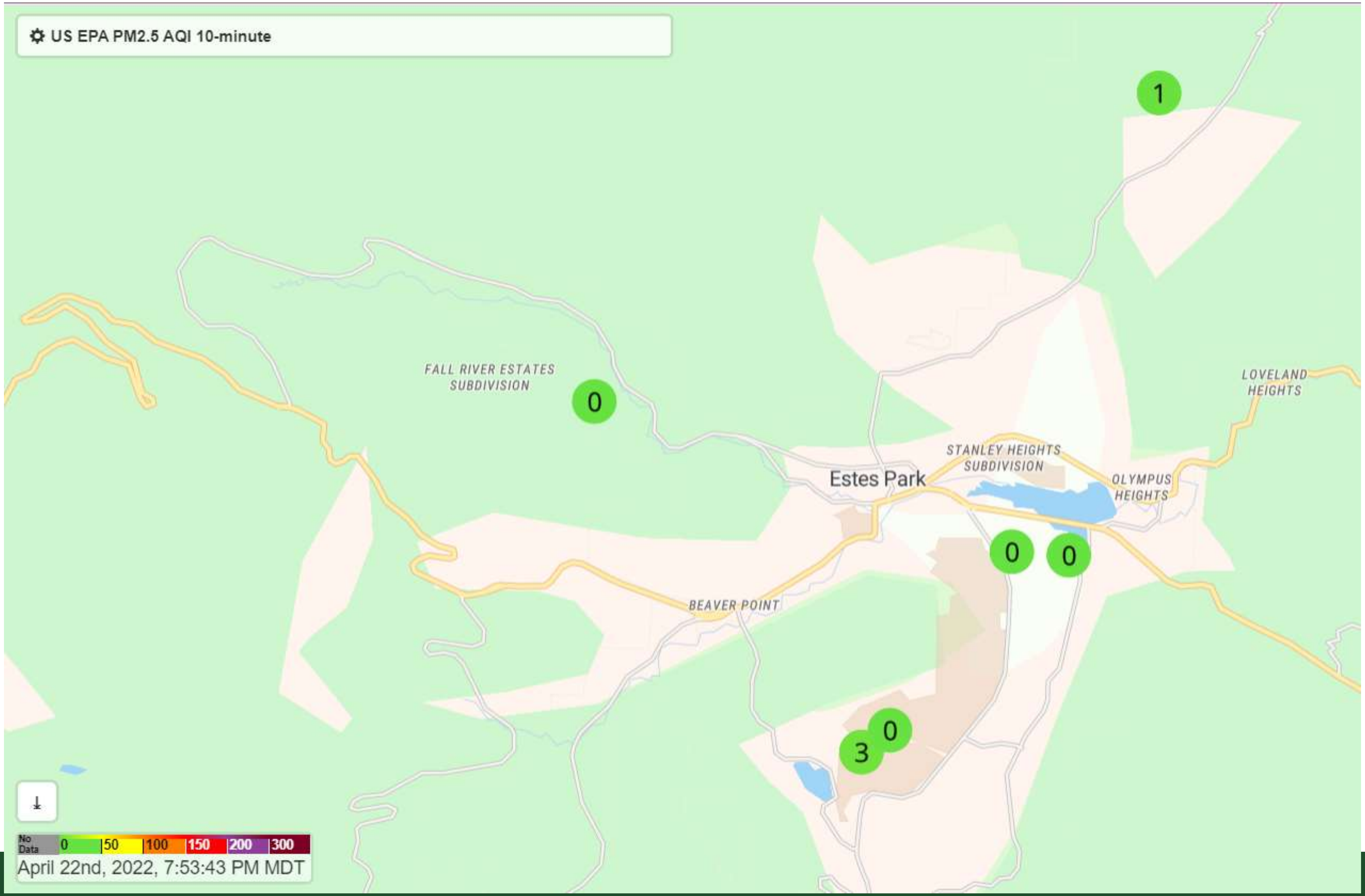
We don’t expect smoke in Estes to be the same as in Fort Collins!



We can improve by including the growing, low-cost PurpleAir monitors!!

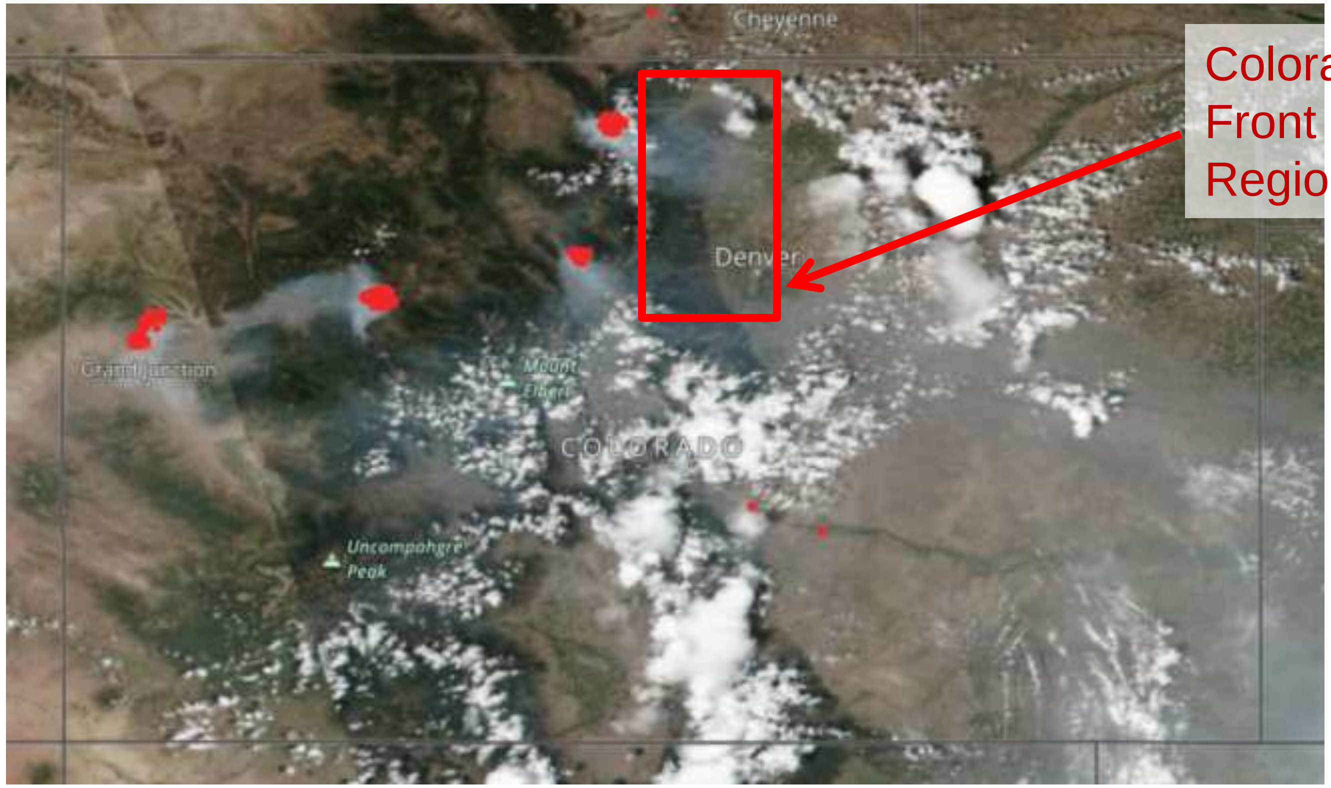


…especially in Estes Park!



Smoke in Colorado: Local fires vs. long-range transport

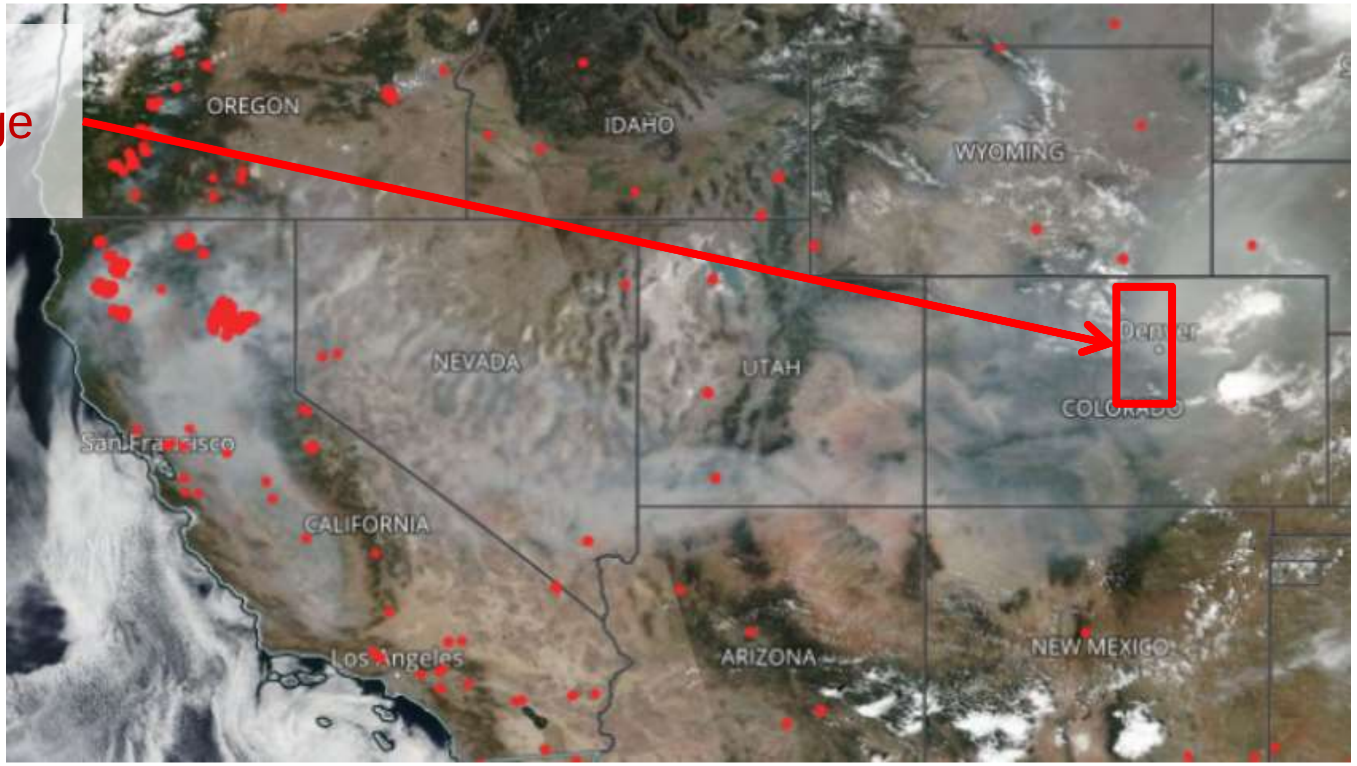
Colorado as viewed by VIIRS, Aug 16, 2020



Large local fires with NoCo smoke impacts

- Relatively infrequent (e.g., 2012, 2020)
- High smoke concentrations (>100 μg m^{-3})
- High awareness
  - Smoke smell, fires in news, views of plumes

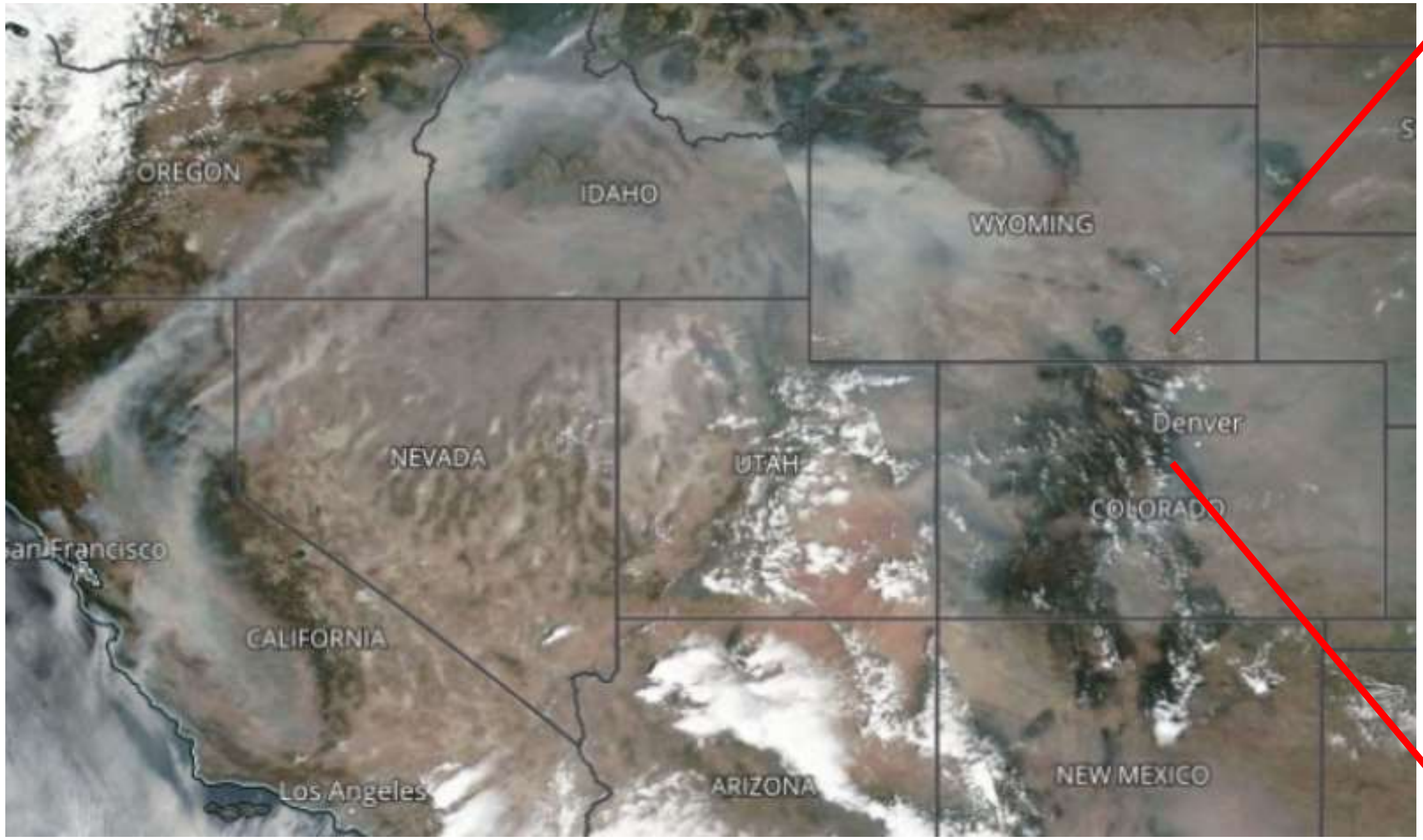
Western US as viewed by VIIRS, Aug 8, 2021

