1. Flint Hills pasture burning: A challenge for air quality

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Pasture burning smoke management
and air quality workshop
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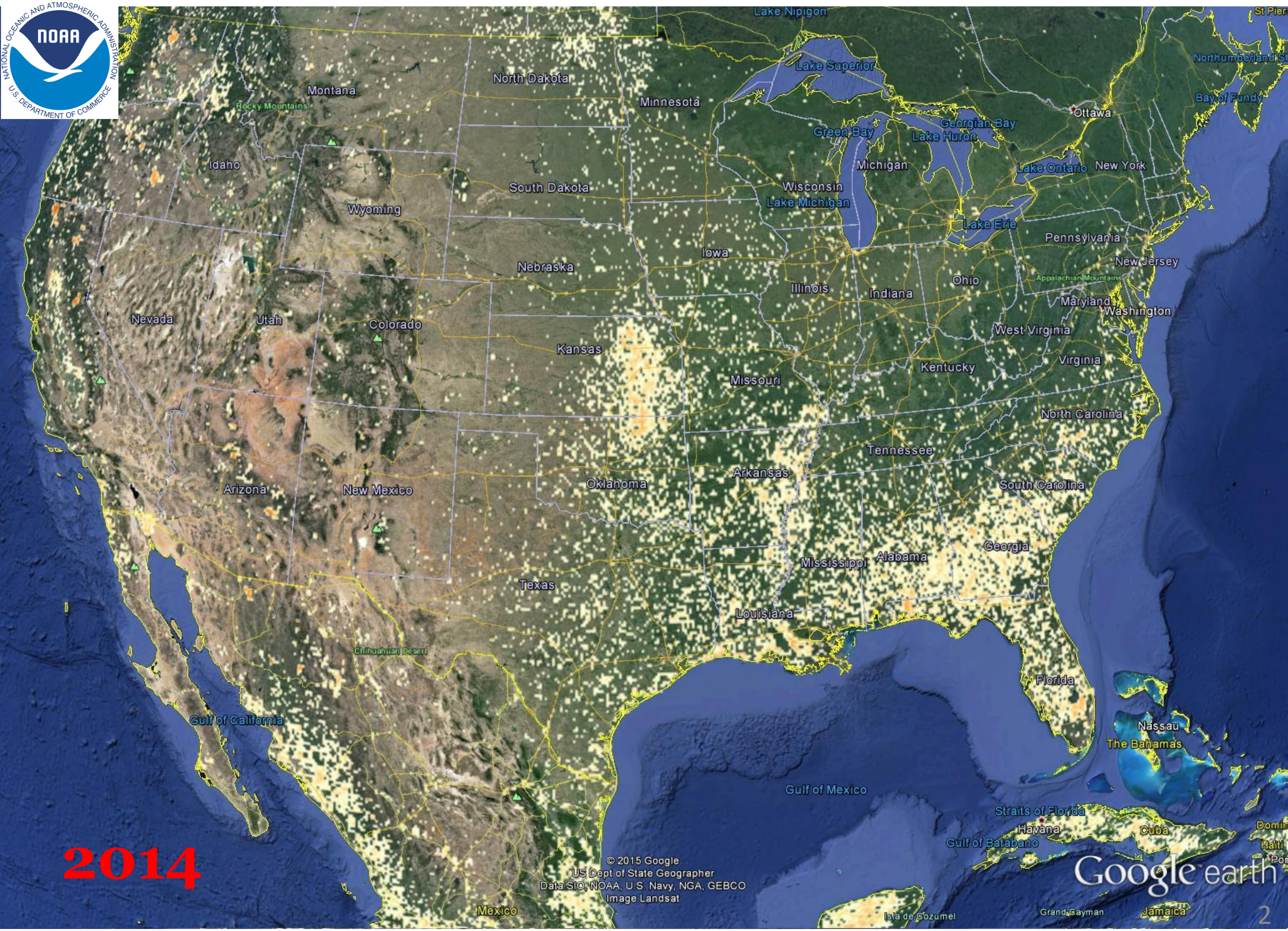
K-STATE Research and Extension | Biological and Agricultural Engineering



Lake Nipigon
Lake Superior
Montana
North Dakota
Minnesota
Rocky Mountains
Ottawa
Northumberland St
Bay of Fundy
Georgian Bay
Green Bay
Lake Huron
Idaho
Michigan
Lake Ontario
New York
South Dakota
Wisconsin
Lake Michigan
Wyoming
Lake Erie
Pennsylvania
Iowa
New Jersey
Nebraska
Appalachian Mountains
Illinois
Indiana
Ohio
Maryland
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Kansas
Virginia
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Tennessee
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Why burning?

- Prescribed fire is a long-standing practice needed for ecosystem management.
- Better than wild fires.

(Photo credit: Judy Crowell)

Smoke is not avoidable

(Photo credit: S. O'Neill)

- What is in the smoke?
- What pollutants are of interest and why?
- How much is emitted?
- How do weather conditions affect dispersion of smoke?
- Fate and transport of smoke components.
- Health and environmental impact of smoke.

Management is Key!

Minimize smoke production

- Not easy
- Need more research

Reduce impact of smoke

- Timing of burn
- Communication

The Regulatory Process

- Clean Air Act (CAA)
- National Ambient Air Quality Standards (NAAQS)
- Six criteria air pollutants
  - Particulate Matter (PM)
  - Ozone (O_3)
  - Nitrogen Dioxide (NO_2)
  - Sulfur Dioxide (SO_2)
  - Carbon Monoxide (CO)
  - Lead (Pb)
- Five year review cycle
- Nonattainment area
- State Implementation Plan (SIP)

