Session 1:
The nature of smoke and basics of the air quality issues

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Pasture burning smoke management
and air quality workshop
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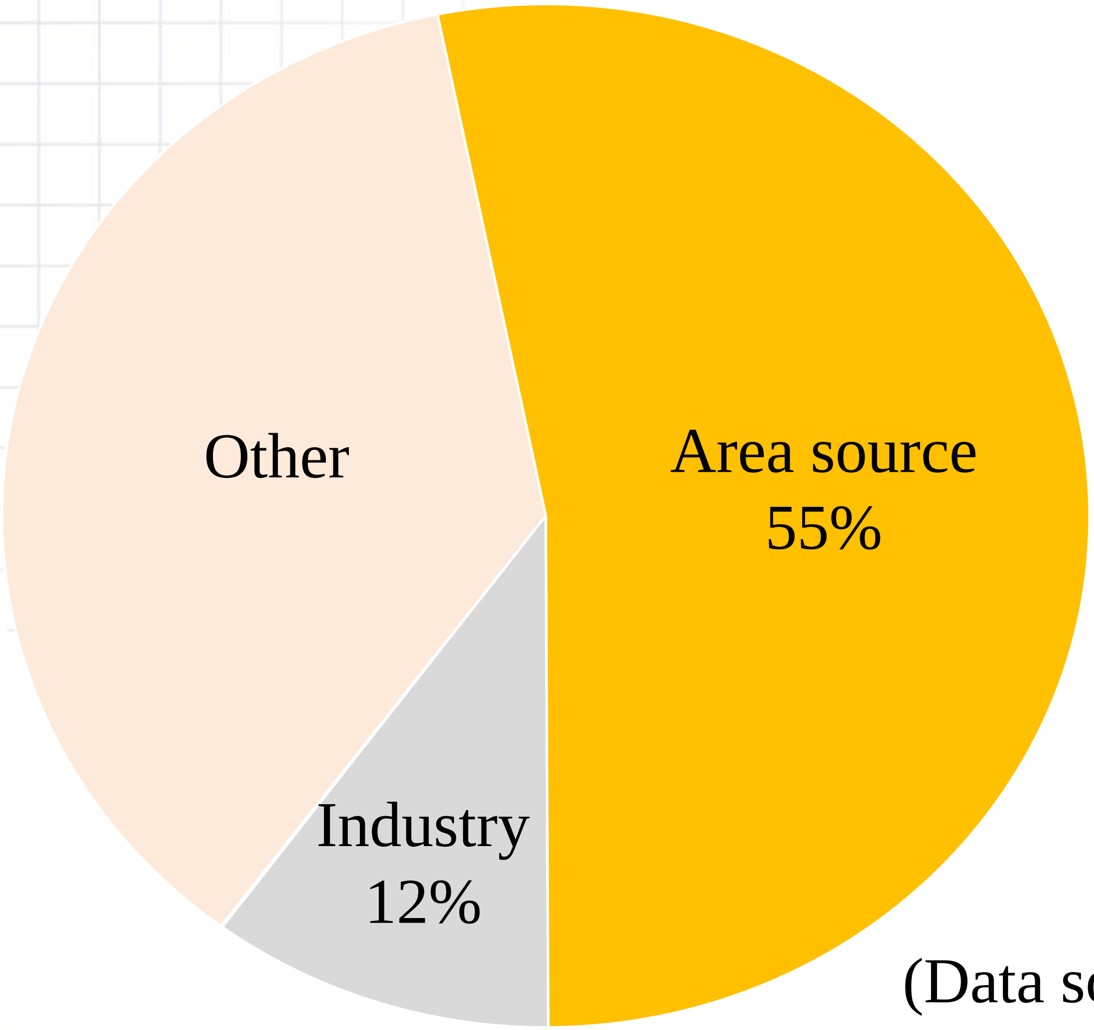
Air pollution sources in Kansas



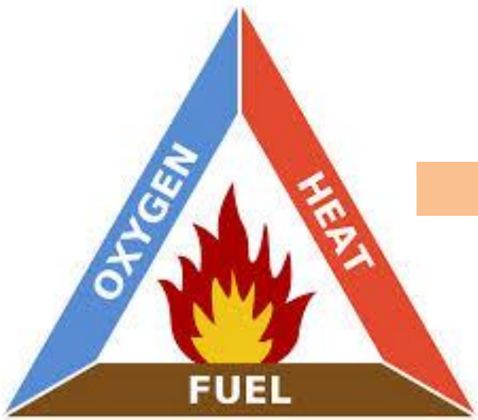
Contribution from pasture burning?