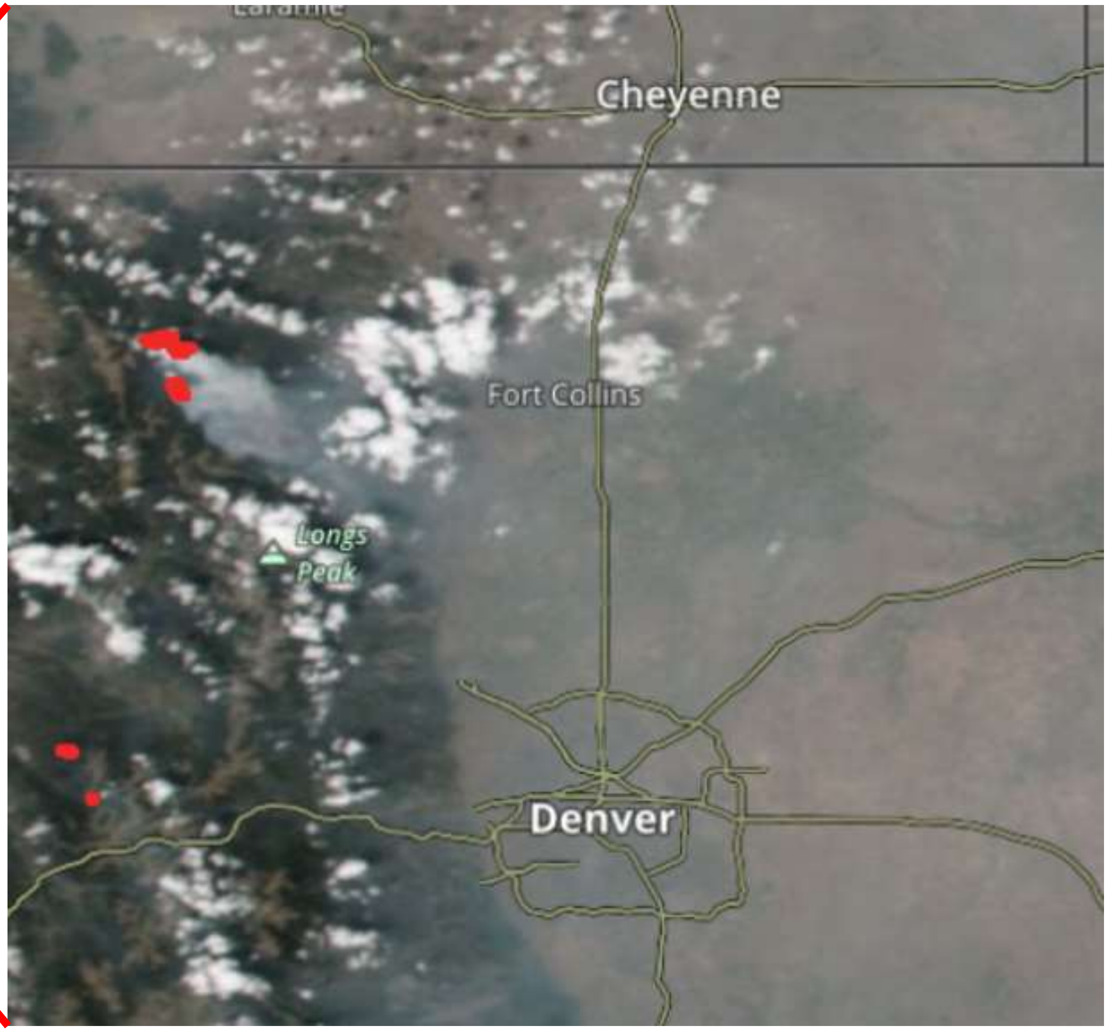


Transported smoke from western fires

- Several days in most years
- Lower smoke concentrations (<100 μg m^{-3})
- Lower awareness
  - No smoke smell, less local concern of fires

Sometimes we're "lucky" enough to have both kinds of smoke!



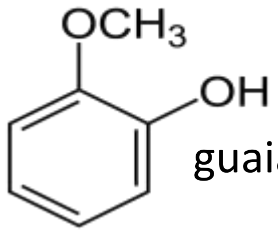


August 21, 2020

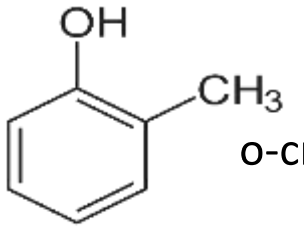
How to tell if it’s local vs. long-range smoke? **Smell**!

- The species in smoke that cause the smell react away within 1 day. Smoke loses its smell!

Smoky-smell chemicals



guaiacol



o-cresol

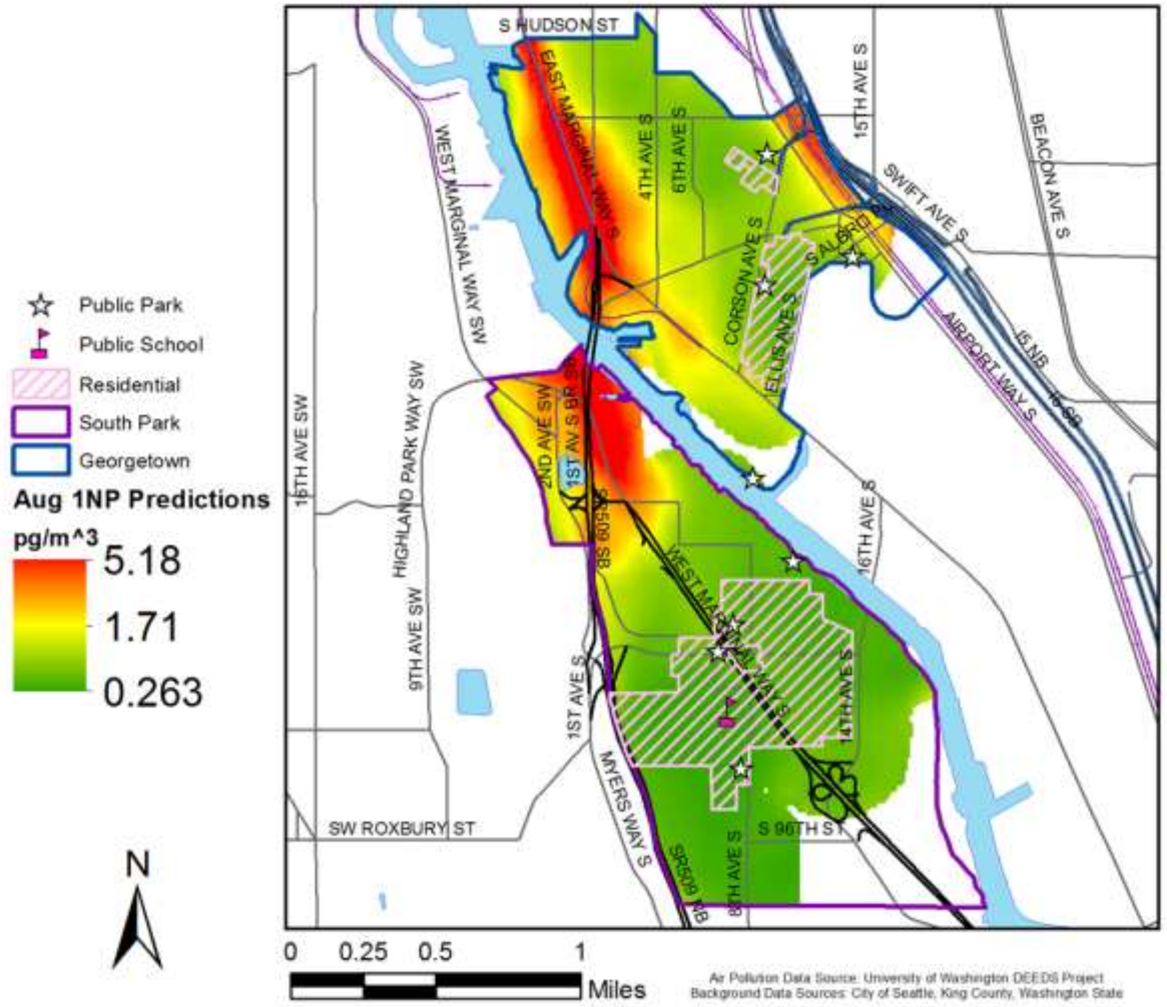
- What did I notice in Fort Collins during August 18-24, 2020?
  - Smoky smell in the morning: local smoke draining down Poudre, mixed with California smoke (highest concentrations in morning)
  - No smoky smell in the afternoons/evenings but still visibly hazy and fairly high PM concentrations: Just California smoke

Intro to air pollution epidemiology

<u>Traffic Related Air Pollution</u>

- **Predictable** $PM_{2.5}$ patterns of exposure over space and time
- **Consistent** set of **exposure assessment** tools:
  - Community: GIS, fixed-site monitors, dispersion models, land use regression, satellite data
  - Personal: personal monitors -> what's in the PM?
- **Flexibility** in **epidemiological** study designs:
  - **Prospective studies** (i.e., cohort)
  - Time-series studies
  - Natural experiments (e.g., policy changes, disasters)

❖ Consistent, predictable exposure assessment leads to **etiologic** data



Neighborhood gradients for 1-nitropyrene (1-NP), a marker of diesel exposure exhaust, Seattle, WA (Source: Schulte et al. 2015)
doi.org/10.1021/acs.est.5b03639

TRAP and WFS epidemiology

Wildfire Smoke

- **Unpredictable** $PM_{2.5}$ patterns of exposure over space and time
- **Variability** in **exposure assessment** tools:
    - Ambient levels: chemical transport models, fixed-site monitors, satellite data, aircraft campaigns
    - Personal: occupational studies
- **Challenges** in epidemiological study designs:
    - **Retrospective studies** (including time series studies, case-crossover studies)
    - **Prospective studies** (Orr *et al.* 2020; Landguth *et al.* 2020) require rapid response at (currently) limited spatial extent

❖ Variable, unpredictable nature of smoke requires creativity for health assessment

Cameron Peak Fire from Fort Collins, CO. Oct 2020
Photo Credit: Ali Akherati, CSU

Case-crossover study design

What is a case-crossover study design?

- An individual serves as their own control
- Eliminates need to adjust for confounding at the individual level
- Good for transient exposures, transient outcomes (e.g., early use was to understand if snow fall was associated with presenting to ED with MI (in Boston – shoveling…)

Example from the air pollution literature:

- Individual goes to the hospital on July 23rd for respiratory problems
- Can understand role of ozone and temperature in hospitalization by looking at *index day* (23rd) compared to other days
- Still investigates question at group level
- Assumes hospitalization is a rare and transient event
- Challenges in selecting referent period

July 1998

Sun	Mon	Tue	Wed	Thu	Fri	Sat
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

July 1998

Sun	Mon	Tue	Wed	Thu	Fri	Sat
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

July 1998

Sun	Mon	Tue	Wed	Thu	Fri	Sat
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

Wildfire Smoke + Health

How do we measure smoke?
What outcomes can we assess?
Are there differences in health effects due to local smoke and long-range transport of smoke?
Can animals help us understand health effects?

Funding from NASA and the AJ Kauvar Family Foundation

Case Study #1: How do we measure smoke?

