How much does Kansas rangeland burning contribute to ambient $O_3$ and PM$_{2.5}$?
- Analysis of data from 2001 to 2016

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Rangeland burning smoke management and air quality workshop
April 3rd, 2017
Satellite fires
FIRMS Web Fire Mapper

https://firms.modaps.eosdis.nasa.gov/firemap/
Smoke and air quality

Complete combustion

Combustion

H₂O

PM

70-90% PM2.5

SVOC

Organic irritants

CO₂

VOC

Form O₃ in the presence of sunlight

CO

NOₓ

Toxic
<table>
<thead>
<tr>
<th>Air pollutants</th>
<th>Observed concentrations in literature</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At the fires</td>
<td>At downwind communities</td>
</tr>
<tr>
<td></td>
<td>148-6865 μg/m³</td>
<td>63-400 μg/m³</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>0.018-0.071ppm</td>
<td>0.009 ppm</td>
</tr>
<tr>
<td>Acrolein</td>
<td>0.03-0.47 ppm</td>
<td>0.02-0.047 ppm</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>600 ppb</td>
<td>-</td>
</tr>
<tr>
<td>Isocyanic acid</td>
<td></td>
<td>0.016 ppm</td>
</tr>
<tr>
<td>PAHs</td>
<td></td>
<td>200 μg/m³</td>
</tr>
<tr>
<td>BaP</td>
<td>0.10-0.16 μg/m³</td>
<td>0.007 μg/m³</td>
</tr>
<tr>
<td>Acenaphthene</td>
<td>0.57-1.53 μg/m³</td>
<td>0.83-0.89 μg/m³</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>0-3.27 μg/m³</td>
<td>0-3.53 μg/m³</td>
</tr>
<tr>
<td>Phenanthrene</td>
<td>0.38 μg/m³</td>
<td>-</td>
</tr>
<tr>
<td>CO</td>
<td>1-140 ppm</td>
<td>1-6 ppm</td>
</tr>
<tr>
<td>O$_3$</td>
<td></td>
<td>Up by 50 ppb</td>
</tr>
</tbody>
</table>

a. NAAQS 24-hr standards; b. NAAQS 8-hr standards; c. NIOSH 8-hr exposure limits; d. OSHA 8-hr exposure limits
Regulations

- Clean Air Act (CAA)
- National Ambient Air Quality Standards (NAAQS)
- Six criteria air pollutants
  - Particulate Matter (PM)
  - Ozone (O₃)
  - Nitrogen Dioxide (NO₂)
  - Sulfur Dioxide (SO₂)
  - Carbon Monoxide (CO)
  - Lead (Pb)
- Five year review cycle
- Nonattainment area
- State Implementation Plan (SIP)

http://www.epa.gov/ttn/naaqs/
<table>
<thead>
<tr>
<th>Year</th>
<th>8-hour</th>
<th>1-hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>120ppb</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>80ppb</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>75ppb</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>70ppb</td>
<td></td>
</tr>
</tbody>
</table>
## Evolution of PM standards

<table>
<thead>
<tr>
<th>Year</th>
<th>PM Type</th>
<th>Annual</th>
<th>24-hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>TSP</td>
<td>75 µg/m³</td>
<td>260 µg/m³</td>
</tr>
<tr>
<td>1987</td>
<td>PM₁₀</td>
<td>50 µg/m³</td>
<td>150 µg/m³</td>
</tr>
<tr>
<td>1997</td>
<td>PM₂.₅</td>
<td>15 µg/m³</td>
<td>65 µg/m³</td>
</tr>
<tr>
<td>2006</td>
<td>PM₂.₅</td>
<td>15 µg/m³</td>
<td>35 µg/m³</td>
</tr>
<tr>
<td>2012</td>
<td>PM₂.₅</td>
<td>Primary 12 µg/m³</td>
<td>35 µg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary 15 µg/m³</td>
<td></td>
</tr>
</tbody>
</table>
Kansas $O_3$ monitoring sites

Nine grey dots: Kansas $O_3$ monitoring network
Yellow dot: Konza Prairie research site

Purple lines: perimeter of the Flint Hills region
• Design value
  – a statistic of air pollutant concentrations.
  – used to compare with air quality standards and to designate nonattainment areas.