http://www.epa.gov/ttn/naaqs/

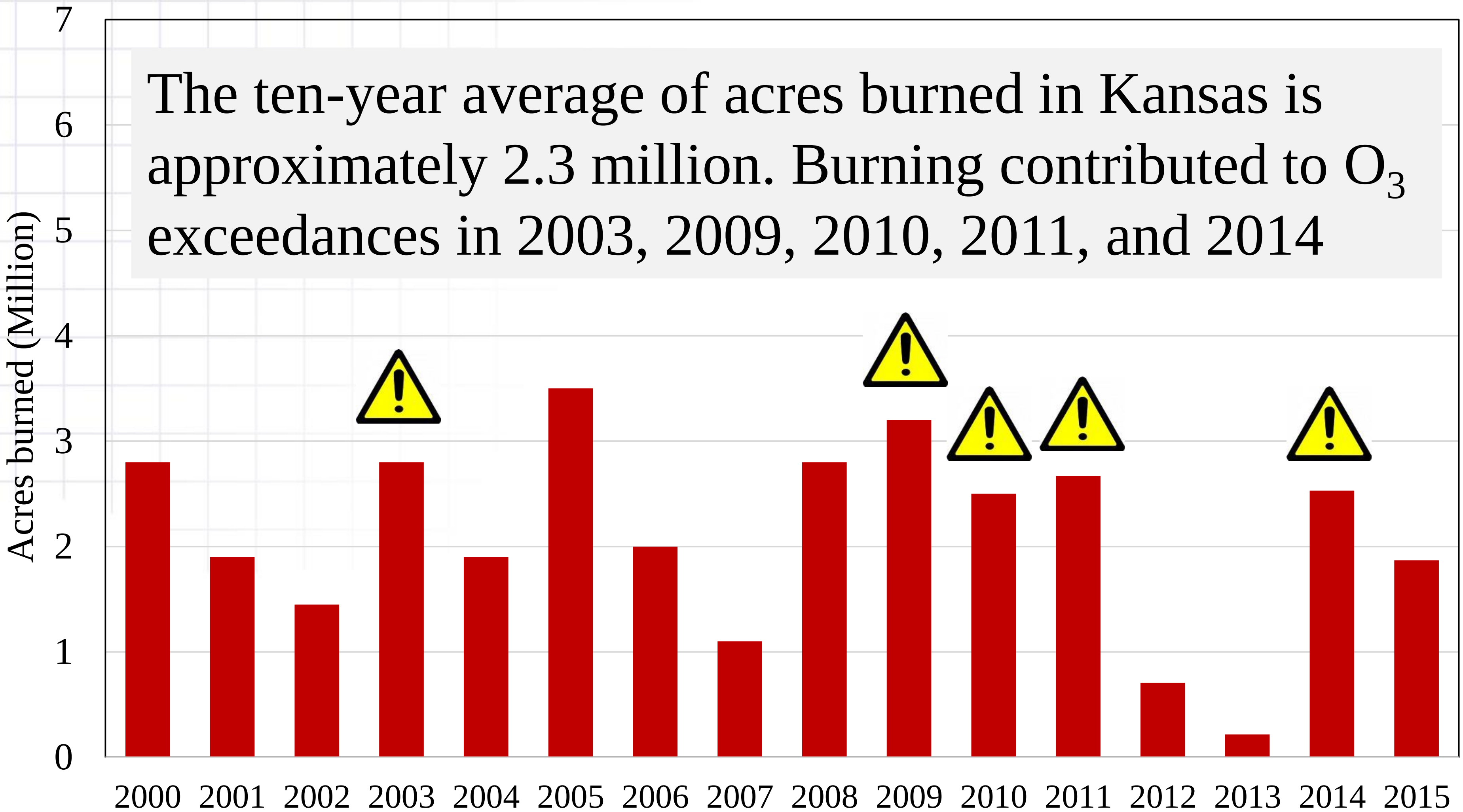
Evolution of PM standards

		Annual	24-hour
1971	TSP	75 µg/m^3	260 µg/m^3
1987	PM_{10}	50 µg/m^3	150 µg/m^3
1997	$PM_{2.5}$	15 µg/m^3	65 µg/m^3
2006	$PM_{2.5}$	15 µg/m^3	35 µg/m^3
2012	$PM_{2.5}$	Primary 12 µg/m^3 Secondary 15 µg/m^3	35 µg/m^3

Evolution of O_3 standards

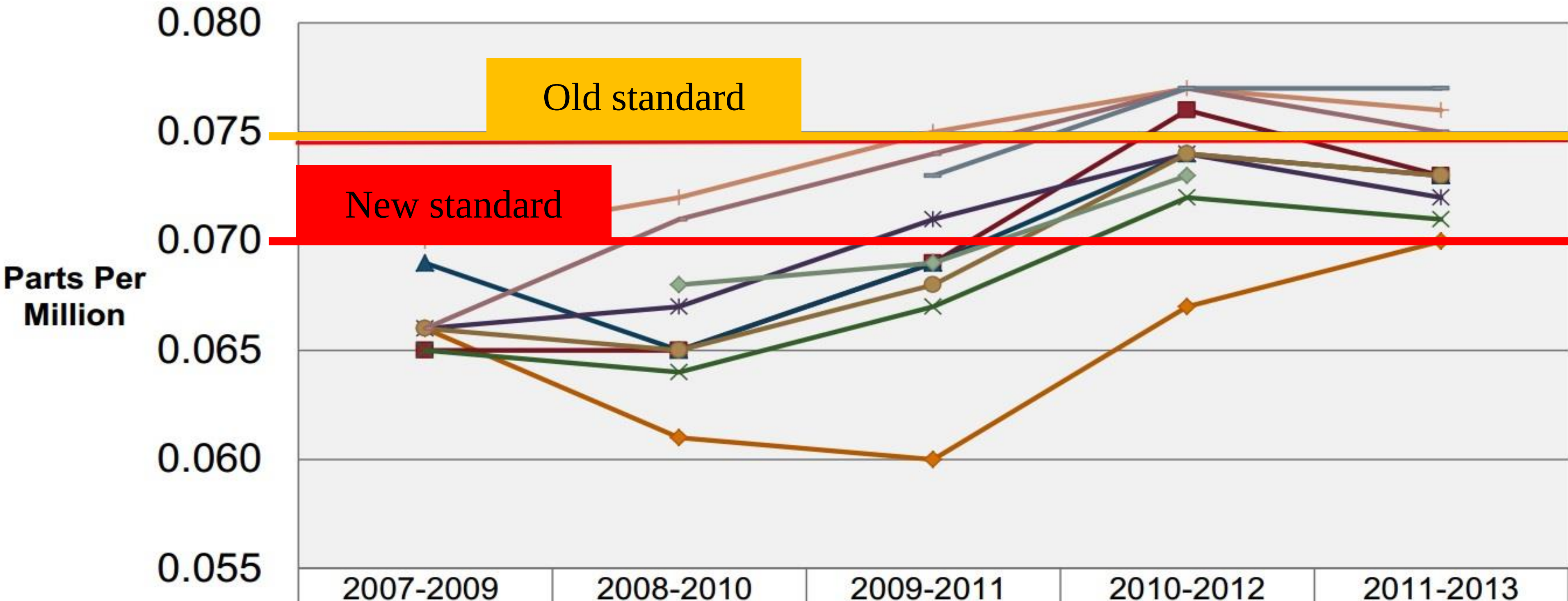
	8-hour	1-hour
1979		120ppb
1997	80ppb	
2008	75ppb	
2015	70ppb	

Flint Hills acres burned 2000-2015



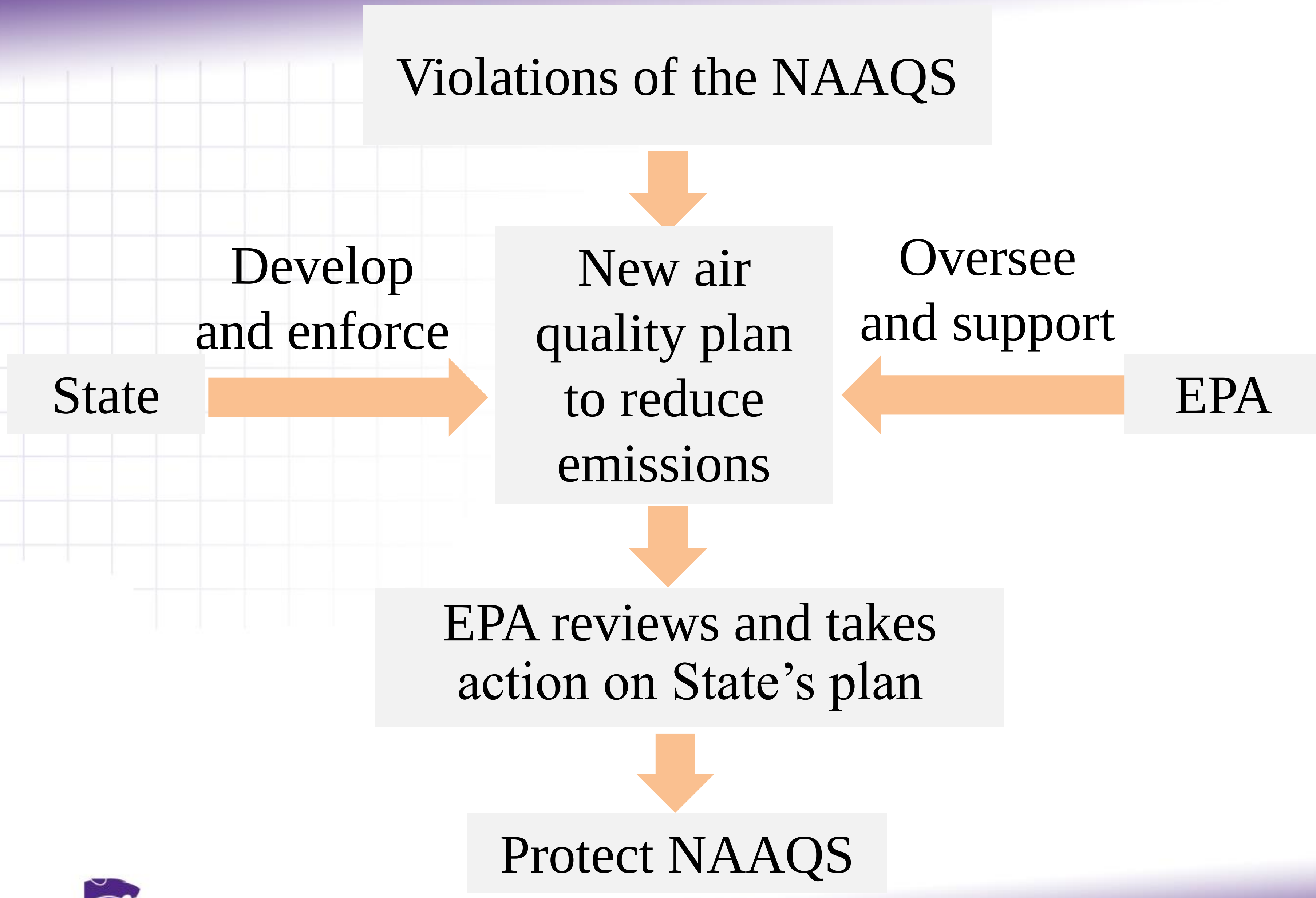
(Source: KDHE)