Washington State 2012 Wildfire Season [Lassman *et al.* 2017; Gan *et al.* 2017]

Initial study challenge: *How do we quantify smoke?*

Exposure assessment tools:

- Chemical transport model (WRF-Chem)
- Ground-based monitoring network (EPA + WA DOE)
- MODIS satellite data on aerosol optical depth

Smoke quantification:

- Geographically weighted regression (GWR)

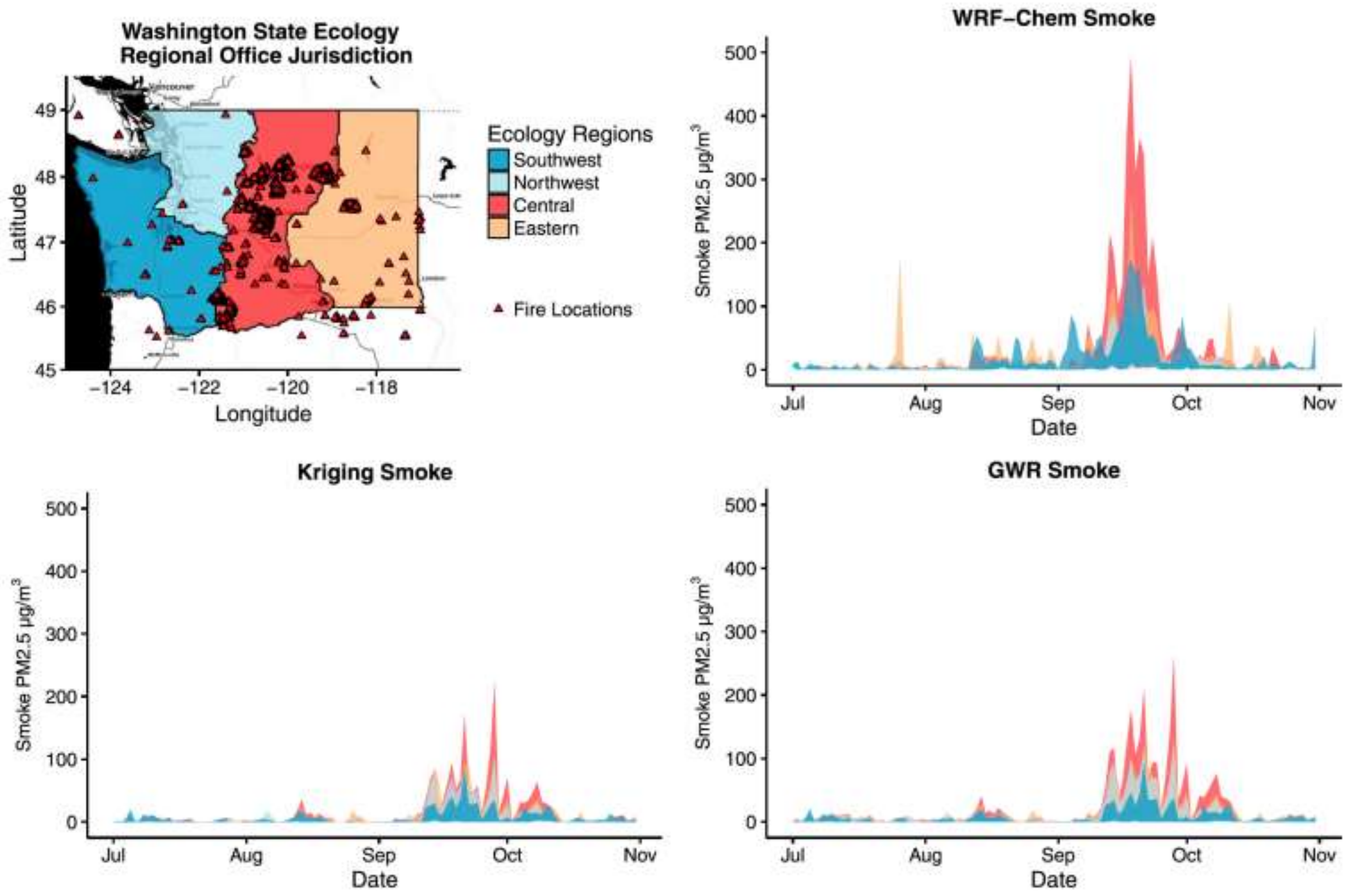
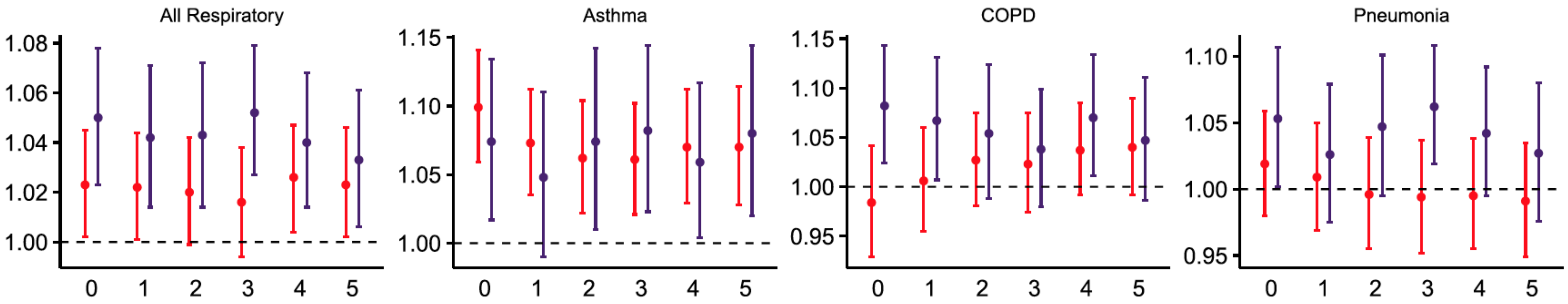


Figure 1. Time series of the range (minimum to maximum) of ZIP code population-weighted $PM_{2.5}$ concentrations of wildfire smoke from 1 July to 31 October 2012 for WRF-Chem smoke, kriging smoke, and geographically weighted ridge regression (GWR) smoke by ecology region.

Case Study #1: Blended Models

Washington State 2012 Wildfire Season [Lassman *et al.* 2017; Gan *et al.* 2017]



Odds ratios and (95% CI) for hospitalizations given a 10 μg/m^3 increase in $PM_{2.5}$ in red (WRF-Chem) and in purple from GWR for lags 0 – 5 (single lag models).

- **Asthma**: effect estimates similar by exposure assessment method
- **COPD**: conflicting inference by exposure assessment method (e.g., lag day 0)
- **Pneumonia**: conflicting inference by exposure assessment method (e.g., lag day 3)
- **All respiratory outcomes:** differences in magnitude of effect

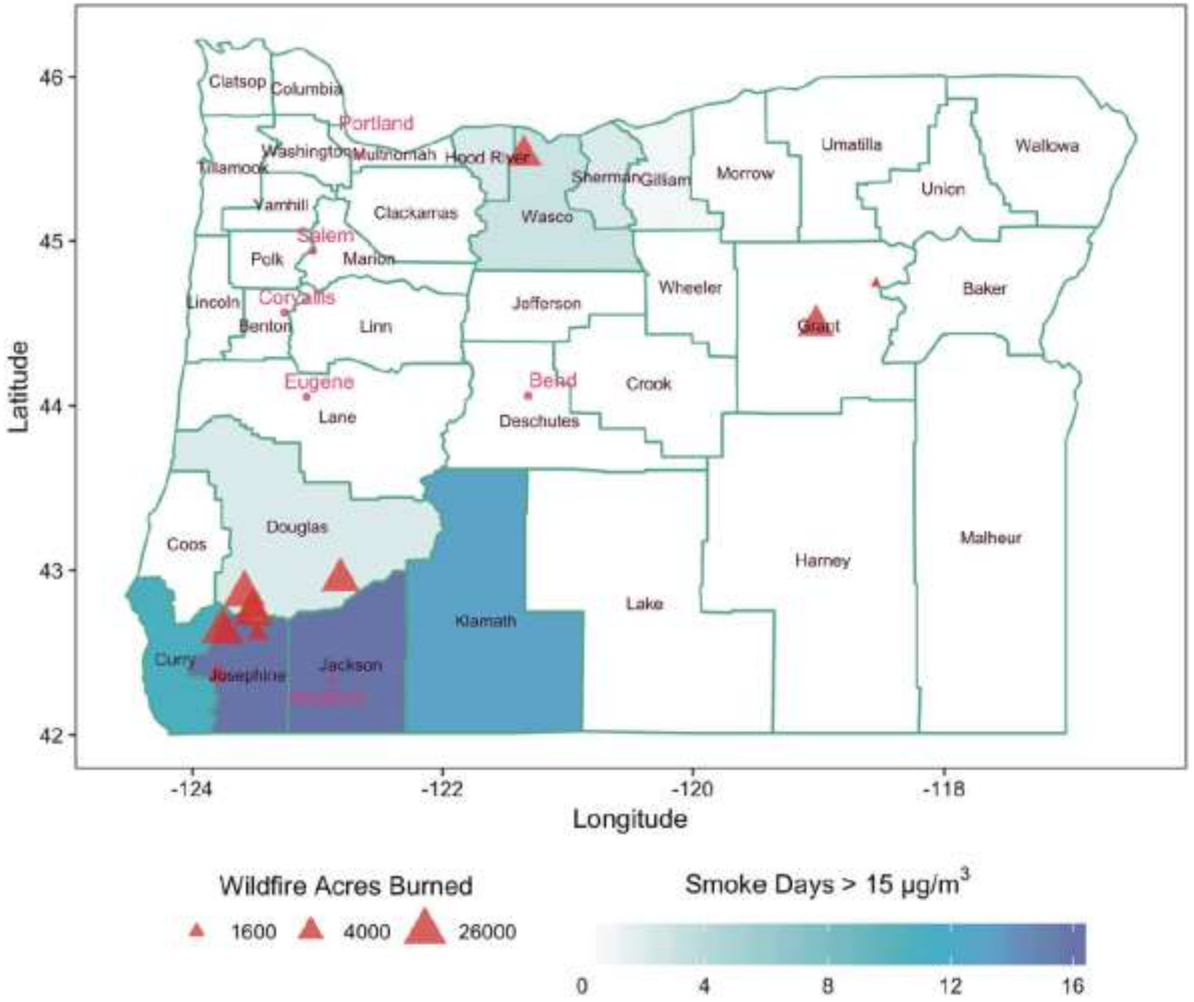
Case Study #2: What outcomes can we measure?

Oregon 2013 Wildfire Season [Gan *et al.* 2020]

Oregon has unique All Payers All Claims (APAC) database that provides all HCU for residents over one year period

- Can we start to investigate other indicators of **asthma-related morbidity**?
- Asthma-related morbidity tends to be lowest in summer months; does wildfire smoke over the summer period **shift patterns** of asthma health care utilization?

Fig. 1 Number of smoke-impacted days where WFS $PM_{2.5} > 15\ \mu g/m^3$ in Oregon State counties from 1 May 2013 to 30 September 2013. Fire locations are represented by triangles and are proportional to acres burned by the fire. Metropolitan areas are represented by circles.



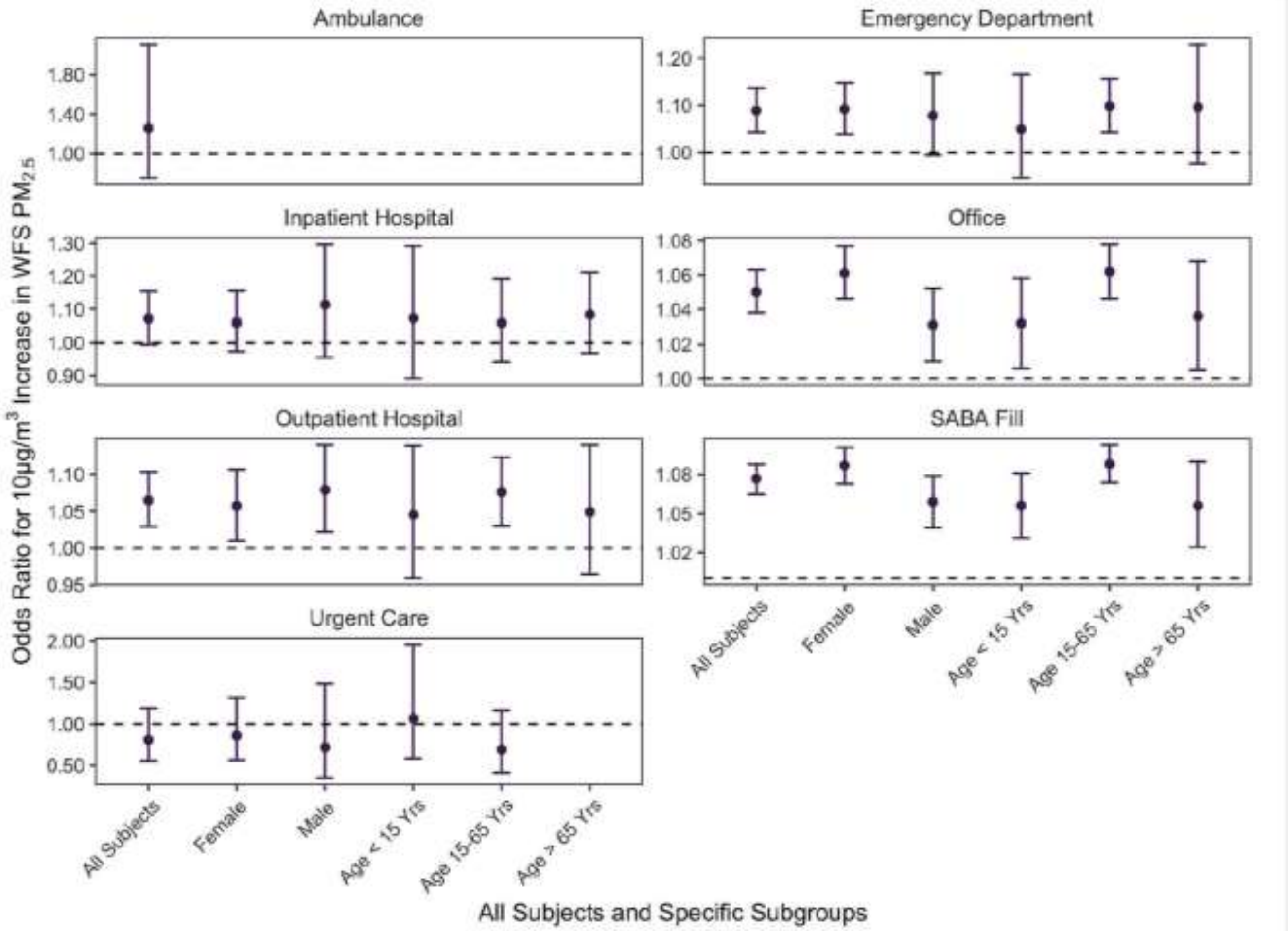
Case Study #2: What outcomes can we measure?