• The design value of O$_3$
  – the annual fourth-highest daily max 8-hour concentration, averaged over 3 years.
Kansas 8hr O$_3$ design values (ppb)

Old standard

New standard

(Data from KDHE, 2010 and 2015. 5-Year Ambient Air Monitoring Network Assessment)
$O_3$ at the Konza Prairie research monitoring site (2002-2013)

Clean Air Status and Trends Network (CASTNET)
Daily max 8hr O$_3$ at the Konza Prairie site (2002-2013)
Highest 8hr O₃ in April vs. acres burned (Konza Prairie site)

\[
y = 6.1192x + 61.498 \\
R^2 = 0.5696
\]
Number of days with $8\text{hr } O_3 > 70\text{ppb}$ in April vs. acres burned (Konza Prairie site)

$R^2 = 0.4421$

Graph showing the correlation between the number of days with $O_3 > 70\text{ppb}$ and acres burned (Million) from 2000 to 2016.

- **Top Graph:** Scatter plot with red dots indicating data points for years 2002, 2005, 2007, and 2009. The trend line shows a positive correlation.

- **Bottom Graph:** A bar graph and line graph showing the number of days with $O_3 > 70\text{ppb}$ and acres burned (Million) from 2000 to 2016.
8hr O$_3$ at the Konza Prairie site (2002-2013)

- O$_3$ > 70 ppb occurred in all years when acres burned ≥ 2 million (except 2009).

- O$_3$ > 70 ppb did not occur for all years when acres burned < 1 million.
Daily max 8hr O$_3$ at the Wichita Health Department site (2001-2016)
Highest 8hr O₃ in April vs. acres burned at the three sites around Wichita

**Sedgwick site (2009-2016)**

\[ y = 8.0806x + 54.405 \]
\[ R² = 0.7455 \]

**Wichita Health Department site (2001-2016)**

\[ y = 7.5445x + 58.025 \]
\[ R² = 0.3295 \]

**Peck site (2001-2016)**

\[ y = 5.9803x + 55.462 \]
\[ R² = 0.3441 \]
Number of days with 8hr $O_3 > 70$ppb in April vs. acres burned at the three sites around Wichita

Sedgwick site
(2009-2016)

Wichita Health Department site
(2001-2016)

Peck site
(2001-2016)
Daily max 8hr O₃ in April at the Wichita Health Department site (2001-2016)
8hr $O_3$ at the three sites around Wichita (2001-2016)

- When acres burned $\geq$ 1.9 million, $O_3 > 70$ppb may occur.
- When acres burned $< 1.9$ million, $O_3 > 70$ppb did not occur.
Daily max 8hr $O_3$ at the Kansas City JFK site (2001-2016)
Highest 8hr $\text{O}_3$ in April vs. acres burned at the three sites around Kansas City

Leavenworth site (2004-2016)

Kansas City JFK site (2001-2016)

Heritage Park site (2004-2016)
Number of days with 8hr $O_3 > 70$ ppb in April vs. acres burned at the three sites around Kansas City

- Leavenworth site (2004-2016)
  - $R^2 = 0.0605$
  - Points for 2005 and 2007

- Kansas City JFK site (2001-2016)
  - $R^2 = 0.1043$
  - Points for 2005

- Heritage Park site (2004-2016)
  - $R^2 = 0.2835$
  - Points for 2005

# of days with $O_3 > 70$ ppb vs. Acres burned (Million)
Daily max 8hr $O_3$ in April the Kansas City JFK site (2001-2016)
8hr $O_3$ at the three sites around Kansas City (2001-2016)

- When acres burned $\geq 1.9$ million, $O_3 > 70$ppb may occur (with less chance than the Wichita sites).

- When acres burned $< 1.9$ million, $O_3 > 70$ppb did not occur (with only one exception at the Leavenworth site).
Daily max 8hr $O_3$ at the Topeka site (2006-2016)
Daily max 8hr $O_3$ in April at the Topeka site (2006-2016)
Number of days with 8hr $O_3 > 70$ppb in April vs. acres burned at all the ten sites

![Graph showing the relationship between the number of days with $O_3 > 70$ppb and acres burned (Million).]