Kansas 8 Hour Ozone Design Values



	2007-2009	2008-2010	2009-2011	2010-2012	2011-2013
JFK	0.066	0.061	0.060	0.067	0.070
Heritage Park	0.065	0.065	0.069	0.076	0.073
Leavenworth	0.069	0.065	0.069	0.074	0.073
Mine Creek	0.065	0.064	0.067	0.072	0.071
Cedar Bluff	0.066	0.067	0.071	0.074	0.072
KNI/Topeka	0.066	0.065	0.068	0.074	0.073
Peck	0.070	0.072	0.075	0.077	0.076
Wichita HD	0.066	0.071	0.074	0.077	0.075
Sedgwick			0.073	0.077	0.077
Konza Casnet		0.068	0.069	0.073	

(Reference: Thomas Gross, KDHE)


Violations of the NAAQS
State
Develop
and enforce
New air
quality plan
to reduce
emissions
Oversee
and support
EPA
EPA reviews and takes
action on State's plan
Protect NAAQS

Consequences of nonattainment

- State Implementation Plan (SIP) preparation
  - enhanced emissions inventory ($)
  - photochemical modeling ($)
  - planning ($)
- Transportation conformity. Potential for loss of highway funds and restrictions on how highway funds can be spent ($)
- Economic development curtailed ($)

One opportunity to receive an exemption

2007 Exceptional Events Rule (EER): Monitoring data can be excluded from non-attainment designations if exceedance is due to an Exceptional Event (EE).

- Natural events
- High wind events
- Natural disasters and associated clean-up activities
- Stratospheric ozone intrusion
- Volcanic & seismic activities
- Wildland fires

Could prescribed burning be qualified as Exceptional Events (EE)?

EPA approval of exceedances for prescribed fires used for resource management purposes is contingent upon

- Basic smoke management practices (BSMP) are being employed, or
- The state having a Smoke Management Program (SMP).

Documentation is Key!

- In order to be considered for EE, technical evidence must be submitted to EPA as a demonstration package, which must include analyses showing that no NAAQS exceedance would have occurred "but for" the EE.
- A quantitative assessment of air quality with and without fire is required, which is a difficult task, especially for O_3.

Basic smoke management practices (BSMP) in the EER

- Steps that will **minimize air pollutant emissions** during and after the burn,
- Evaluate dispersion conditions to **minimize exposure** of sensitive populations,
- Actions to **notify populations and authorities** at sensitive receptors and contingency actions during the fire to reduce exposure of people at such receptors,
- Identify steps taken to **monitor the effects** of the fire on air quality, and
- **Identify procedures** to ensure that burners are using basic smoke management practices.

Seven elements of a basic smoke management plan suggested by EPA

Permit	A process for granting approval to conduct prescribed burns
Reduction	Methods for minimizing air pollutants emissions by considering alternative treatments and/or reducing fuel levels before burning
Management	Outlining smoke management considerations for each burn
Notification	Plans to notify the public and reduce exposure should smoke intrusions occur
Education	Public education and awareness programs
Enforcement	Surveillance and enforcement procedures for ensuring that smoke management programs are effective
Evaluation	Procedures for periodically evaluating smoke management programs

Reasons for having the Flint Hills smoke management plan (SMP)

- To avoid exceedances of the NAAQS.
- To receive an exemption/flag in the event of an exceedance of the NAAQS.

The goal

Keep pasture burning , but in a manner that minimize adverse environmental and social effects from prescribed fires through reduction and communication.

- To maintain the Flint Hills ecosystem and related economy.
- To reduce air quality and economic impacts on downwind communities;

History of the Flint Hills SMP

2003 episode: KDHE and agricultural interests took an initial voluntary educational approach to address the air quality issue.

2009 episode: EPA denied KDHE's request to flag 2009 O_3 exceedance data due to lack of SMP

2010 episode: Formal Flint Hills Advisory Committee was formed; A subcommittee was tasked to write SMP; KDHE adopts SMP in late December 2010; Implementation of the plan is proceeding.

2011 episode: Exceptional event was granted for exceedance of NAAQS

Content of the Flint Hills SMP

- Recommended practices to reduce the air quality impacts of prescribed range burning, and tools (website) to assist land managers and local fire officials in making burning decisions.
  - www.ksfire.org with a modeling tool to predict plume movement and other burn resources
- A data collection pilot program with goal to develop a reporting system.
  - Use of a burn checklist