Oregon 2013 Wildfire Season [Gan *et al.* 2020]

Stratum-specific odds ratios (and 95% CI) for asthma health care utilization given a 10 μg/m^3 increase in WFS $PM_{2.5}$ (same day association)

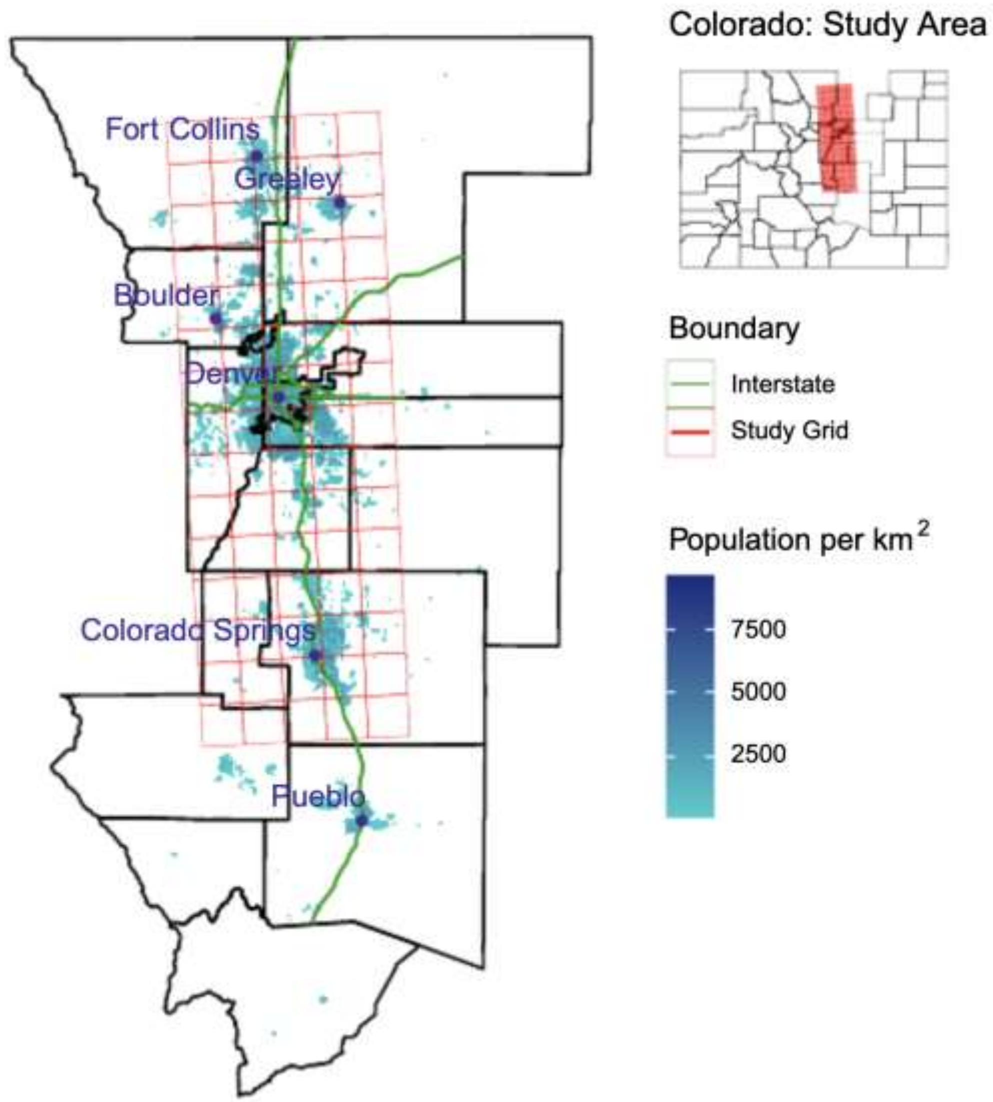
- Confirmation of previous patterns (e.g., ED visits, hospitalizations)
- Indication of sub-acute indicators for asthma-related morbidity
  - SABA prescription refills
  - Office visits

  For all demographic groups
- No indication of significant increases in urgent case use, inpatient hospitalizations, or ambulance calls



Case Study #3: Local and Long Range Smoke

Colorado Front Range 2010 – 2015



Study area: Colorado 2010 - 2015

Northern Colorado Regional Airport looking west, August 29th, 2015
Photo credit: Sheryl Magzamen, CSU

Case Study #3: Local and Long Range Smoke

Colorado Front Range 2010 – 2015

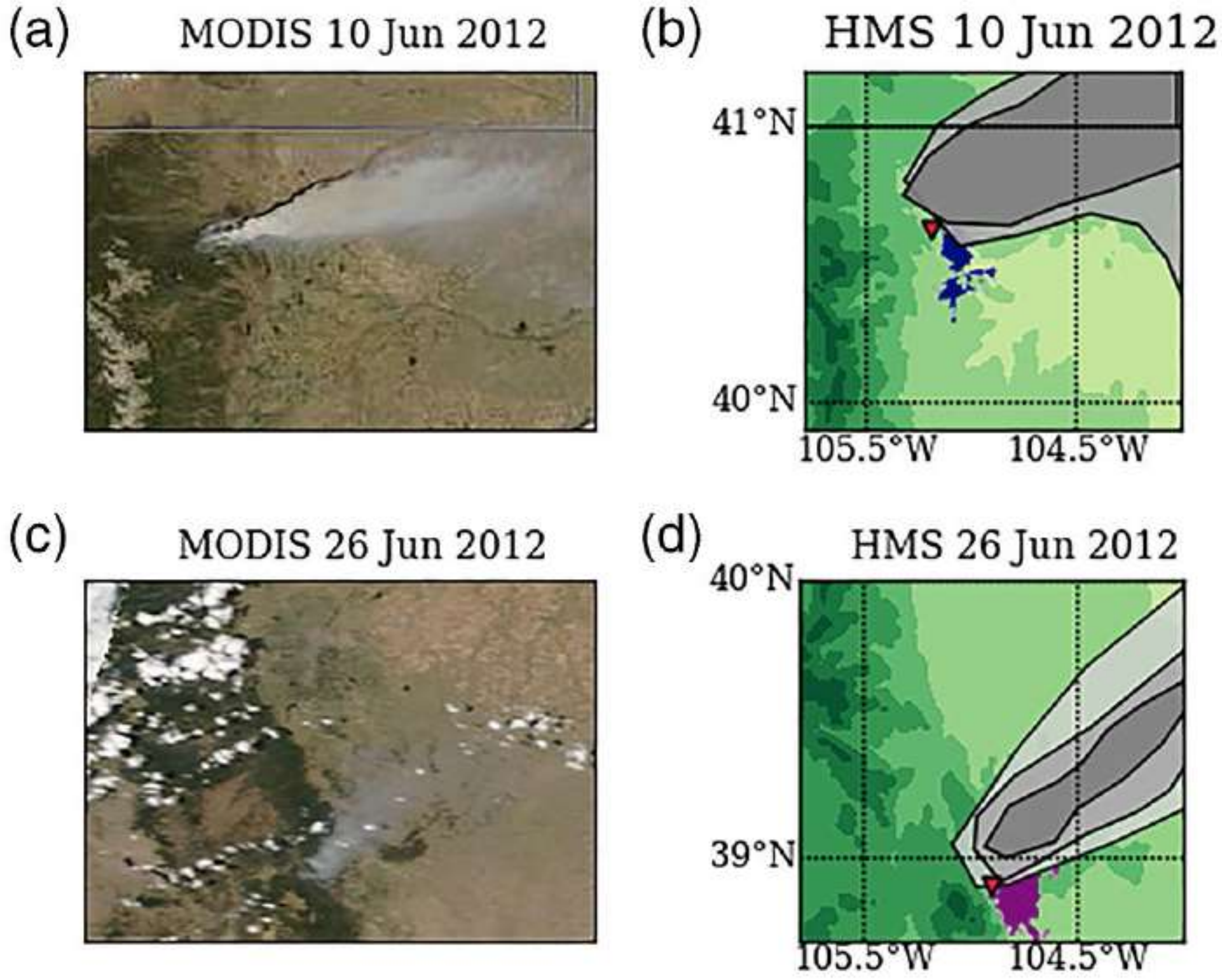
Initial study challenge: *How do we quantify smoke in a diverse topographical region?*

Exposure assessment tools:

- Ground-based monitoring network
- NOAA HMS smoke plume polygons

Smoke quantification:

- [Smoothed surface of total $PM_{2.5}$ – seasonal average $PM_{2.5}$ (non-smoke days) + smoke polygon present] = Wildfire smoke $PM_{2.5}$ (O'Dell *et al.* 2019)
  doi.org/10.1021/acs.est.8b05430