(Data source: KDHE)

- 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.

(Photo credit: S. O’Neill)

A complex mixture of oxidized products including gases and particles



Fire triangle

Results

Smoke

Ash

Heat

Application

Destroy waste

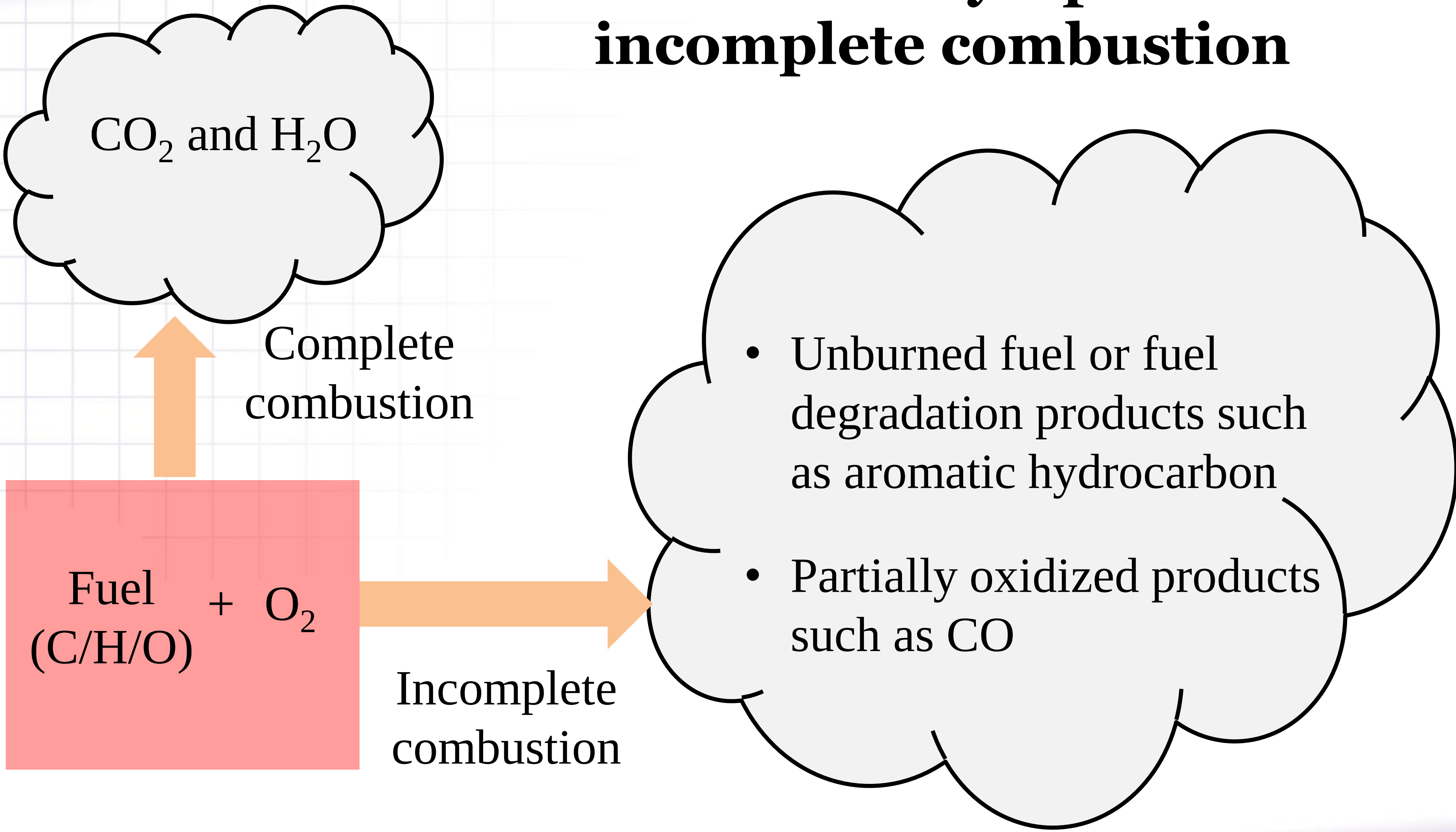
Produce energy

Prescribed fire is a tool for ecosystem management