Smoke management

Minimize smoke production

- Not easy
- Need more research

The burn checklist

Reduce impact of smoke

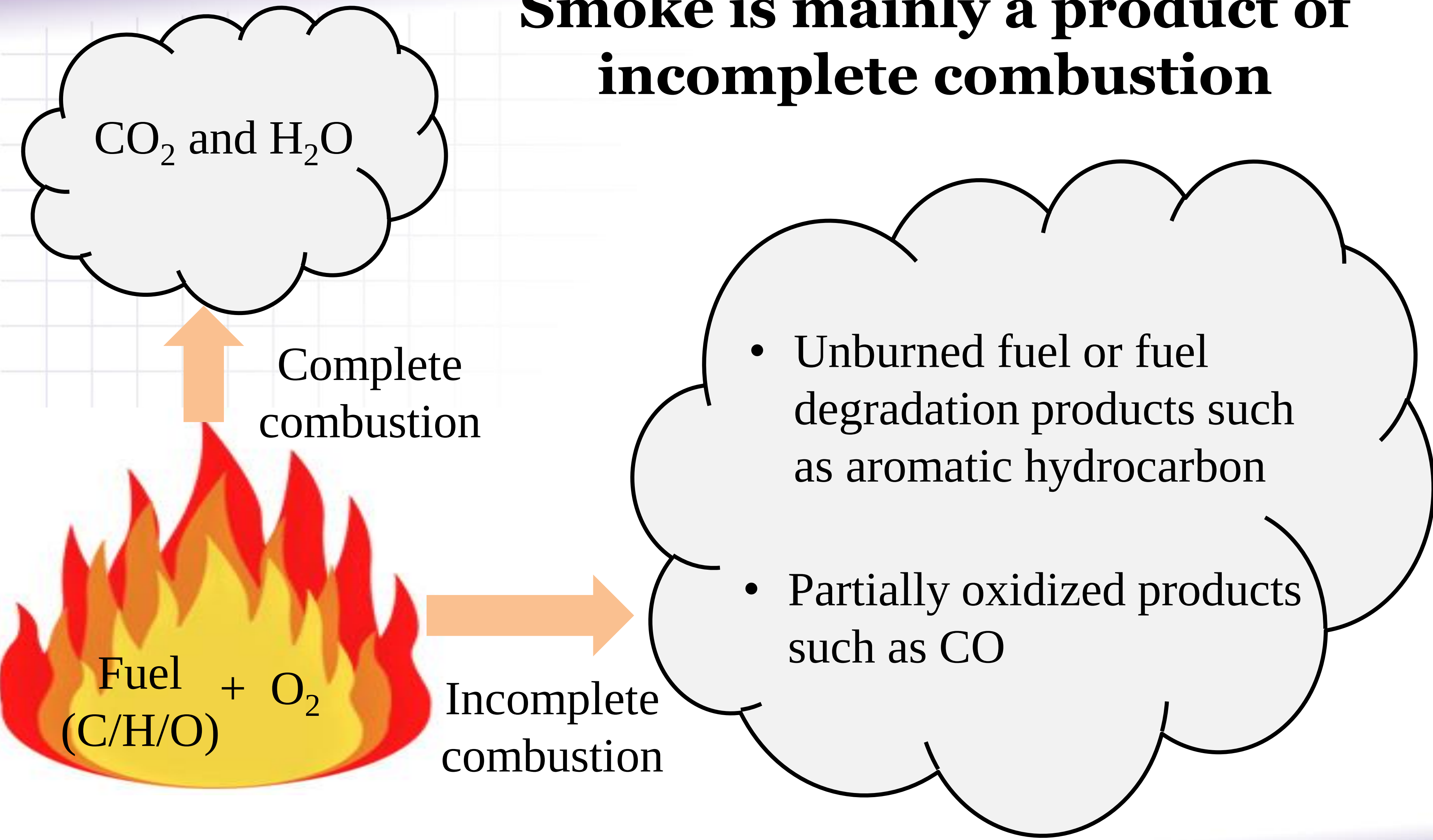
- Timing of burn
- Communication

The modeling tool

Why you should consider smoke management as part of your burn operations

- Be sensitive to public concern, and retain relationships with air quality regulators, who are committed to protect air quality standards.
- If the SMP is not effective enough to prevent an exceedance of the NAAQS, then certain contingency measures may need to be considered.

Smoke is mainly a product of incomplete combustion

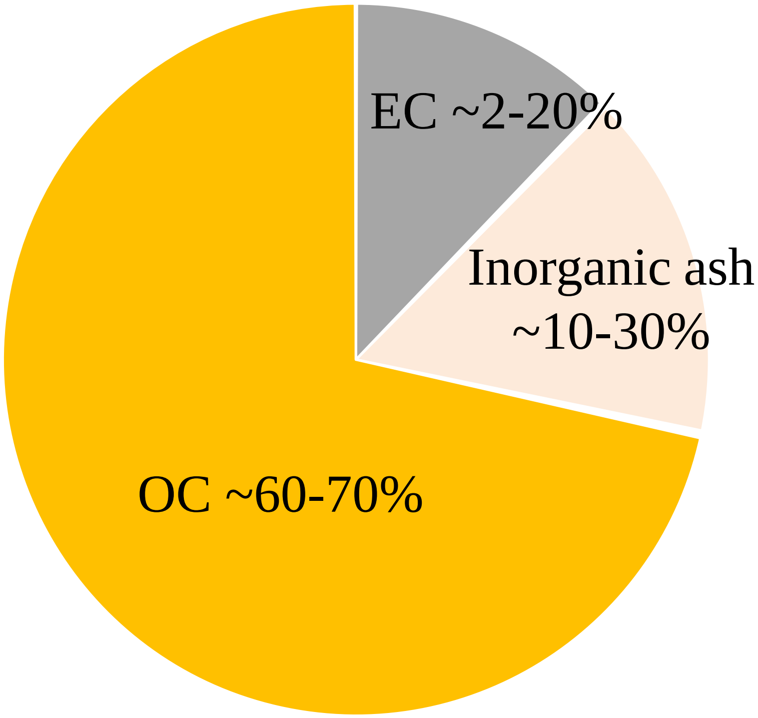


Main components of vegetation fire smoke

- **Particulate matter (PM)**
- VOCs (Acrolein, formaldehyde, isocyanic acid, …)
- SVOCs (polycyclic aromatic hydrocarbons (PAHs), …)
- Permanent gases (CO_2, CO, CH_4, NO_x, …)
- Water vapor
- **O_3 (Secondary product of NO_x and VOCs)**

Particulate matter (PM) in smoke

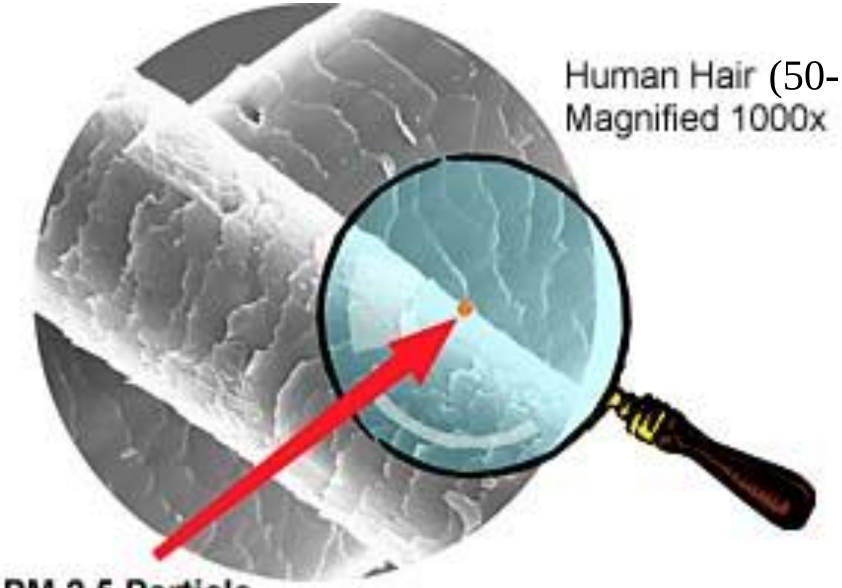
- Smoke PM acts as a vehicle to carry absorbed hazardous compounds into the respiratory tract.
  - VOCs
  - SVOCs
  - Toxic metal elements
- PM under the influence of fire smoke could be more damaging to human health than normal urban particles.



Composition of smoke PM

Size of smoke PM

- ~90% of PM in smoke is PM_{10}
- ~70 % of PM is $PM_{2.5}$
- Size distributions of smoke PM generally can be represented by a bimodal log-normal distribution.
- Fine particles are produced from combustion, and larger particles are entrained into the smoke as a result of the turbulence generated by the fire.



Managing smoke exposure

~100 µm

This is inadequate to protect your lungs from the fine particles in smoke

N95 masks are designed to filter out 95% of test particles as small as 0.3 µm

Impacts of the small size of smoke PM

Health effect

- Can reach deeper into human respiration system;
- Can cause an inflammatory response even though the material itself is nontoxic.

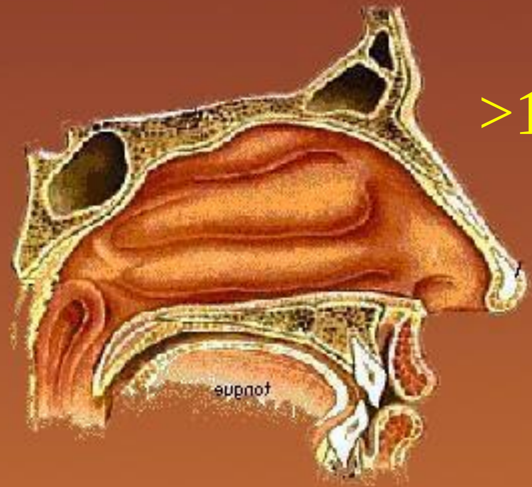
Lifetime

- Not easily removed by gravitational settling and can be transported over long distances (100-1000km);
- Lifetime is from days to weeks

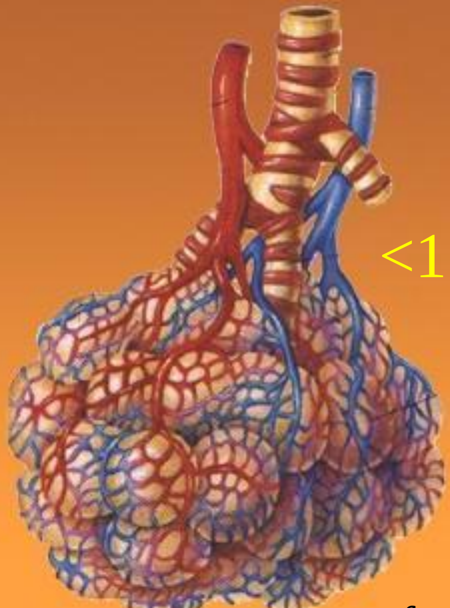
Visibility

- Size near the wavelength of visible light (0.4-0.7μm) and therefore can efficiently scatter light and reduce visibility.