Satellite and NOAA smoke polygon images: Colorado 2010 - 2015

Case Study #3: Local and Long Range Smoke

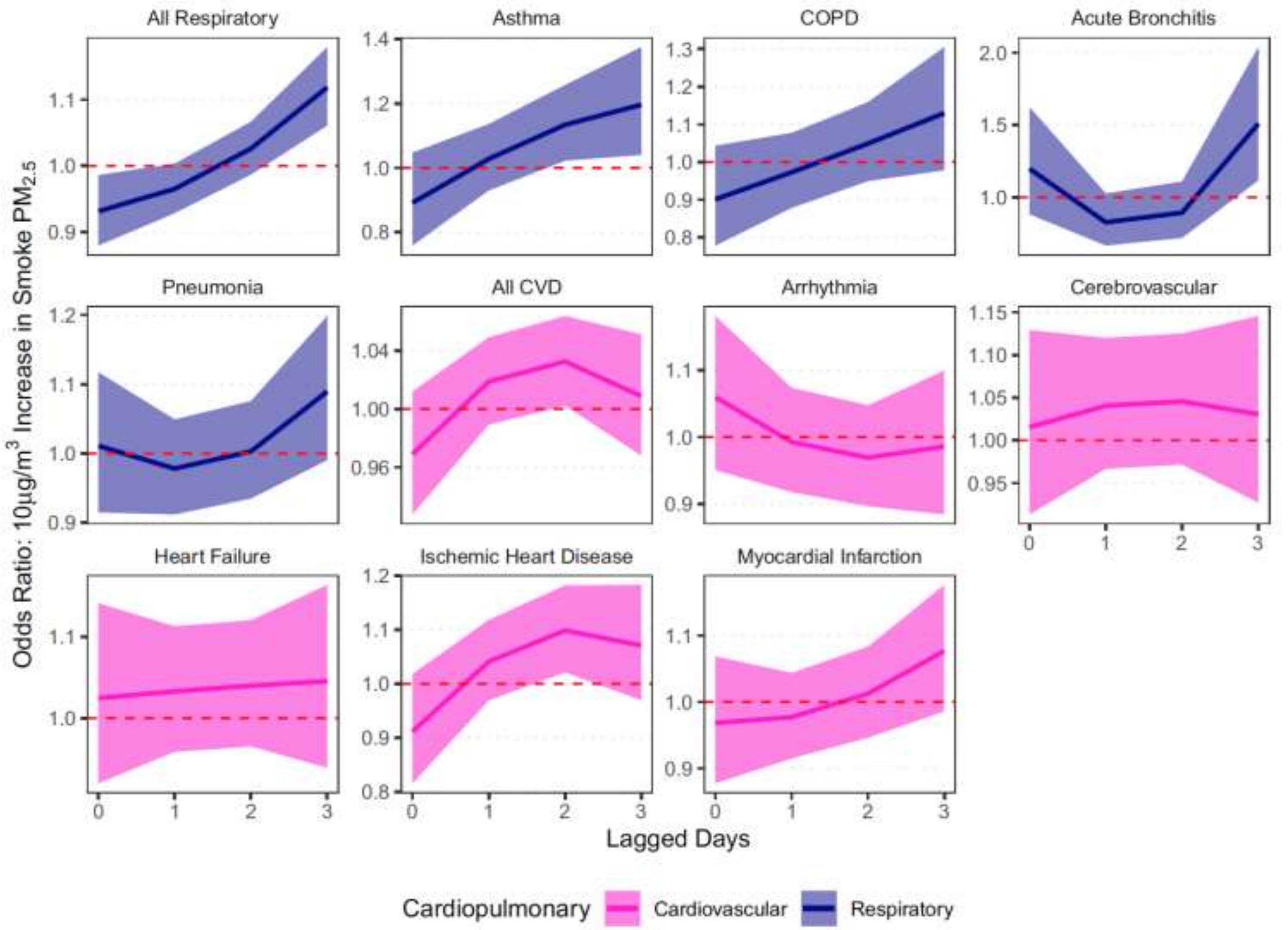
Colorado Front Range 2010 – 2015

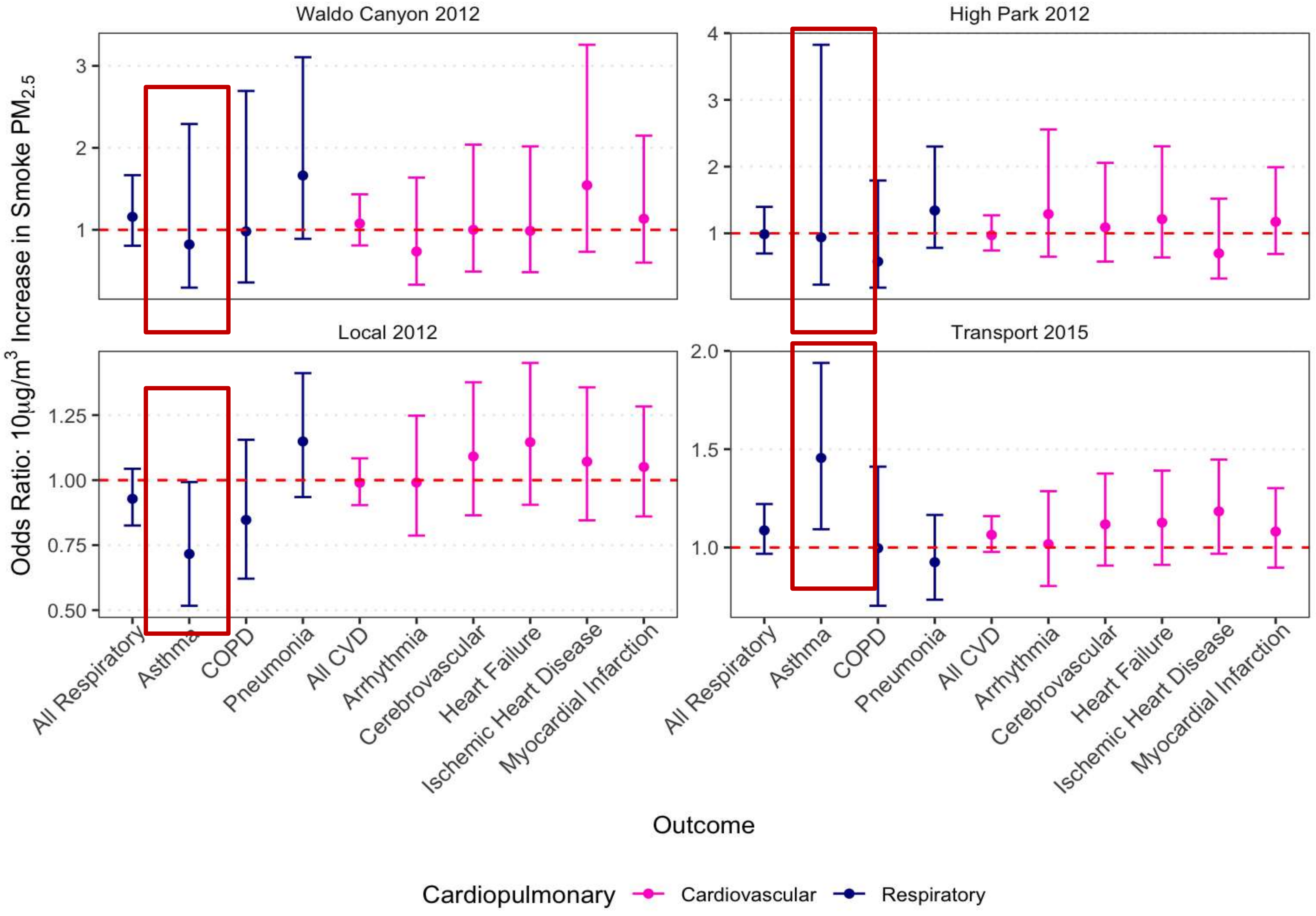
Increased risk (and confidence bands) for hospitalizations given a 10 µg/m³ increase in wildfire smoke $PM_{2.5}$

- All respiratory, asthma, and acute bronchitis were significant for smoke level three days prior to event
- Ischemic heart disease was significant for smoke level two days prior

Mortality data:

- Asthma deaths (3 days prior to event) and cardiac arrest deaths (same day as event) deaths were significantly associated with smoke



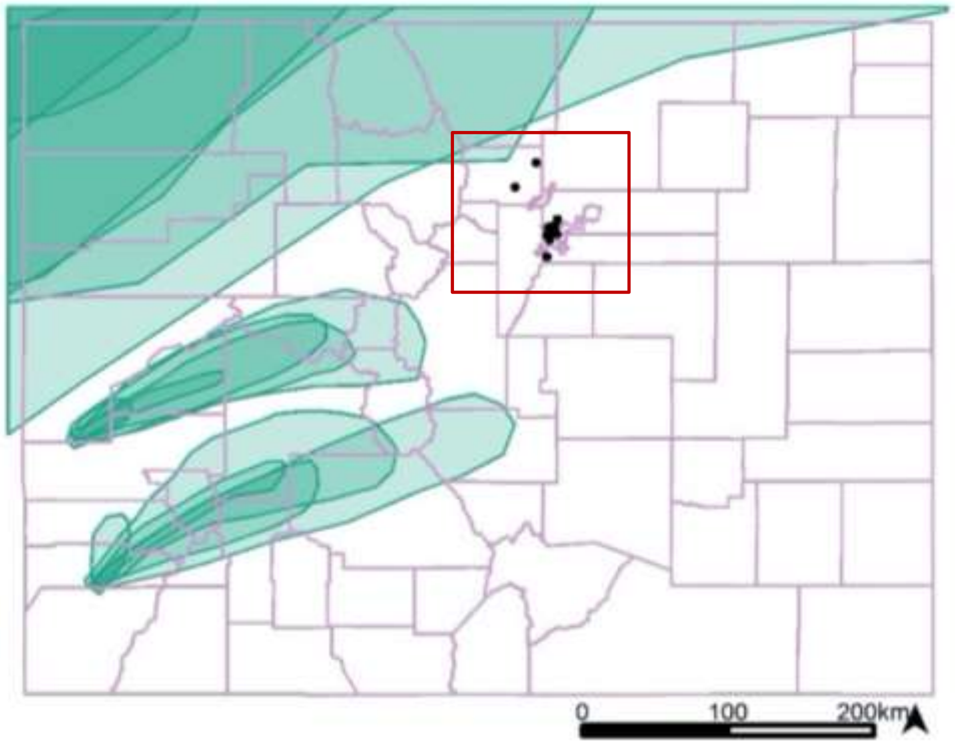


Cumulative effect (total wildfire smoke exposure up to three days prior to event) of a 10 μg/m^3 increase in wildfire smoke $PM_{2.5}$ on the risk for a cardiovascular + respiratory inpatient hospitalizations for selected fires and seasons

Case Study #3: Take aways

What could explain these findings?

- Hyperlocal nature of wildfire smoke: exposure misclassification
- Increased toxicity (e.g., oxidative potential) of aged smoke
  - Counterpoint: O'Dell *et al.* 2020 found increased levels of hazardous air pollutants in fresh smoke
  - Difficulty to assess retrospectively given exposure assessment methods



Metro Denver EPA AQS monitors (red box) and HMS smoke polygons, shaded by smoke intensity, August 5, 2018 (Source: Martenies et al. 2021)

- Emergency response associated with local fires (+ media + sensory indicators of smoke) promoted evacuation, mitigation, avoidance behaviors that protected residents from acute fire effects but also reduced exposures to smoke

O'Dell: doi.org/10.1021/acs.est.0c04497, Martenies: doi.org/10.1029/2020GH000347

Translational Medicine

Can production animals serve as sentinels for health effects of wildfire smoke?

Case Study: Colorado, 2018 – 2019

[Beaupied, Martinez *et al.* 2021]

Funding from the Colorado State University One Health Institute

Case Study #4: Cows as Canaries

Why cows?

- Mammals: Similar respiratory and cardiovascular, and reproductive systems
- Studies in animal athletes (e.g., sled dogs and sport horses) and companion animals have demonstrated adverse effects of air pollution on cardiopulmonary function
- Production animals: large fraction of time spent outdoors and limited protection during extreme air pollution
- Dairy cows have long lifetimes and high metabolic demands associated with milk production

Photo credit: Heather Martinez, CSU

Case Study #4: Cows as Canaries

Colorado Northern Front Range 2018 – 2019 {

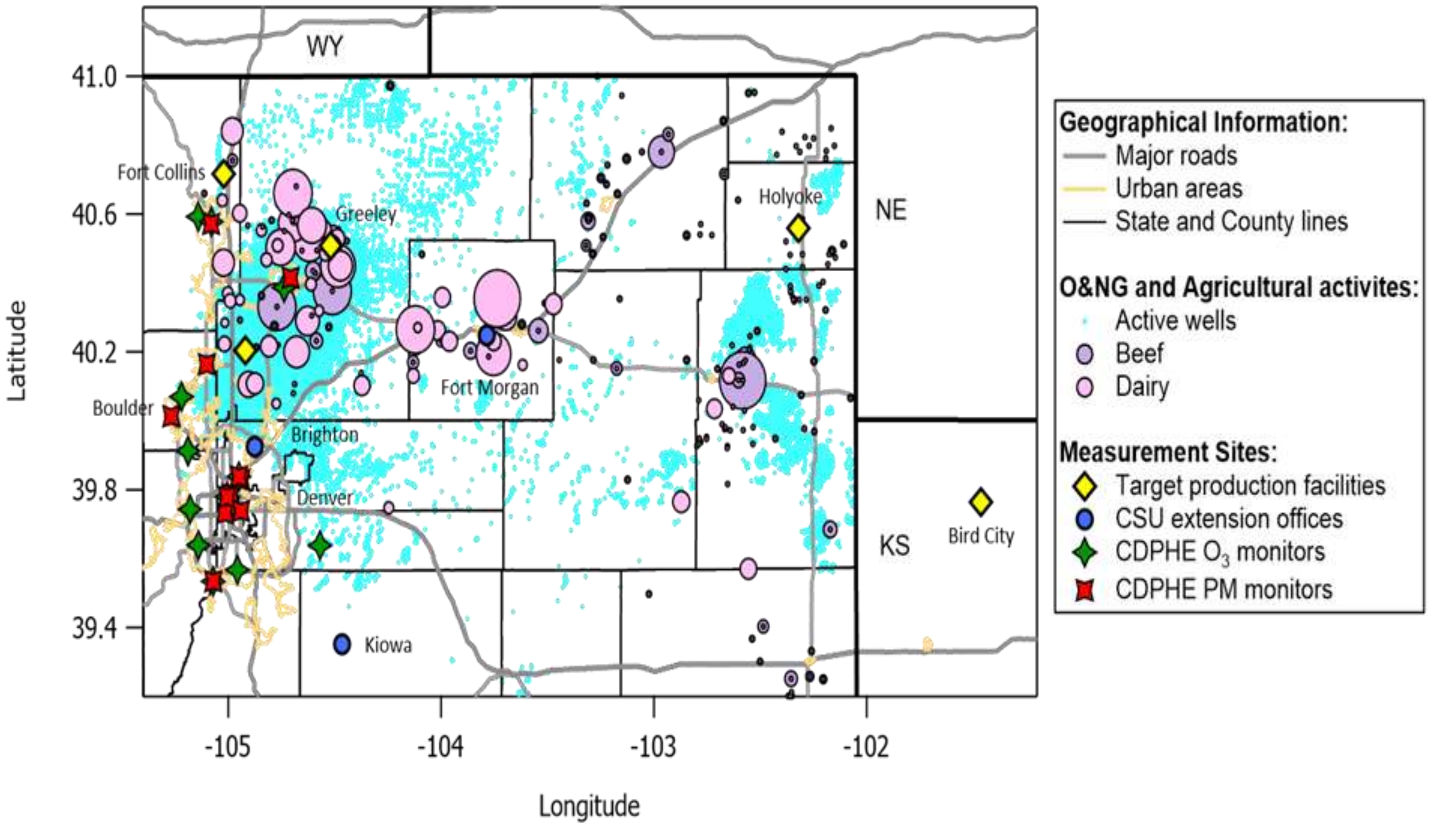
Initial study question: *In agricultural areas with limited federal air quality monitoring, does ozone impact dairy cattle health?*

Exposure assessment tools:

- Ground-based monitoring network (O_3, $PM_{2.5}$, CO)
- NOAA HMS smoke plume polygons

Epidemiologic study design:

- Time-series of air pollutants with daily milk production and somatic cell count, three dairies