- Recall that wildfire is a fire that is unwanted from a human point of view
- Prescribed fire is used to accomplish management goals
- Smoke is unlike most other pollutant sources – it is not avoidable and a direct control device can not be put on it.

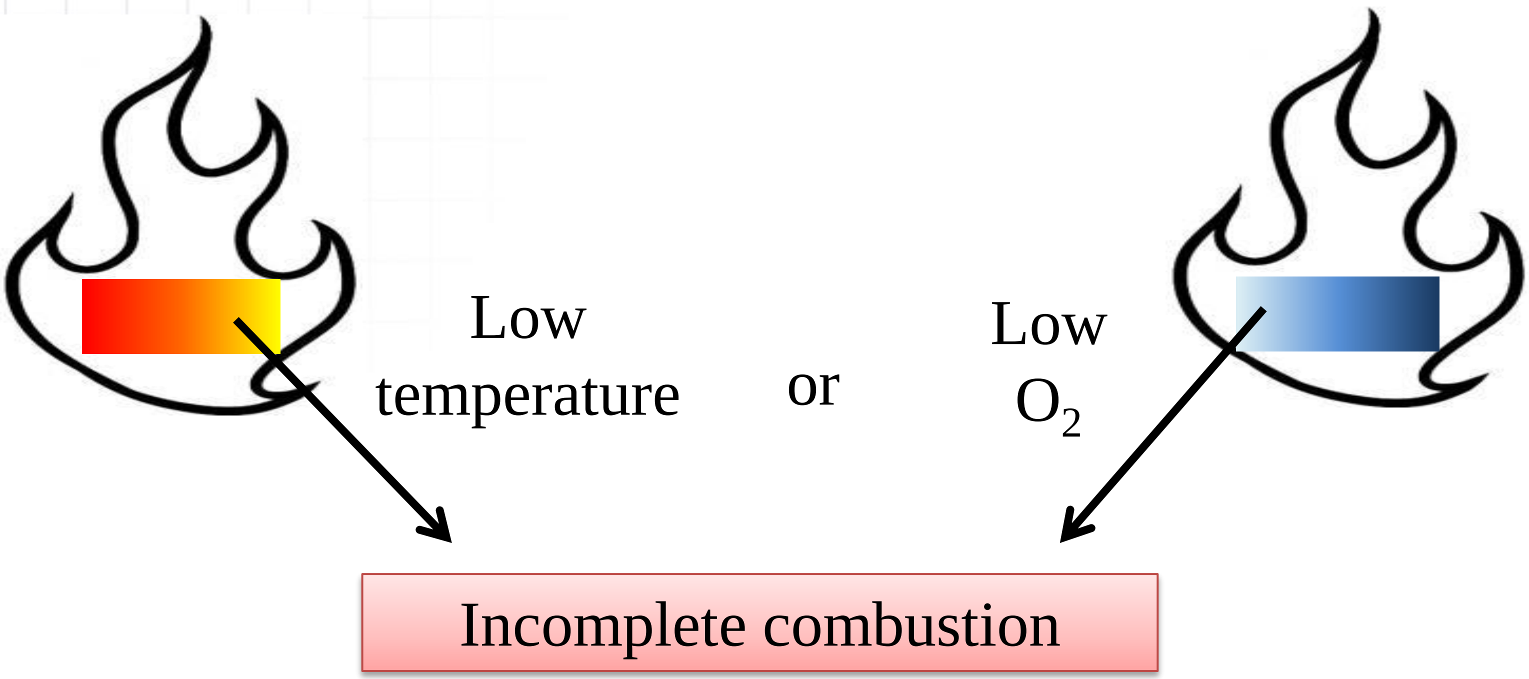
Management is Key!