Where are particles removed or deposited?



>10 µm: nasal passages



<1 µm: in alveoli

Reference: Susan O’Neill

Volatile organic compounds (VOCs)

- Organic irritants
  - Formaldehyde: a carcinogen linked to nasal and throat cancer and leukemia.
  - Acrolein: a potent lachrymatory agent.
  - Isocyanic acid: contribute to cardiovascular problems and inflammation.
- **Precursor of O_3**

Semi-volatile organic compounds (SVOCs)

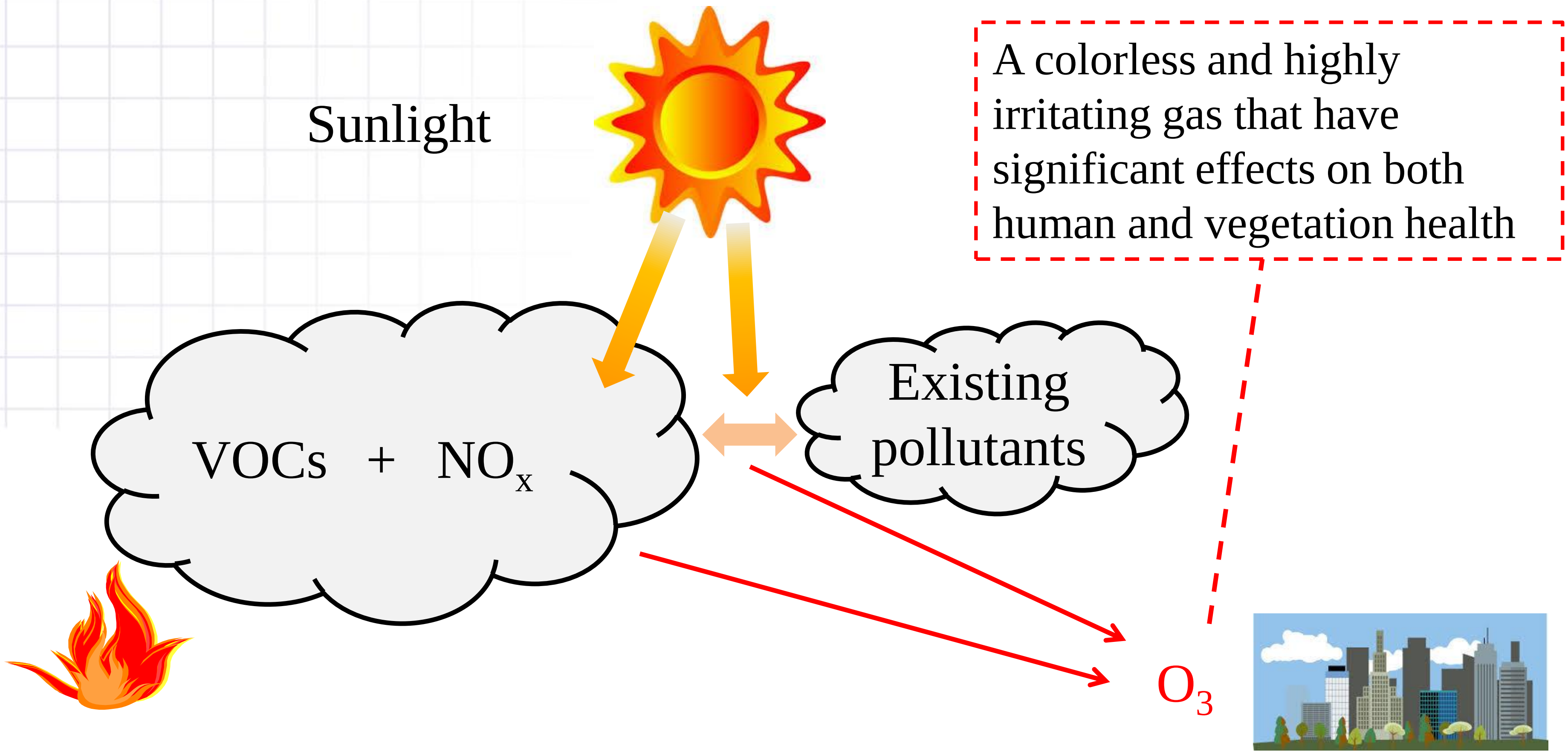
- Complex molecules such as polycyclic aromatic hydrocarbons (PAHs).
  - Benzo(a)pyrene (BaP), naphthalene, and anthracene, …
  - Can be adsorbed onto fine particles or as volatiles in the vapor phase; can be transported long distances.
  - Potentially carcinogenic and mutagenic.

- PAHs emissions were more strongly influenced by burning conditions than by the type of fuel.
  - For low-intensity fires, the ratio of BaP to PM is higher by almost 2 orders of magnitude.

Permanent gases

- CO_2, CH_4
  - Greenhouse gases
- CO
  - Toxic
- NO_x (NO and NO_2)
  - Due to the low combustion temperatures in vegetation fires, the nitrogen species emissions are mainly based only on fuel nitrogen.
  - Precursor of O_3