- When acres burned $\geq 1.9$ million, $O_3 > 70$ppb occurred at least at one of the 10 sites.
- When acres burned $< 1.1$ million, $O_3 > 70$ppb did not occur.
Factors that affect ambient $O_3$

- Seasonal cycle
- $O_3$ on the previous day
- Air temperature
- Solar radiation
- Relative humidity
- Wind speed
Daily max 8hr O$_3$ at the Konza Praire site
O$_3$ on non-rainy days

O$_3$(d) = 30.5 + 4.75\sin\left(\frac{2\pi(d+284)}{365}\right) + 0.47O$_3$(d)$_0$ + 0.17T$_{\text{max}}$ + 0.13(T$_{\text{max}}$ - T$_{\text{min}}$) - 15.6RH - 0.57V

R$^2$ = 0.71

O$_3$ on the previous day
Daily max air temperature
Air heated by solar radiation

Air heated by solar radiation
O$_3$ on rainy days

$$\text{O}_3(d) = 37.5 + 4.40 \sin \left( \frac{2\pi(d+284)}{365} \right)$$

+ 0.44O$_3$(d)$_0$  \[O_3 \text{ on the previous day} \]

+ 0.15T$_{\text{max}}$  \[\text{Daily max air temperature} \]

+ 0.29(T$_{\text{max}}$ - T$_{\text{min}}$)  \[\text{Air heated by solar radiation} \]

- 25.5RH

- 0.64V

R$^2$=0.68
### 8hr $O_3$ at the Konza Prairie site (2002-2013)

<table>
<thead>
<tr>
<th></th>
<th>Annual average</th>
<th>April average (rainy days)</th>
<th>April average (non-rainy days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured $O_3$ (ppb)</td>
<td>43.0</td>
<td>48.3</td>
<td>53.2</td>
</tr>
<tr>
<td>Modeled $O_3$ (ppb)</td>
<td>43.0</td>
<td>47.5</td>
<td>50.1</td>
</tr>
<tr>
<td>Residual (ppb)</td>
<td>0</td>
<td>0.8</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Likely due to burning
Multi-year average O₃ at different sites (non-rainy days in April)

Highest model $R^2$ at Cedar Bluff, lowest burning interference, $R^2=0.76$

Measured O₃ (ppb)

- 53.2
- 50.1
- 48.9
- 47.2

Modeled O₃ (ppb)

- 49.6
- 50.1
- 48.3
- 50.1

Highest model $R^2$ at Cedar Bluff, lowest burning interference, $R^2=0.76$
Average $O_3$ model residuals in April (non-rainy days) (Likely due to burning)

<table>
<thead>
<tr>
<th>Site</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Konza Prairie site</td>
<td>3.1 ppb</td>
</tr>
<tr>
<td>Topeka site</td>
<td>2.4 ppb</td>
</tr>
<tr>
<td>Three Wichita sites</td>
<td>0.7, 1.3, 1.7 ppb</td>
</tr>
<tr>
<td>Three Kansas City sites</td>
<td>0.4, 1.2, 1.5 ppb</td>
</tr>
<tr>
<td>Cedar Bluff site</td>
<td>0.7 ppb</td>
</tr>
</tbody>
</table>
### Average of days with $O_3>70$ ppb in April (47 days in total)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average 2001-2016</th>
<th>April average 2001-2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Max 8hr $O_3$</td>
<td>77±5 ppb</td>
<td>43.9-53.2 ppb</td>
</tr>
<tr>
<td>$O_3$ on the previous day</td>
<td>60±11 ppb</td>
<td>-</td>
</tr>
<tr>
<td>Daily maximum air temperature</td>
<td>24.5±4.5 ºC</td>
<td>20.7±5.5 ºC</td>
</tr>
<tr>
<td>$T_{\text{max}}-T_{\text{min}}$</td>
<td>16.6±5.3 ºC</td>
<td>12.3±5.0 ºC</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>738±279 Langley</td>
<td>607±304 Langley</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>54±10 %</td>
<td>67±14 %</td>
</tr>
<tr>
<td>Wind speed</td>
<td>3.4±1.8 m/s</td>
<td>4.1±2.0 m/s</td>
</tr>
<tr>
<td>$O_3$ model residuals</td>
<td>21±9 ppb</td>
<td>-</td>
</tr>
</tbody>
</table>