Smoke is mainly a product of incomplete combustion



Complete combustion is almost impossible to achieve

In a typical fire, substantial temperature and concentration gradient exist in the buoyancy-induced turbulent flow.



Stoichiometric air-to-fuel ratios of common fuels

Fuel	Ratio by mass
Gasoline	14.7 : 1
Diesel	14.5 : 1
Natural gas	17.2 : 1
Propane	15.67 : 1
Ethanol	9 : 1
Hydrogen	34.3 : 1

Fuel-air equivalence ratio Φ is defined as

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

		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

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.

Smouldering is a typically incomplete combustion.

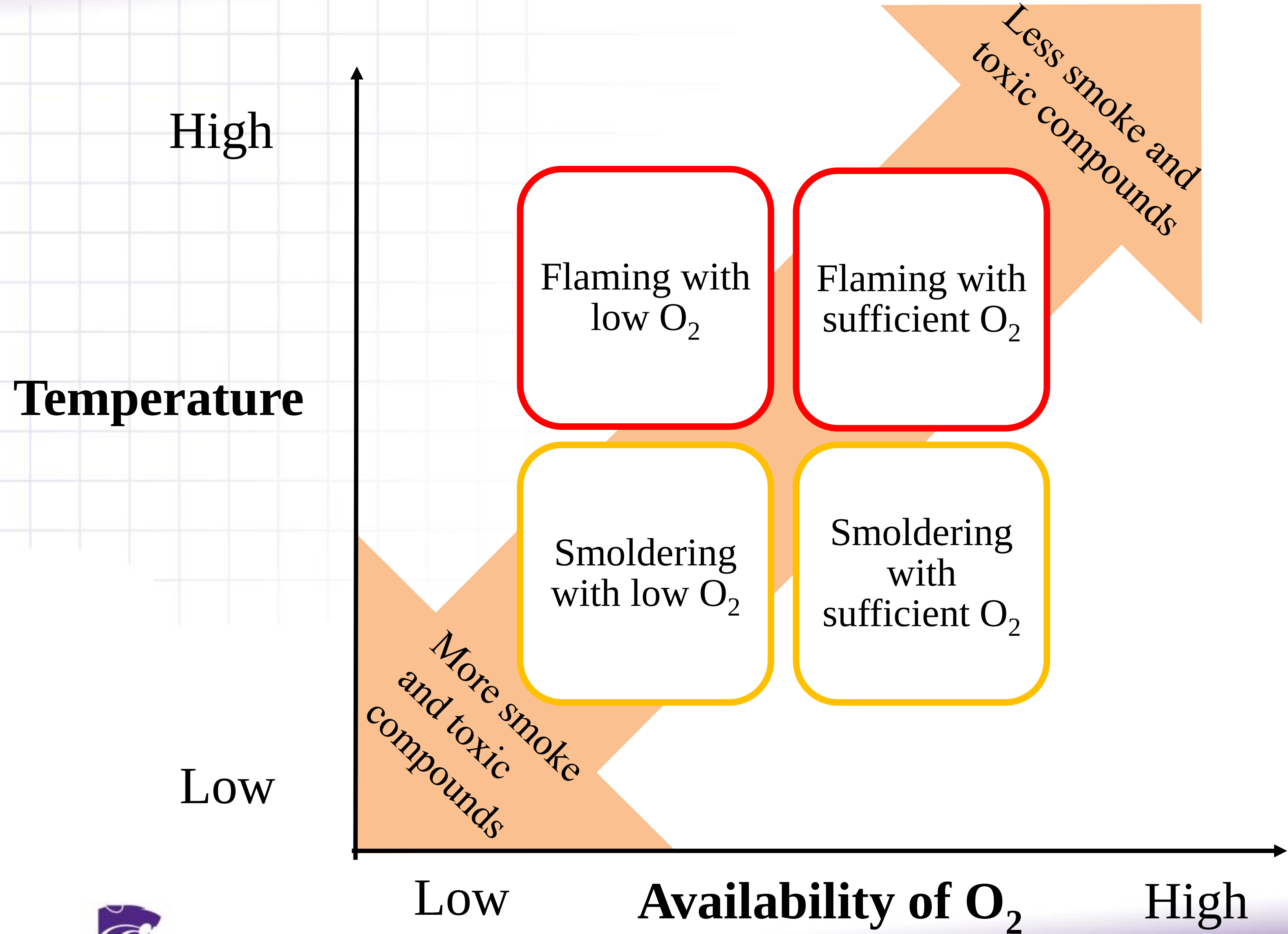
Many solid materials can sustain a smouldering reaction, including cellulose and wood.