Secondary pollutants of the smoke plume



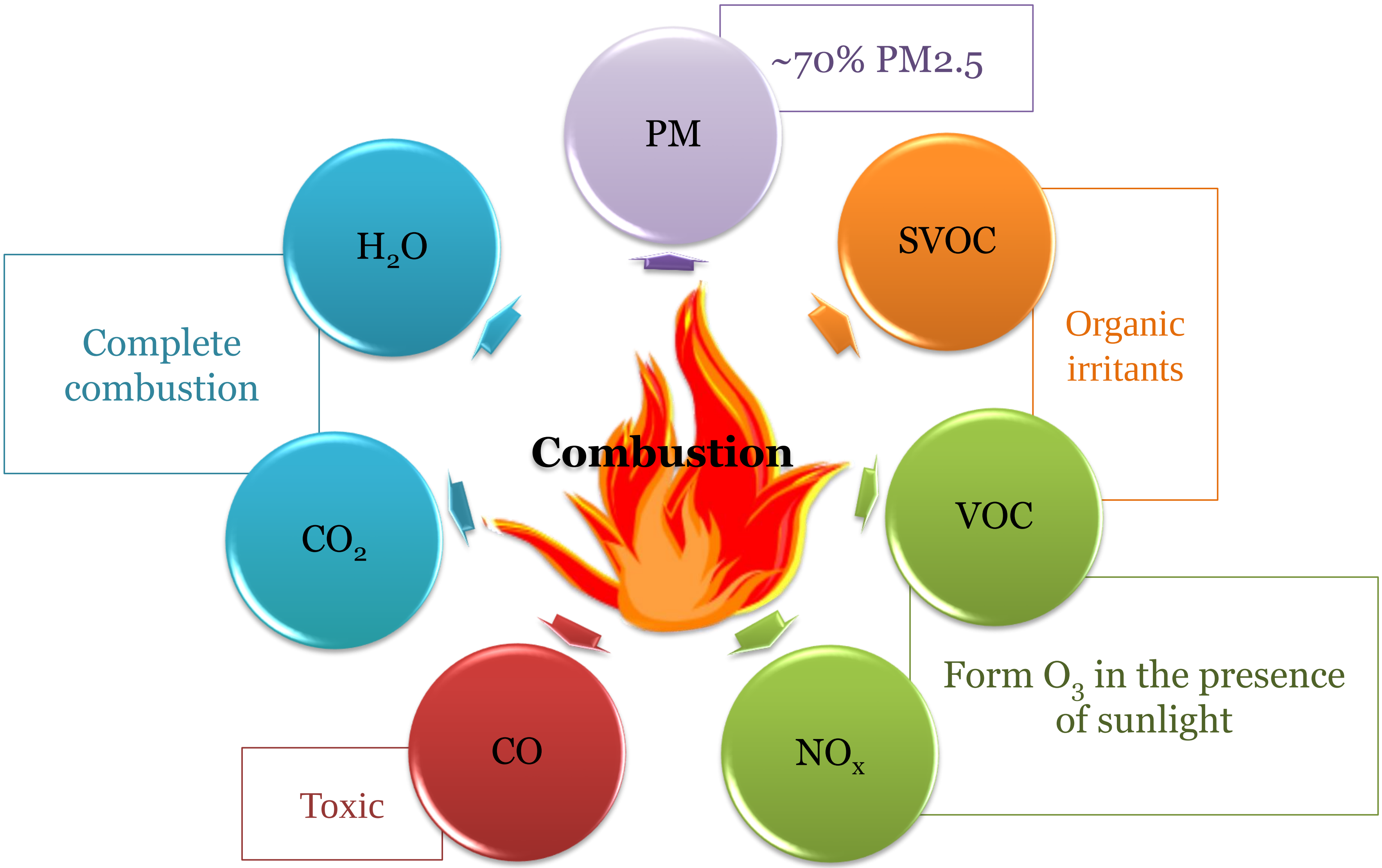
Other potential trace components

- Herbicides and insecticides
  - may become re-suspended in the air.
- Dioxins
  - are found in soils in remote areas and are sometimes present in vegetation fire smoke
- Sulfur-based compounds
  - can be produced when sulfur-rich vegetation or soil are burned.
- Free radicals
  - may persist up to 20 min following formation and may be of concern to people exposed to them because free radicals may react with human tissues

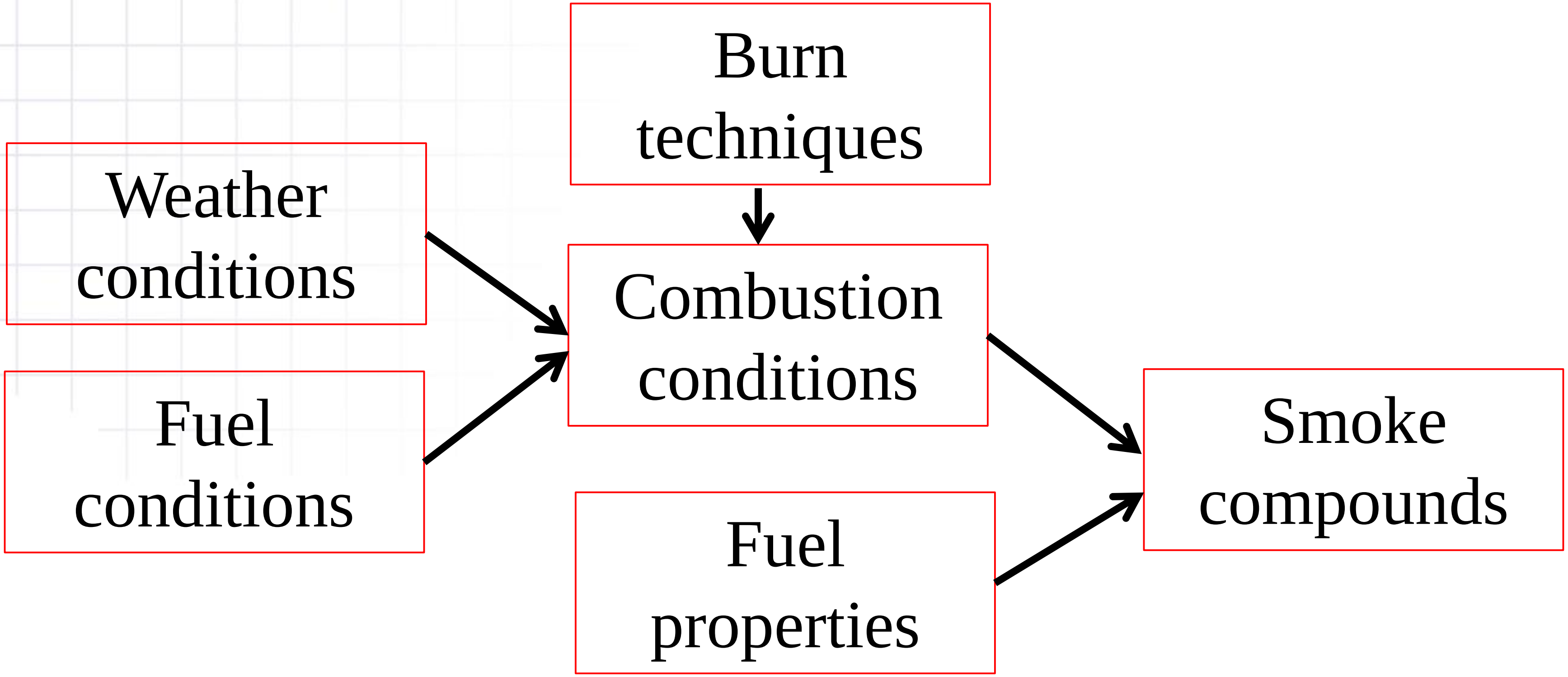
Air pollutants	Observed concentrations in literature		Standards
	At the fires	At downwind communities	
$PM_{2.5}$	148-6865 μg/m^3	63-400 μg/m^3	[a]35 μg/m^3
Acrolein	0.018-0.071ppm	0.009 ppm	[c]0.1 ppm
Formaldehyde	0.03-0.47 ppm	0.02-0.047 ppm	[c]0.016 ppm
Isocyanic acid	-	600 ppb	-
PAHs	-	-	[d]200 μg/m^3
BaP	0.10-0.16 μg/m^3	0.007 μg/m^3	-
Acenaphthene	0.57-1.53 μg/m^3	0.83-0.89 μg/m^3	-
Naphthalene	0-3.27 μg/m^3	0-3.53 μg/m^3	-
Phenanthrene	0.38 μg/m^3	-	-
CO	1-140 ppm	1-6 ppm	[b]9 ppm
O_3	-	Up by 50 ppb	[b]75 ppb