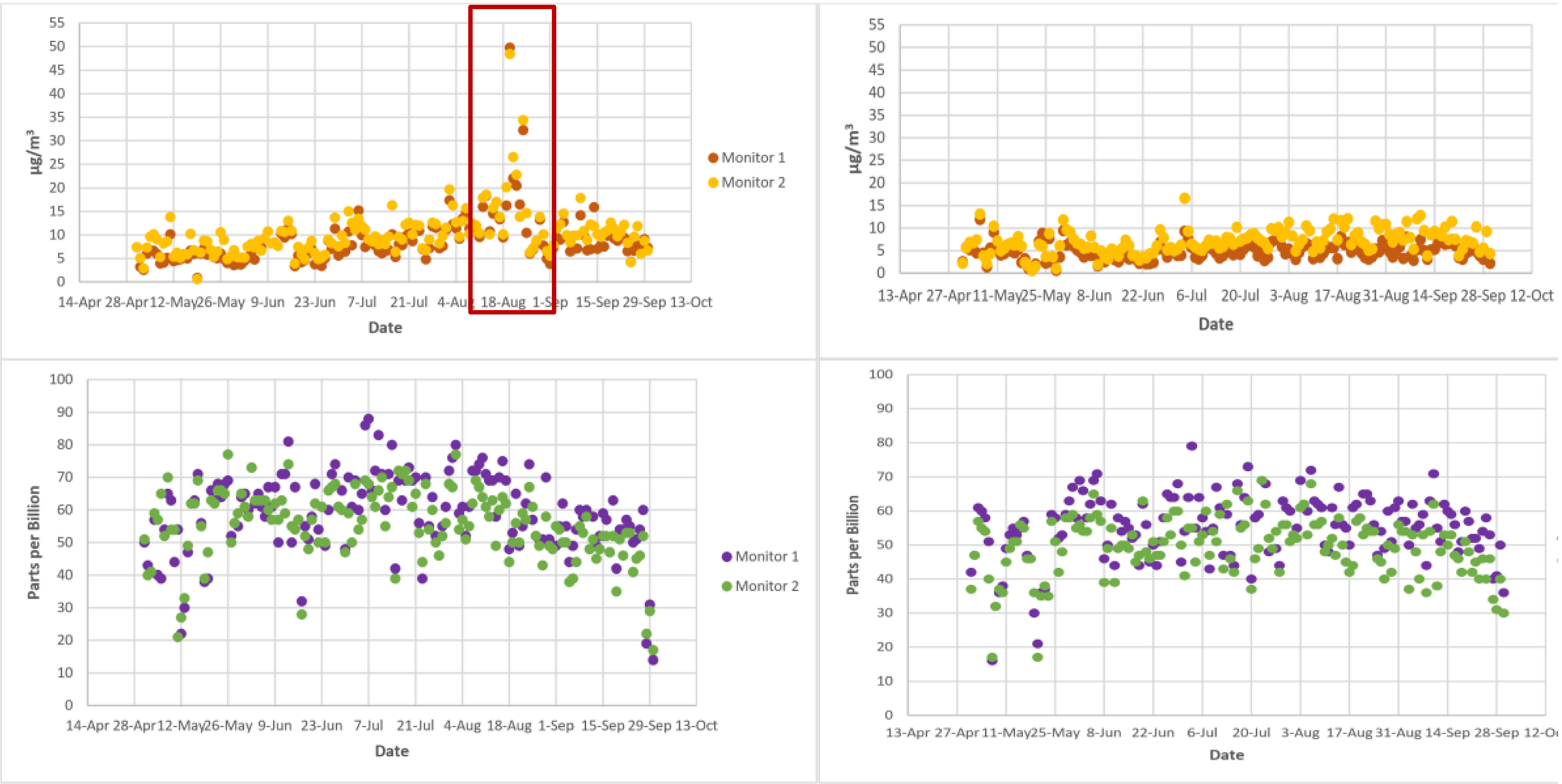
Map of northeastern Colorado and parts of neighboring states. Colored circles show the locations of cattle-related agricultural activities and active oil and natural gas wells in relation to major roadways and urban areas.

Case Study #4: Cows as Canaries

Colorado Northern Front Range 2018 – 2019

$PM_{2.5}$
2018 (L)
2019 (R)

O_3
2018 (L)
2019 (R)



Case Study #4: Cows as Canaries

Increase in somatic cell counts (cells/mL) and 95% confidence intervals (CI) for a 10-unit change in exposures

	Model 1		Model 2		Model 3		Model 4		Model 5	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Temp	28,700	17,700, 39,690	18,600	7,480, 29,780	51,000	38,630, 63,320	41,000	28,680, 53,340	14,500	3,400, 25,680
$PM_{2.5}$	--	--	**59,100**	**42,490, 75,620**	--	--	**60,980**	**44,200, 77,760**	**105,500**	**90,030, 121,050**
O_3	--	--	--	--	-29,200	-37,190, -21,120	-29,700	-37,520, -21,870	-13,000	-20,040, -5,980
CO	--	--	--	--	--	--	--	--	-12,200	-13,550, -10,840

With top 5% of $PM_{2.5}$ values (smoke days) removed

	Model 1		Model 2		Model 3		Model 4		Model 5	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Temp	27,700	16,670, 38,650	5,900	-5,610, 17,490	50,300	38,010, 62,610	25,700	13,040, 38,370	6,600	-4,970, 18,130
$PM_{2.5}$	--	--	**128,500**	**100,870, 156,040**	**--**	**--**	**128,300**	**101,210, 155,340**	**141,900**	**117,050, 166,720**
O_3	--	--	--	--	-30,300	-38,440, -22,100	-26,200	-33,910, -18,590	-11,600	-18,650, -4,580
CO	--	--	--	--	--	--	--	--	-12,000	-13,380, -10,670

Case Study #4: Cows as Canaries

Changes in milk production (lbs./cow/day) and 95% confidence intervals (CI) for a 10-unit change in exposures

	Model 1		Model 2		Model 3		Model 4		Model 5	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Temp	-1.4	-1.8, -0.9	-0.9	-1.4, -0.5	-1.7	-2.2, -1.3	-1.4	-1.9, -0.9	-1.2	-1.7, -0.6
$PM_{2.5}$	--	--	**-2.5**	**-3.2, -1.8**	**--**	**--**	**-2.6**	**-3.3, -1.9**	**-3.5**	**-4.3, -2.6**
O_3	--	--	--	--	5.0	1.7, 8.3	6.1	0.3, 0.9	0.5	0.2, 0.86
CO	--	--	--	--	--	--	--	--	0.2	0.1, 0.2

With top 5% of $PM_{2.5}$ values removed

	Model 1		Model 2		Model 3		Model 4		Model 5	
	β	95% CI	β	95% CI	β	95% CI	β	95% CI	β	95% CI
Temp	-1.3	-1.7, -0.9	-0.9	-1.4, -0.4	-1.8	-2.3, -1.3	-1.4	-1.9, -0.8	-1.1	-1.6, -0.6
$PM_{2.5}$	--	--	**-2.5**	**-3.7, -1.3**	**--**	**--**	**-2.5**	**-3.7, -1.3**	**-3.4**	**-4.7, -2.1**
O_3	--	--	--	--	0.6	0.3, 0.9	0.6	0.3, 0.9	0.5	0.2, 0.8
CO	--	--	--	--	--	--	--	--	0.2	0.1, 0.3

Cows: Take aways

- $PM_{2.5}$, and not O_3, was significantly associated with increases in inflammatory markers and decreases in milk production
  - Reduced health impacts of heat
- When high $PM_{2.5}$ (i.e., wildfire smoke days) were removed from the analysis, results for inflammatory markers were stronger
  - Results for milk production were similar
  - Indication of potential toxicity of $PM_{2.5}$ by source?
- Daily markers of inflammation and metabolic output in mammalian species possible due to nature of dairy production

Photo credit: freeimages.com

Food for Thought

What does the future hold?

Keeping safe during wildfire smoke season

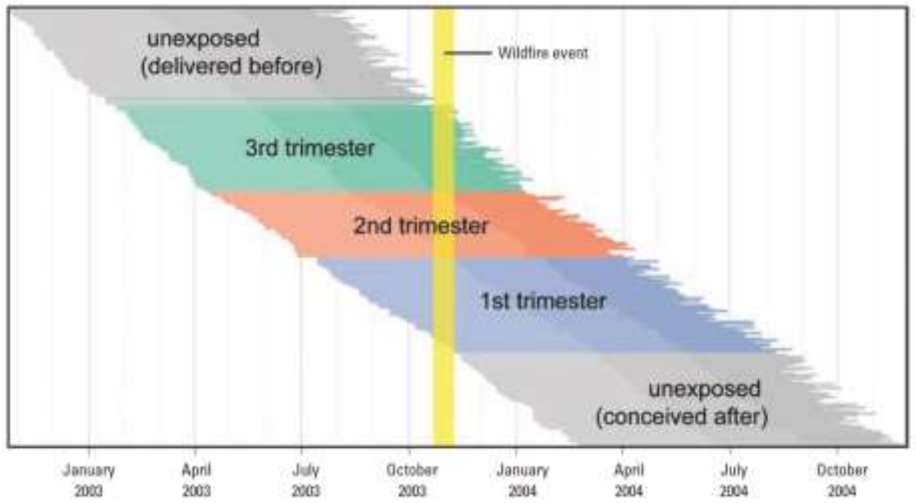
Next Steps: Health effects of $PM_{2.5}$ by source

Where we excel:

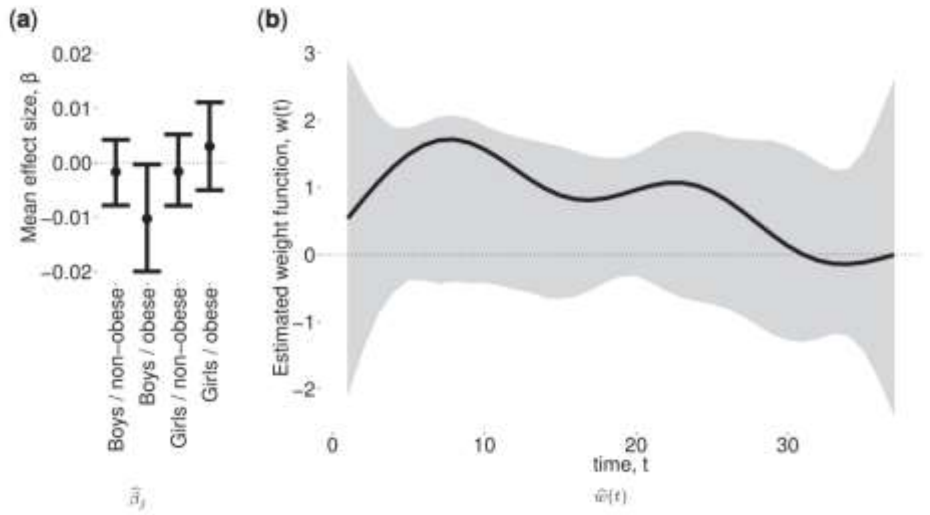
- Traffic/point source air pollutants, both short-term and long-term health effects
- Short-term impacts of WFS on cardiorespiratory health care utilization

What we lack: differences by source

- Biomass burning results in different particle composition and toxicity due to fuel, burn intensity, transport, mixing
- Windows of susceptibility ("critical windows") known for limited set of outcomes



[**Figure** from Holstius *et al.* 2012]



[**Figure** from Wilson *et al.* 2017]

Holstius: doi.org/10.1289/ehp.1104515, Wilson: doi.org/10.1093/aje/kwx184

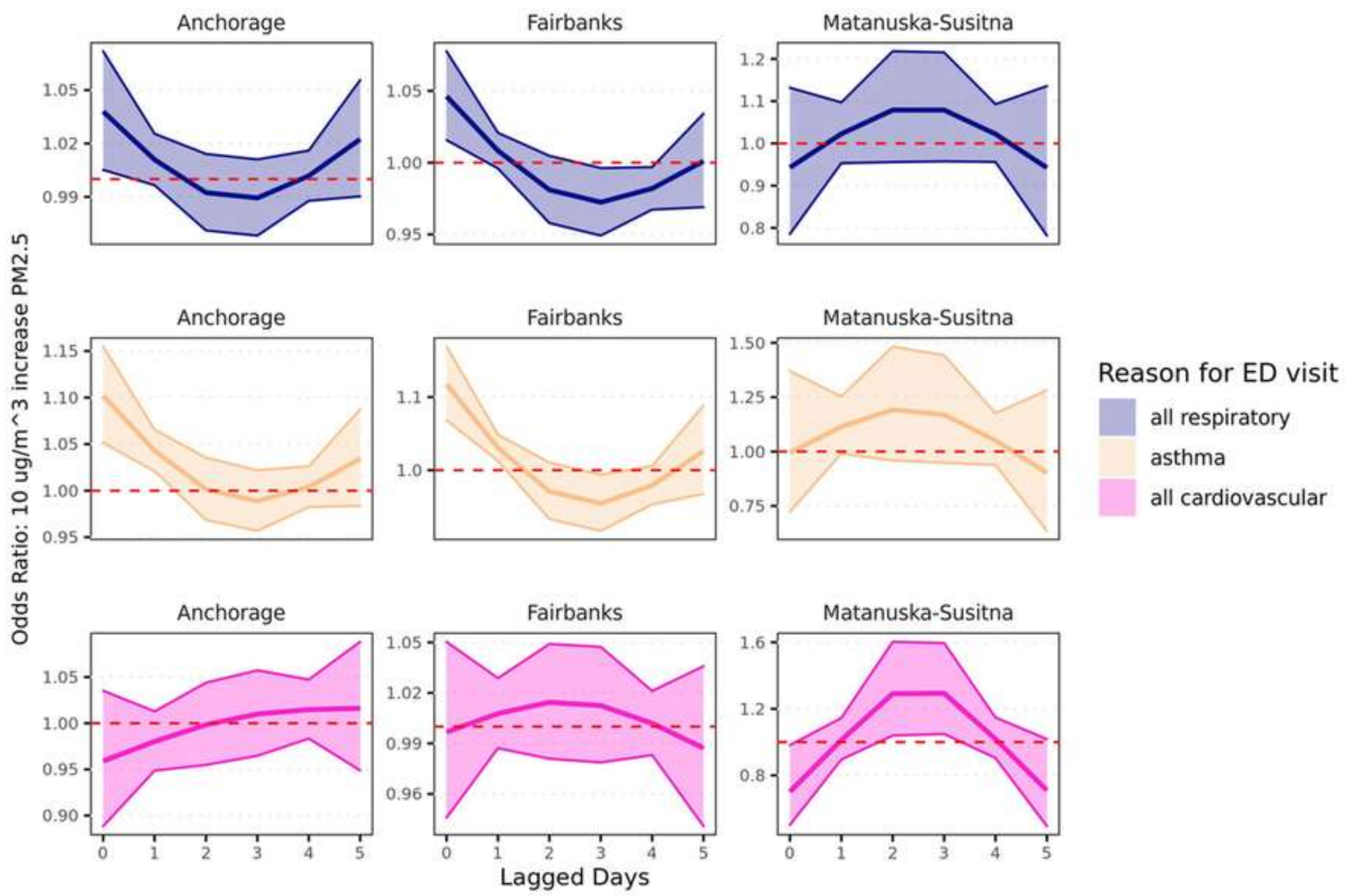
Next Steps: Public health implications of land management decisions