- 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.

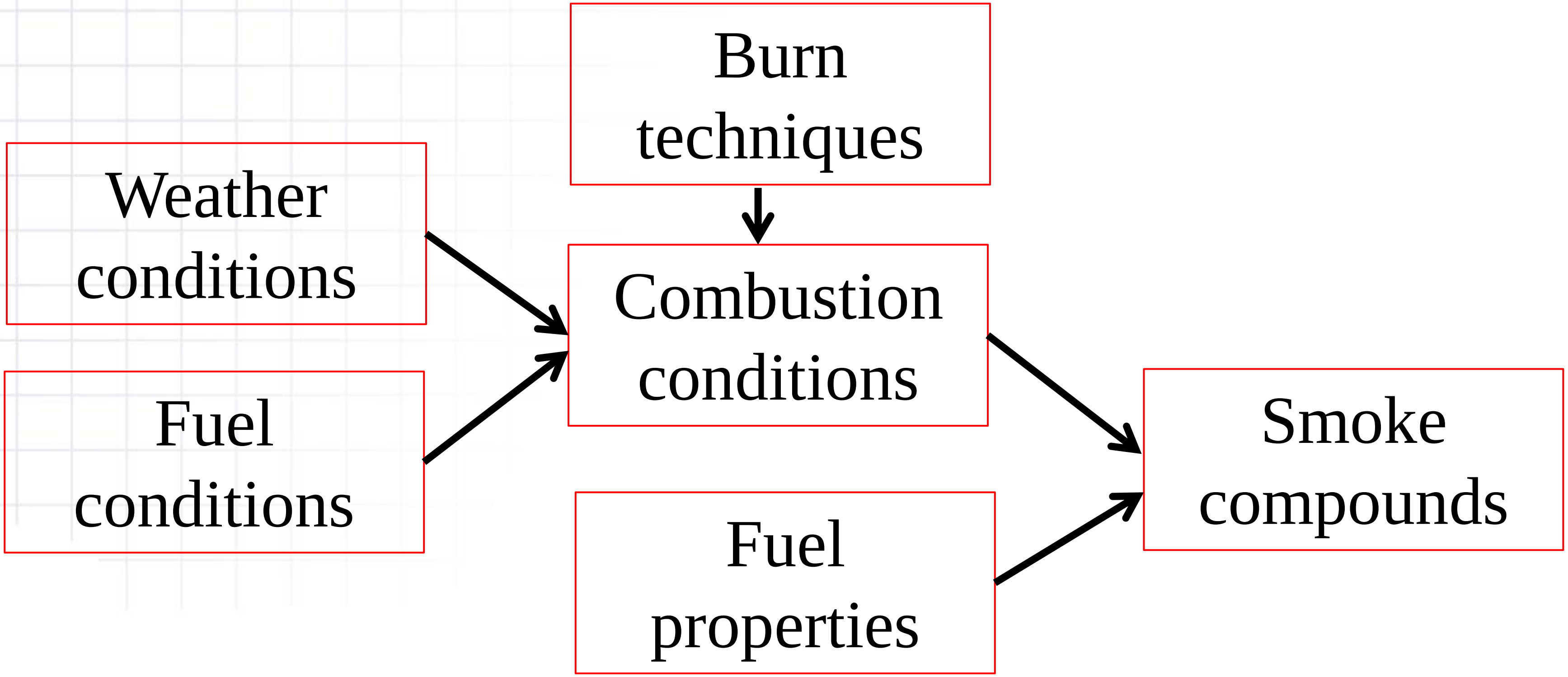
Flaming **Smouldering**

(Photo credit: Rein, 2009)