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

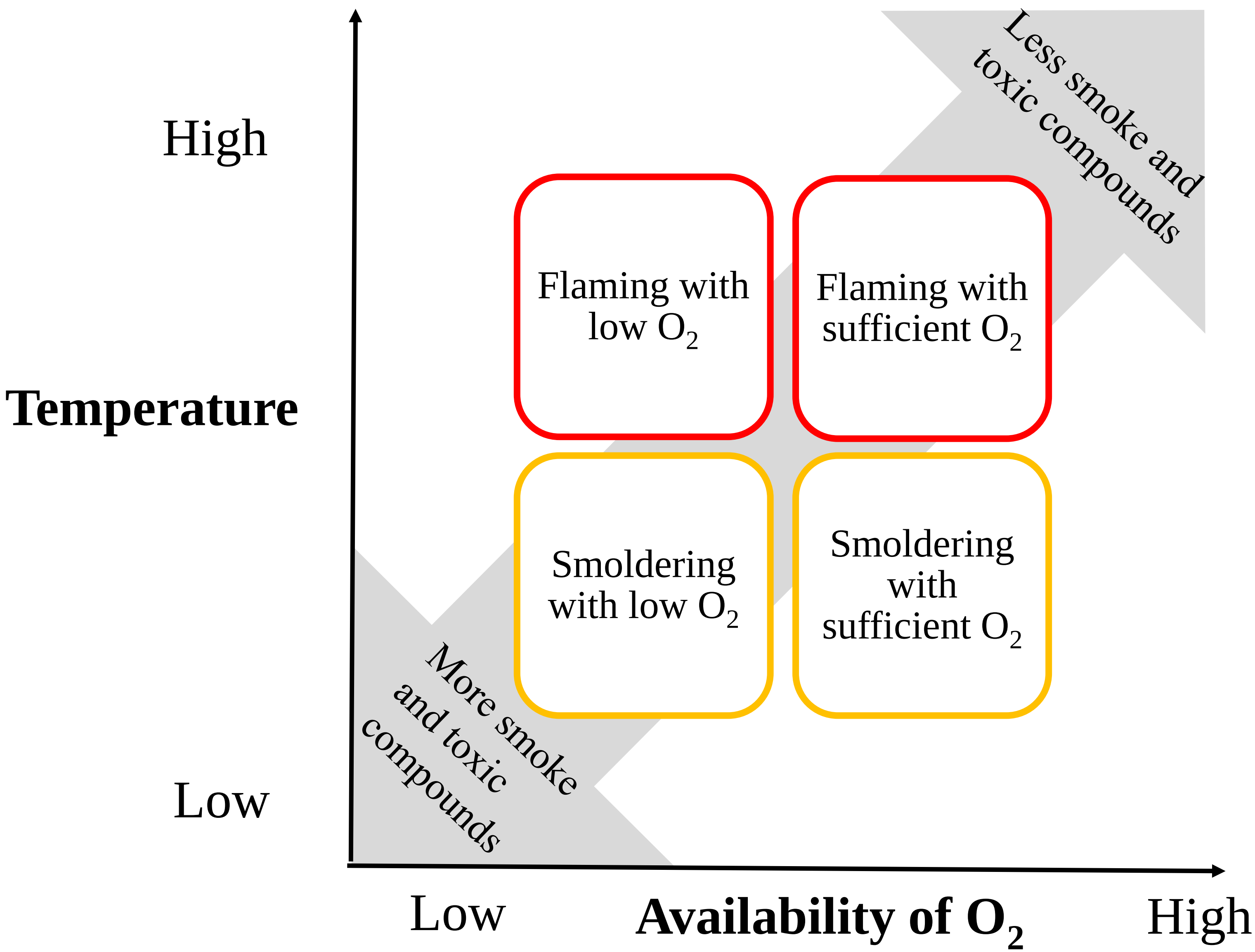
Summary of smoke composition



Not all smoke is equal



Smoke and combustion conditions



Smouldering is a typically incomplete combustion.

Many solid materials can sustain a smouldering reaction, including cellulose and wood.

- Low temperature.
- A surface phenomenon (occurs on the surface of solid rather than in gas phase).
- Slow but persistent (about ten times slower than flames spread over a solid).
- A significant fire hazard.
- Emits much more toxic smoke than flaming fires.

Flaming **Smouldering**

(Photo credit: Rein, 2009)

Fuel-air equivalence ratio

$$\Phi = \frac{\text{actual fuel to air ratio}}{\text{stoichiometric fuel to air ratio}}$$

		Typical CO/CO_2 ratio (v/v)
$\Phi < 1$	Well-ventilated flames	<0.05
$\Phi = 1$	Stoichiometric flames	~0.05
$\Phi > 1$	Under-ventilated flames	0.2-0.4

Availability of O_2 depends on wind, turbulence, and characteristics of the fuel, such as vegetation density, shape, and structure.

Fuel properties

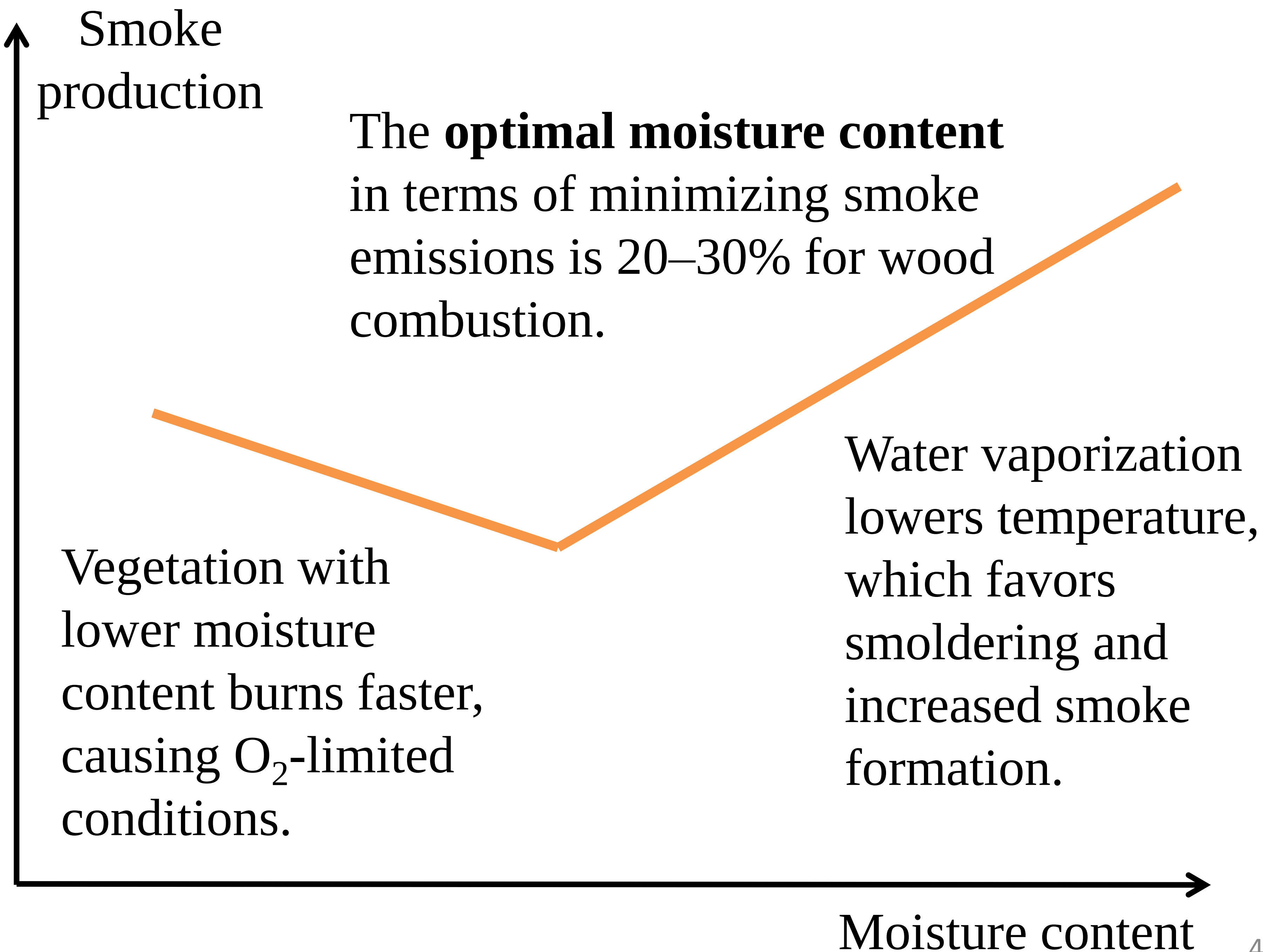
Air and fuel temperature

The equivalence ratio

- The heating value and the specific heat capacity.
- Moisture content: water vaporization lowers temperature.

Combustion temperature

- Φ <1, overoxidized, the excess O_2 must be heated to the product temperature and thus the temperature drops.
- Φ >1, underoxidized, no enough O_2 to burn fuel to the most oxidized state, so energy released is less and temperature drops as well.


Smoke production
The **optimal moisture content** in terms of minimizing smoke emissions is 20–30% for wood combustion.
Water vaporization lowers temperature, which favors smoldering and increased smoke formation.
Vegetation with lower moisture content burns faster, causing O_2-limited conditions.
Moisture content

In open vegetation fires, different combustion conditions may occur simultaneously at different locations within the fire environment. Their proportions and the prevalent conditions vary over time.

(Photo credit: Kenneth Craig, et al)

Estimation of smoke emissions

Inventory estimates of emissions of smoke components from open fires are traditionally calculated using the following equation:

$$\text{Emissions} = A \times FL \times \beta \times EF$$

- A is burned area, ha;
- FL is fuel load, kg DM/ha;
- β is burn efficiency (fraction of biomass consumed), %;
- EF is emission factor, g/kg DM.