Land management decisions:

- Balancing ecosystem health and natural fire regimes with preservation of human life and structures
- Feasibility of suppression

What we lack: integration of health impacts in downwind communities

- Short-term v. long term impacts
- Intensity, frequency, season for wildfires is changing



Results of analyses for 10 µg/m³ increase in wildfire smoke $PM_{2.5}$ stratified by study site for all respiratory, asthma, and all cardiovascular ED visits by major population borough, Alaska 2015 - 2019 (Source: Hahn et al. 2021) doi.org/10.1029/2020GH000349

Current Challenges: Public Health + Safety

Kodros *et al.* 2021: ***Collection efficiency of N95 masks have potential for protection during wildfire smoke events, particularly compared to other mask types***
doi.org/10.1029/2021GH000482

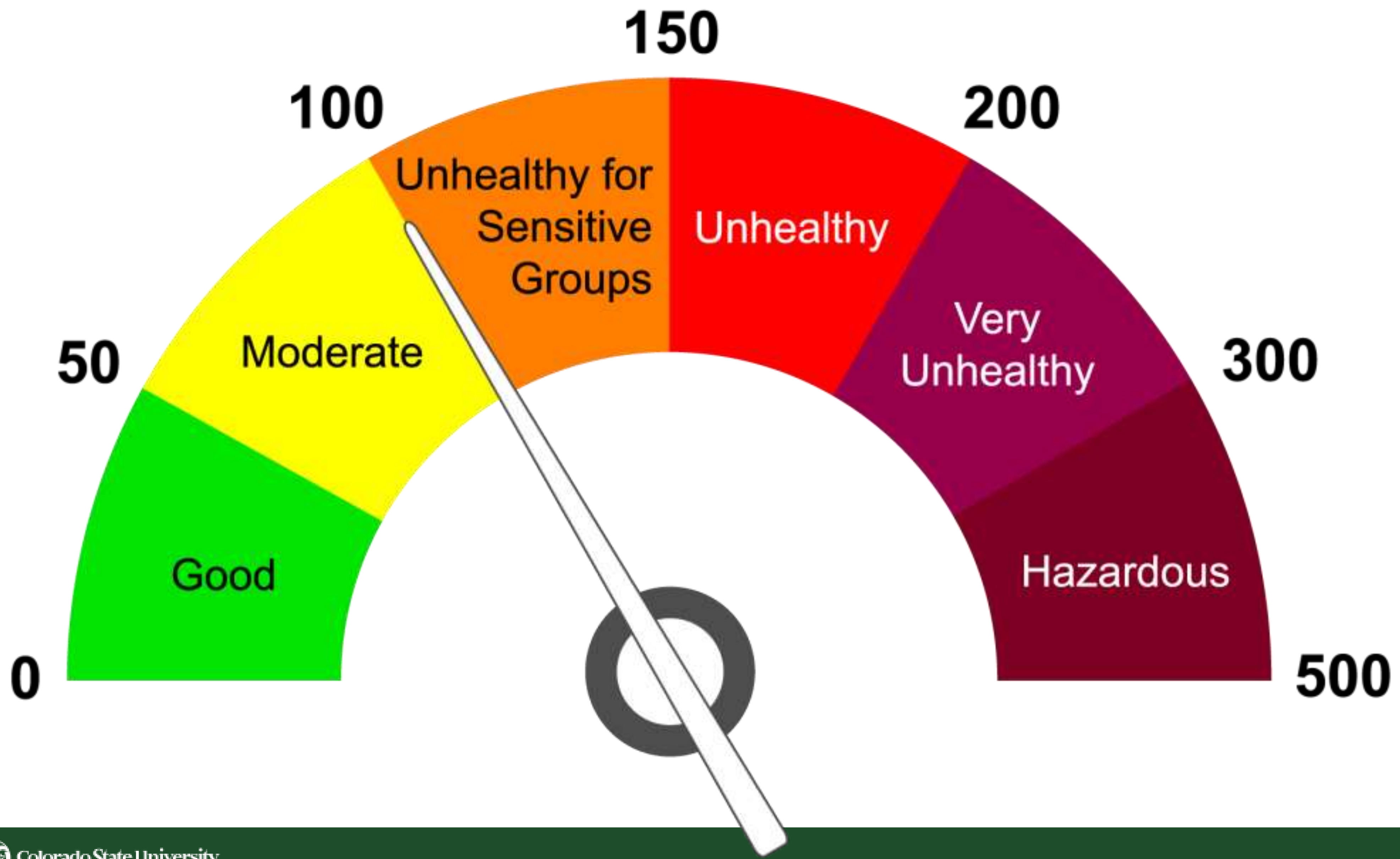
May *et al.* 2021: ***Low-cost filtration methods (box fan + high efficiency furnace filter) can effectively filter wildfire PM$_{2.5}$*** doi.org/10.4209/aaqr.210046

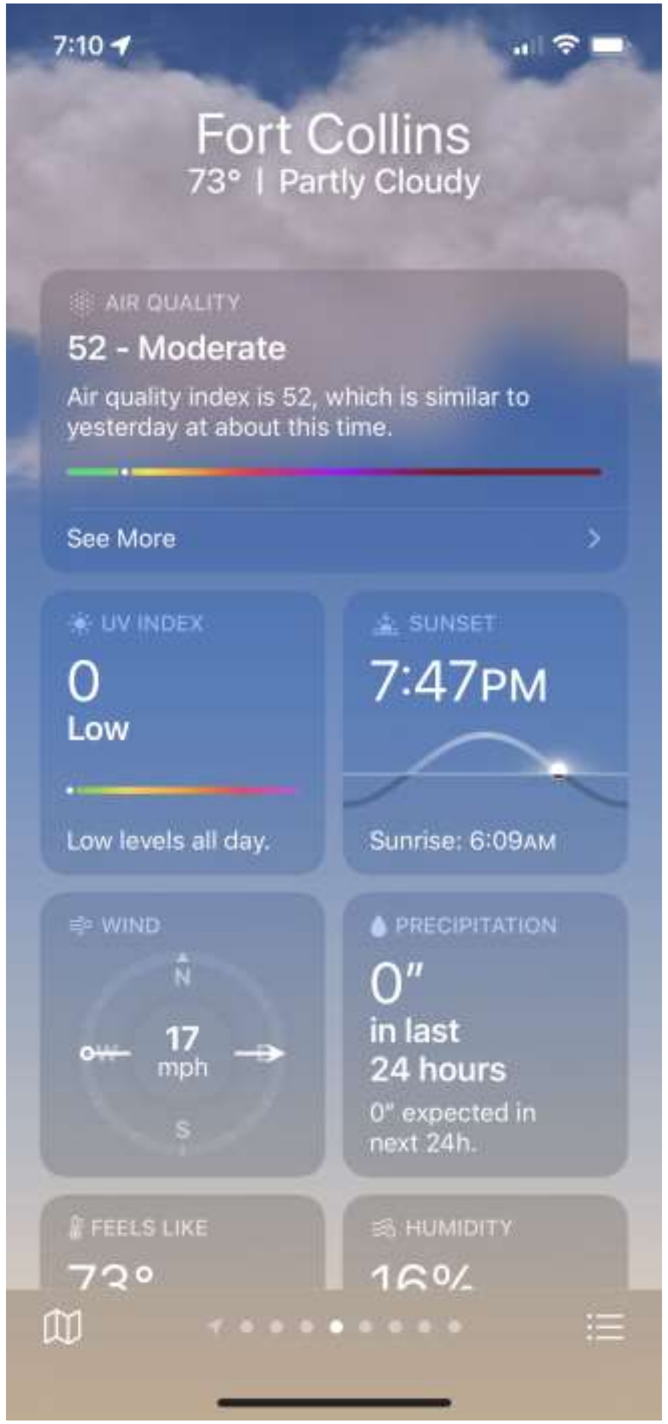
Technology: ***AQI available on smartphones, operating systems, apps available, focus on market segementation*** **(Hano *et al.* 2020)** doi.org/10.3389/fpubh.2020.00143

Media: ***Attention to air quality, particularly as a national issues, to inform public***

Being Air Quality Aware

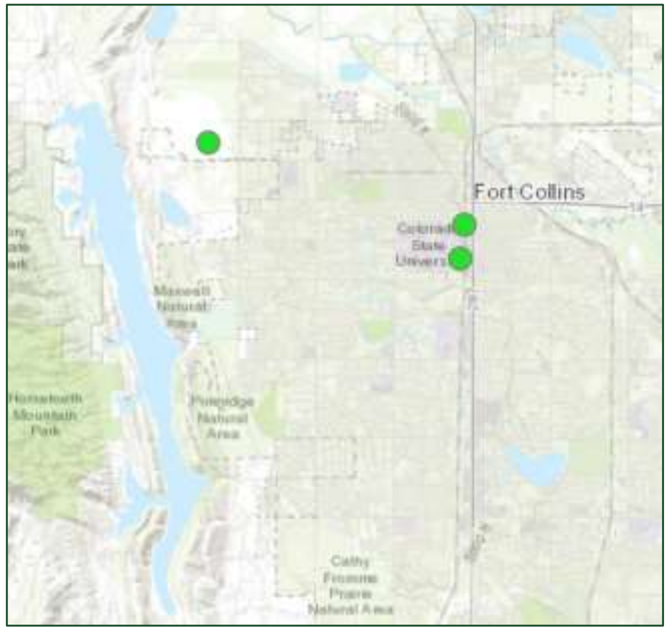
Local air quality is available on the web (airnow.gov) and on smartphones.



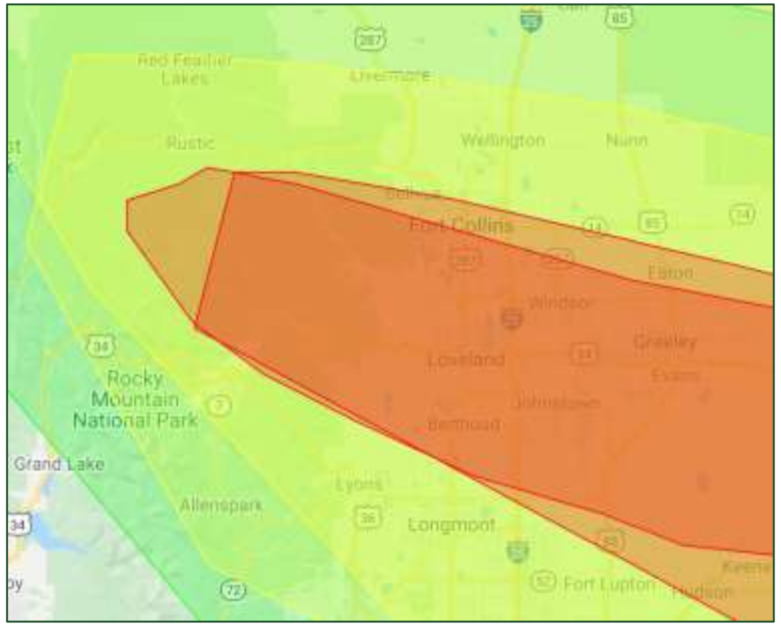


Being Air Quality Aware

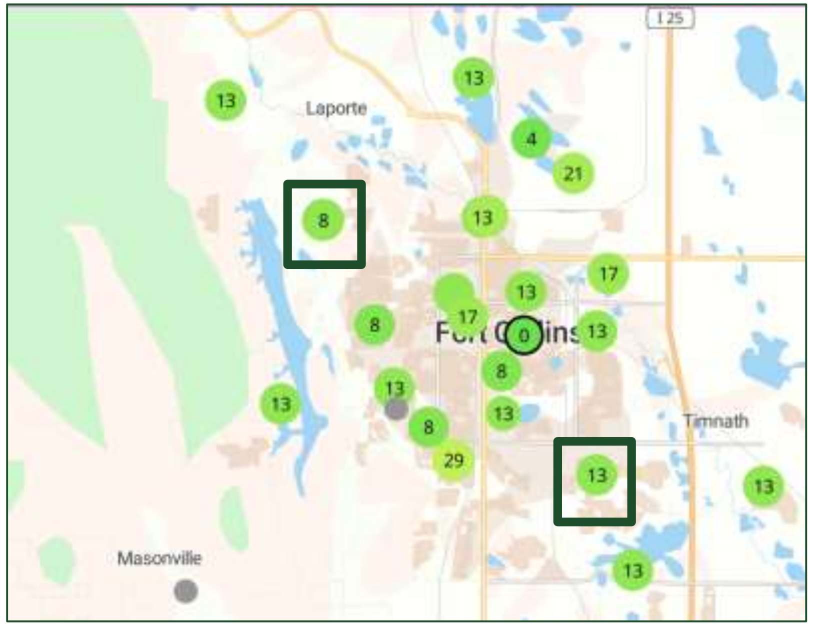
Cameron Peak Fire, Northern Colorado, August – October 2020