Smoke and combustion conditions



Not all smoke is equal

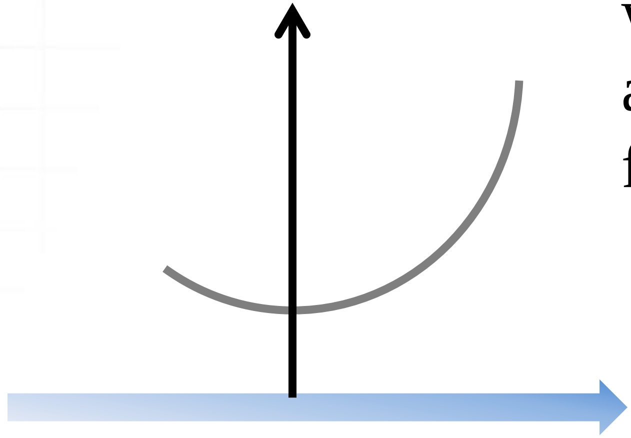


Availability of O_2 depends on wind, turbulence, and characteristics of the fuel, such as vegetation density, shape, and structure.

Optimal moisture content of vegetation fuel

Vegetation with lower moisture content burns faster, causing O_2-limited conditions.

Smoke production



Water vaporization lowers temperature, which favors smoldering and increased smoke formation.

Lower moisture content

Higher moisture content

The optimal moisture content in terms of minimizing smoke emissions is 20–30% for wood combustion.

Open vegetation fires

In open vegetation fires, a moving fire front passes through a fuel bed, such as a grassland or forest. Different combustion conditions may occur simultaneously at different locations within the fire environment. Their proportions and the prevalent conditions vary over time, typically with more flaming in the earlier part of the fire and more smoldering during the latter part.