*Likely due to burning*
PM$_{2.5}$ from smoke

- ~70 to 90% of smoke particles is PM$_{2.5}$.
- Include primary particles and secondary organic particles that are formed through gas-to-particle conversion processes.
- Acts as a vehicle to carry adsorbed hazardous compounds into the respiratory tract.
- Could have greater health impact than normal urban particles.
PM$_{2.5}$ speciation data at the Tallgrass IMPROVE site

IMPROVE: Interagency Monitoring of Protected Visual Environments
Annual average contributions to PM$_{2.5}$ from the five source categories at the Tallgrass site

Results of receptor modeling
Monthly variation of PM$_{2.5}$ contributions from the five source categories at the Tallgrass site

<table>
<thead>
<tr>
<th>Month</th>
<th>S1: Nitrate/agricultural</th>
<th>S2: Sulfate/industrial</th>
<th>S3: Crustal/soil</th>
<th>S4: Primary smoke particles</th>
<th>S5: Secondary organic particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Feb</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Mar</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Apr</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>May</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Jun</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Jul</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Aug</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Sep</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Oct</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Nov</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Dec</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

The graph shows the percentage contribution of each source category over the months of the year, with the highest contribution in April (49%) and the lowest in January (11%).
• Featured with high nitrate associated with NH\textsubscript{3} emissions.
• High in winter and low in summer.
• Can be modeled using meteorological predictors.
- Featured with high sulfate associated with SO$_2$ emissions.
- Decreasing trend reflected regulation effects.
- High in summer due to photochemistry effect and presence of oxidants on secondary sulfate formation.
2011 Kansas Emissions Inventory - SO2

(from KDHE, 2015. 5-Year Ambient Air Monitoring Network Assessment)
• Identified by soil elements (Si, Fe, Al, …).
• Spikes were observed on windy days.
• Characterized mainly by non-soil potassium.
• Spikes were consistently observed in April.
S4-Primary smoke particles
S5—Secondary organic particles

Identified by large OC/EC ratio.
S5 correlated with S4 with Pearson correlation coefficient of 0.49.
S5-Secondary organic particles
Importance of secondary organic particles

Mass of secondary organic particles from burning \( \approx 4 \times \) Mass of primary smoke particles
Average S4 and S5 in April vs. acres burned (Tallgrass site)

- **S4**: Primary smoke particles ($\mu$g/m$^3$)
  - Equation: $y = 0.3097x + 0.718$
  - $R^2 = 0.1517$

- **S5**: Secondary organic particles ($\mu$g/m$^3$)
  - Equation: $y = 1.6847x + 2.3137$
  - $R^2 = 0.2206$
Highest S4 and S5 in April vs. acres burned (Tallgrass site)

S4-Primary smoke particles (μg/m³)

\[ y = 0.6281x + 3.3607 \]
\[ R^2 = 0.0406 \]

S5-Secondary organic particles (μg/m³)

\[ y = 5.2872x + 9.5592 \]
\[ R^2 = 0.1142 \]
Highest PM$_{2.5}$ in April vs. acres burned (Tallgrass site)

\[ y = 7.1196x + 15.295 \]
\[ R^2 = 0.1744 \]

- When acres burned \( \geq 2.5 \) million, PM$_{2.5}$ > 35\(\mu g/m^3\) may occur.
- When acres burned < 2.5 million, PM$_{2.5}$ > 35\(\mu g/m^3\) did not occur.
O$_3$ and PM$_{2.5}$

- O$_3$ and PM$_{2.5}$ controls are traditionally considered separately because their high pollution periods are not concurrent on seasonal timescales.
  - O$_3$ usually peaking in summer and PM$_{2.5}$ often peaking in winter.
  - Higher temperature and lower RH promote O$_3$ formation but cause volatilization of nitrate aerosols.
Daily max 8hr O₃ at the Konza Praire site

Daily PM₂.₅ at the Tallgrass site
Meteorological effect modeling

Daily max 8hr $O_3$

Daily $O_3$ residuals

P<0.01

Significant effect

Poor correlation

Receptor modeling

Daily PM$_{2.5}$

Daily S1, S2, S3, S4, S5
Influence of $O_3$ from the previous day

Weather conditions

$O_3$

S5-Secondary organic particles

S4-Primary smoke particles

VOCs+$NO_x$

Interaction

Existing pollutants

S2- Sulfate/Industrial