Fort Collins EPA Monitors

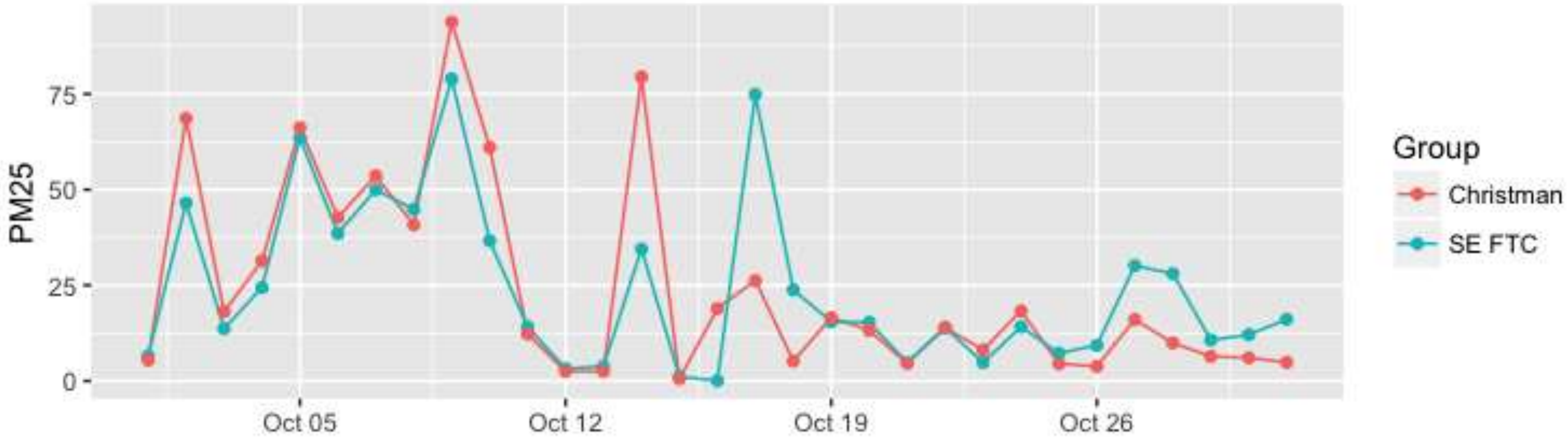


HMS Smoke Polygons 10/17/20



Fort Collins Purple Air Monitors

Time series of $PM_{2.5}$ October 1 – October 31, 2020. On peak smoke days in Fort Collins, two monitoring stations 13 km apart demonstrated high degree of variability.

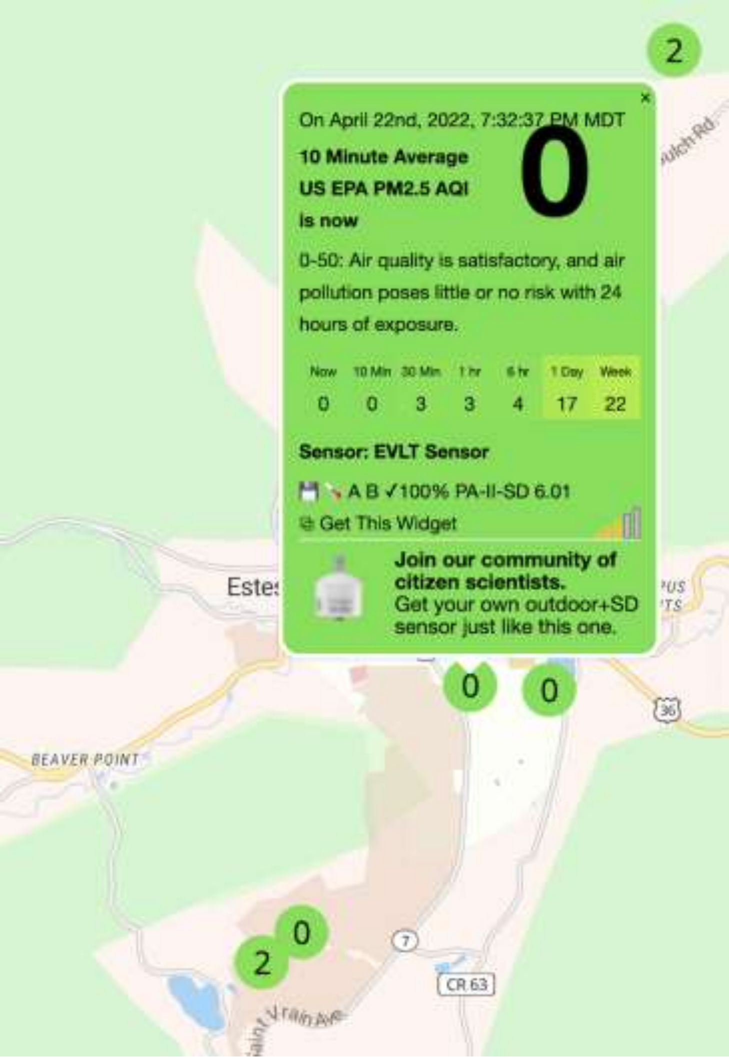


Being Air Quality Aware

EVLT's very own Purple Air monitor (map.purpleair.com)

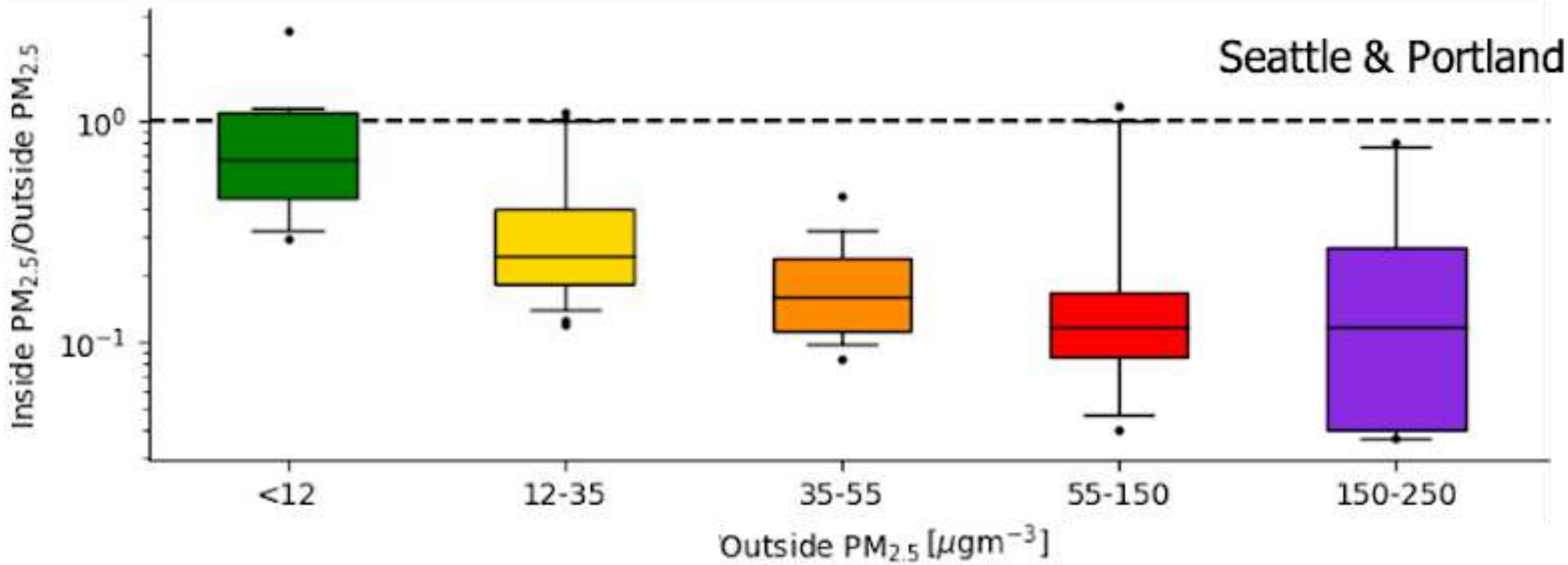
Joanna easily handles installation

EVLT Sensor – Ready to go!



EVLT Sensor on the PA website

Recommendation: Indoors generally much cleaner than outdoors during smoke events



Based on nearby outdoor and indoor PurpleAir monitors during the 2021 smoke season.

“Something you already know, now with numbers!”

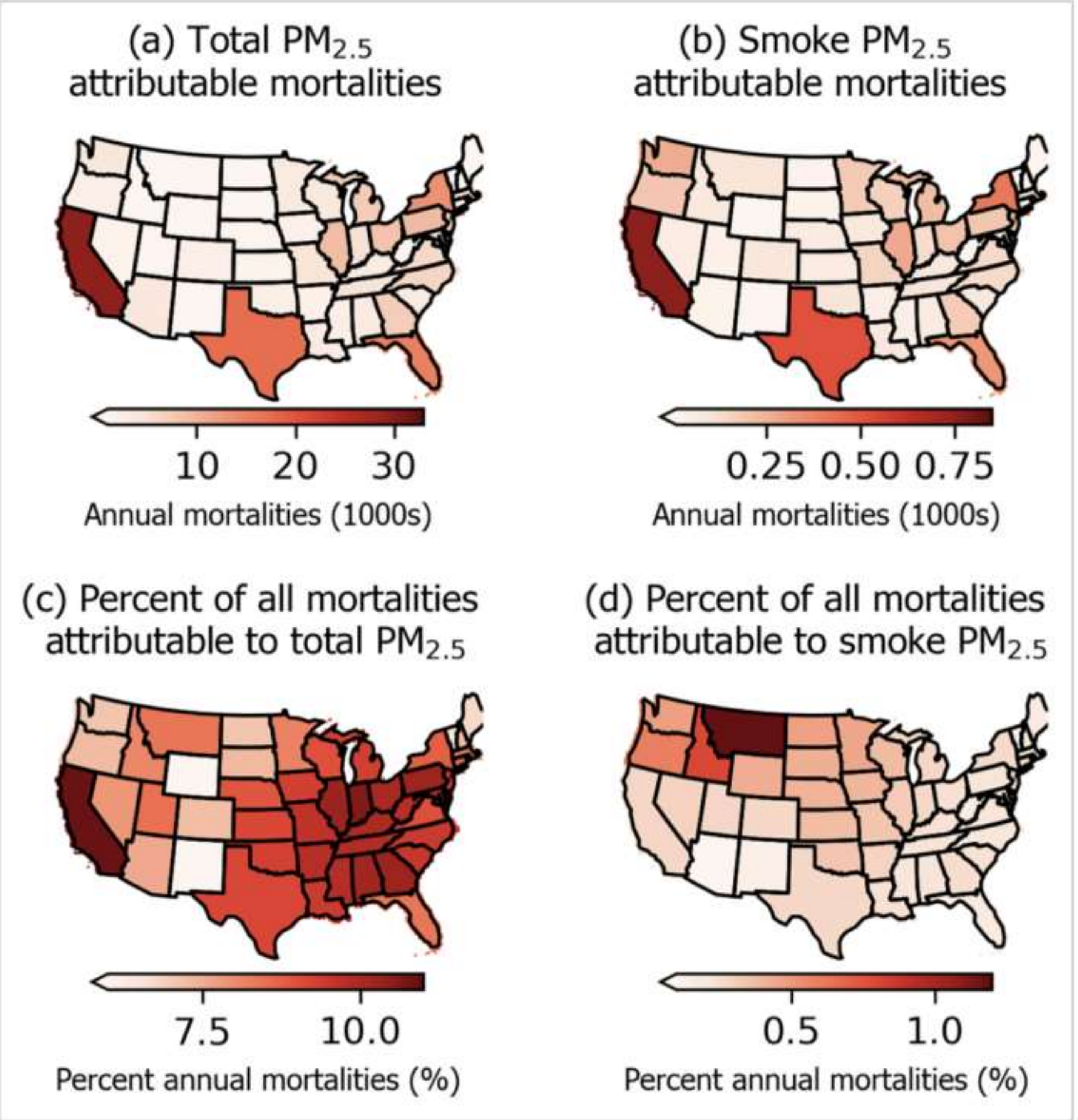
O’Dell et al., submitted, 2021.

Health impact assessment: wildfire smoke mortality, United States

O'Dell *et al.* 2021, *GeoHealth*

Wildfire smoke: Not just a western US problem

doi.org/10.1029/2021GH000457



In summary

- Wildfire smoke poses new scientific challenges for the research community
  - Exposure assessment
  - Subclinical health effects
  - Long-term health effects
  - Repeated exposures of wildfire smoke
- Working to find creative solutions to research challenges
- We don’t have the same policy levers for reductions in wildfire smoke as we do for other sources of $PM_{2.5}$
  - Action required by people rather than the sources
  - Reliant on media to communicate messages on smoke and health
- Environmental injustice implications in smoke exposure
  - Repeated exposures and ability to mitigate/avoid exposures

CSU, NCAR, CDPHE and UAA Teams: Kevin Berg, Kirk Bol, Emily Fischer, Bonne Ford, Ryan Gan, Micah Hahn, Shantanu Jathar, Grace Kuiper, Jingyang Liu, Sheena Martenies, Kate O'Dell, Gabi Pfister, Jeff Pierce, Zoey Rosen, Olivia Sablan, Kellin Slater, John Volckens, Ander Wilson

Funding Sources: NIH-OD, NASA, AJ Kauvar Family Foundation, NFS EPSCoR

Thank you

Colorado State University