Empirical emission factors in literature

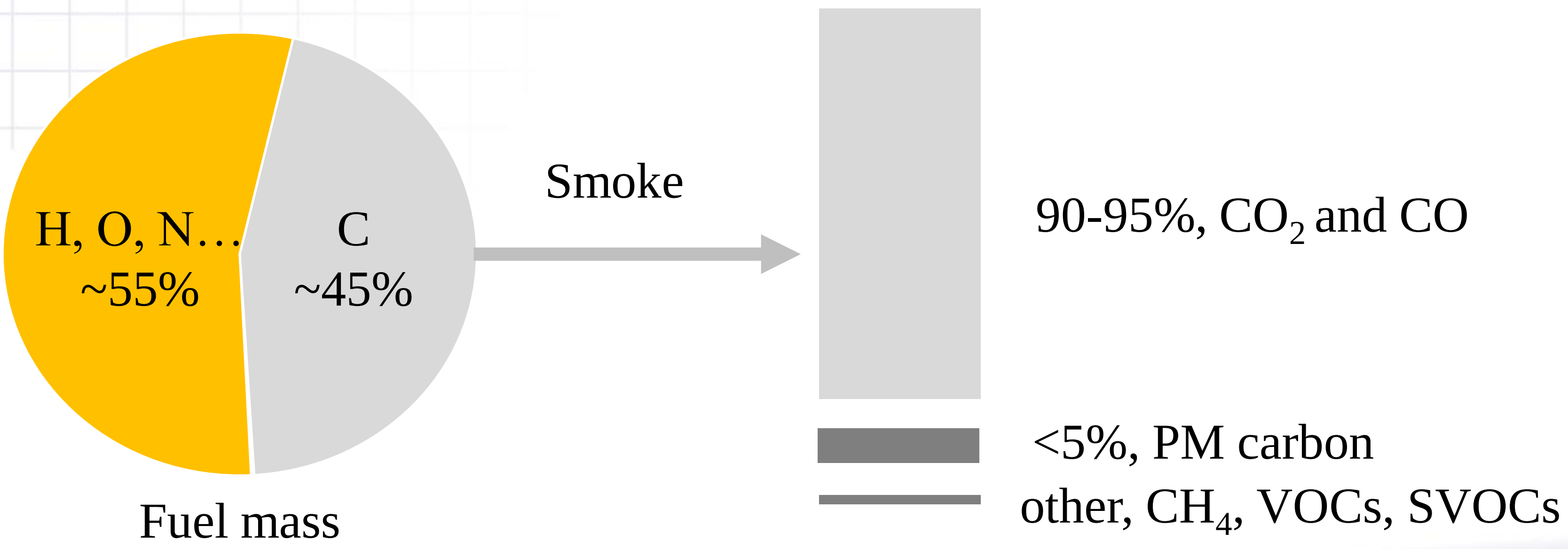
Emission factor is defined as the amount of a smoke component generated per unit mass of fuel burned.

Air pollutants	Emission factor
$PM_{2.5}$	5 - 9 g/kg DM
NO_x	2 - 4 g/kg DM
VOCs	Up to 1.4 g/kg DM

(Ward, 1990; Andreae and Merlet, 2001; Butler and Mulholland, 2004; Urbanski et al., 2009)

Carbon balance of fire smoke

Emission factors can be estimated from emission ratios, which relates the emission of a smoke component of interest to that of a reference component, such as CO_2 or CO.



$PM_{2.5}$ emission
Prescribed burn vs. cars

~28 kg $PM_{2.5}$

Burned area: 1 ha

Assuming 4000 kg DM/ha fuel load.

≈

~28 kg $PM_{2.5}$

4,000,000 car miles

Based on $PM_{2.5}$ emission factor for 2014 model gasoline passenger cars: 0.007g/mile (Cai et al., 2013)

NO_x emission
Prescribed burn vs. cars

~12 kg NO_x

↑

Burned area: 1 ha

↑

Assuming 4000 kg DM/ha fuel load.

≈

~12 kg NO_x

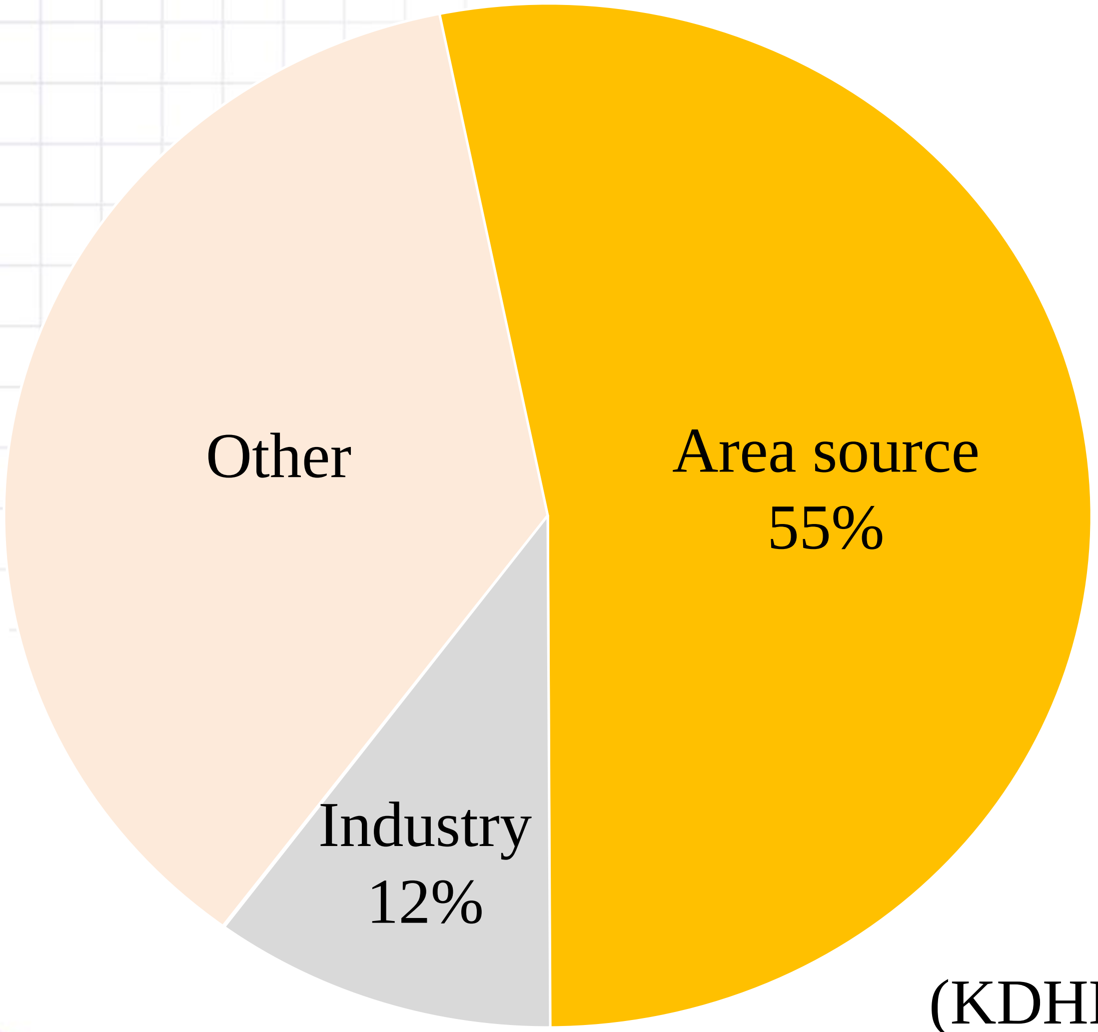
↑

100,000 car miles

↑

Based on NO_x emission factor for 2014 model gasoline passenger cars: 0.12g/mile (Cai et al., 2013)

Air pollution sources in Kansas



Contribution from pasture burning?

(KDHE air quality report)