Minimize smoldering combustion

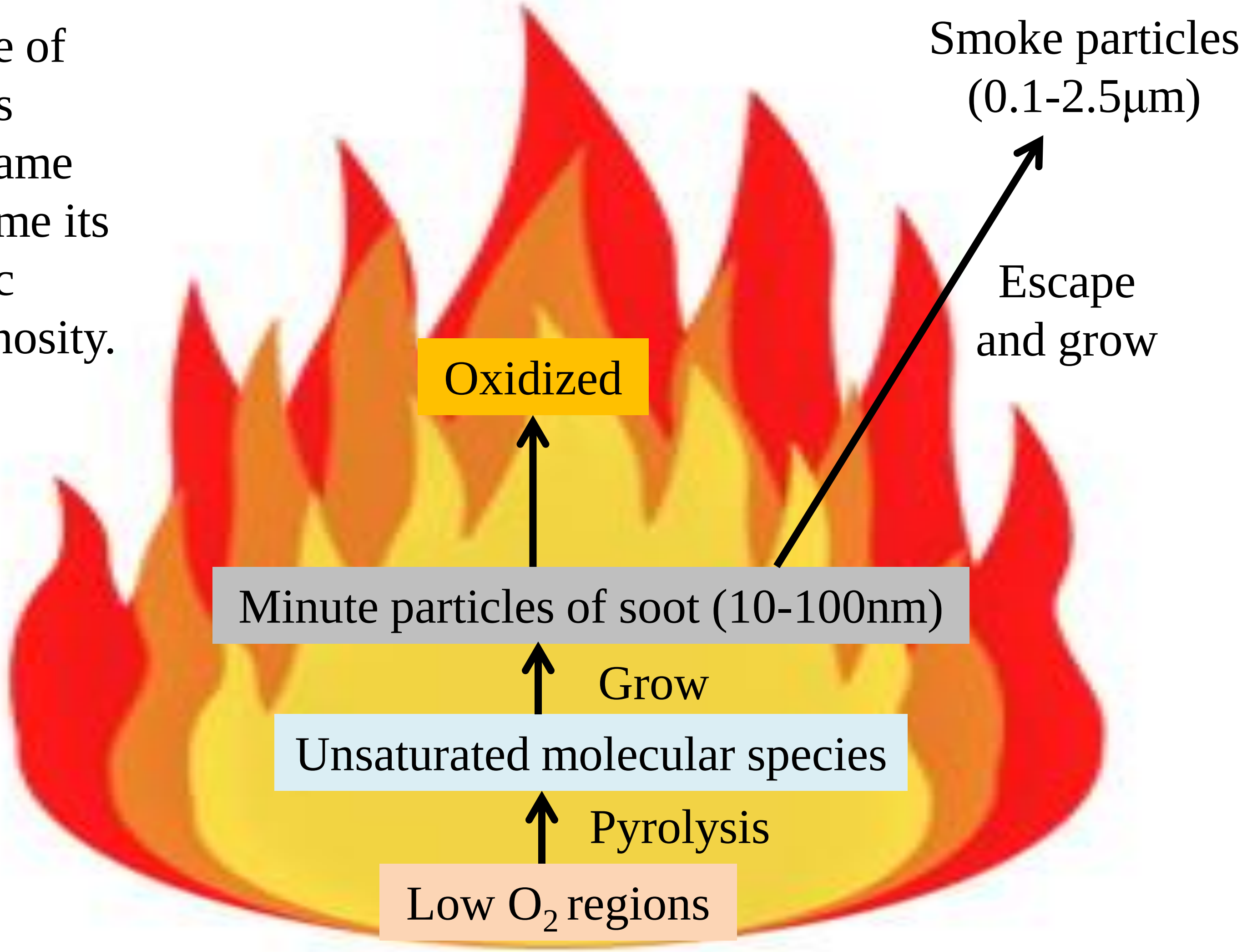
- The overall mixture of combustion products is usually determined by the amount of smoldering combustion.
- Nature thick fuel and organic soil prone to smouldering combustion.
  - Natural thick fuels include stumps, snags, downed logs, large branches and roots.
  - Organic soils include hummus, duff, peat, coal seams and others.

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)**

Generation of particulates in smoke

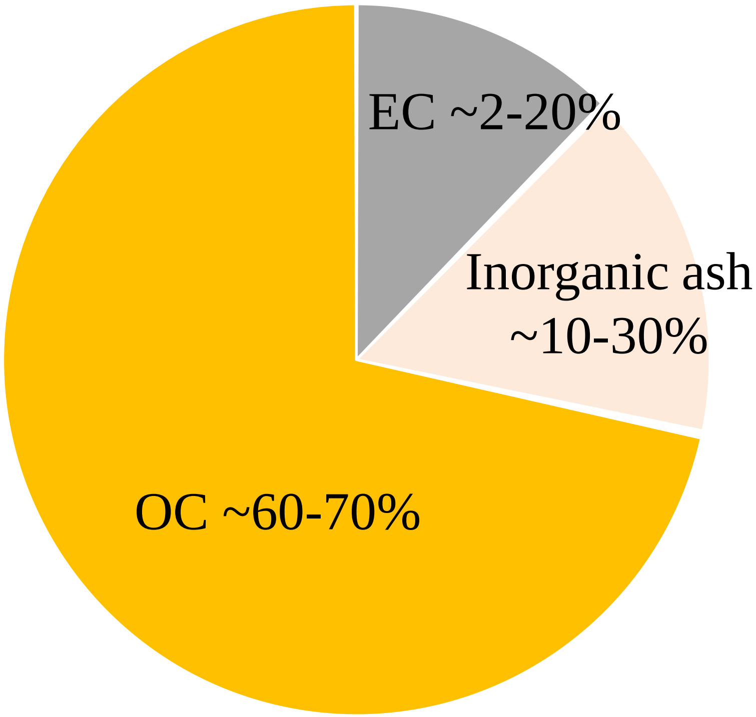
The presence of soot particles within the flame gives the flame its characteristic yellow luminosity.



Particulate matter (PM) in smoke

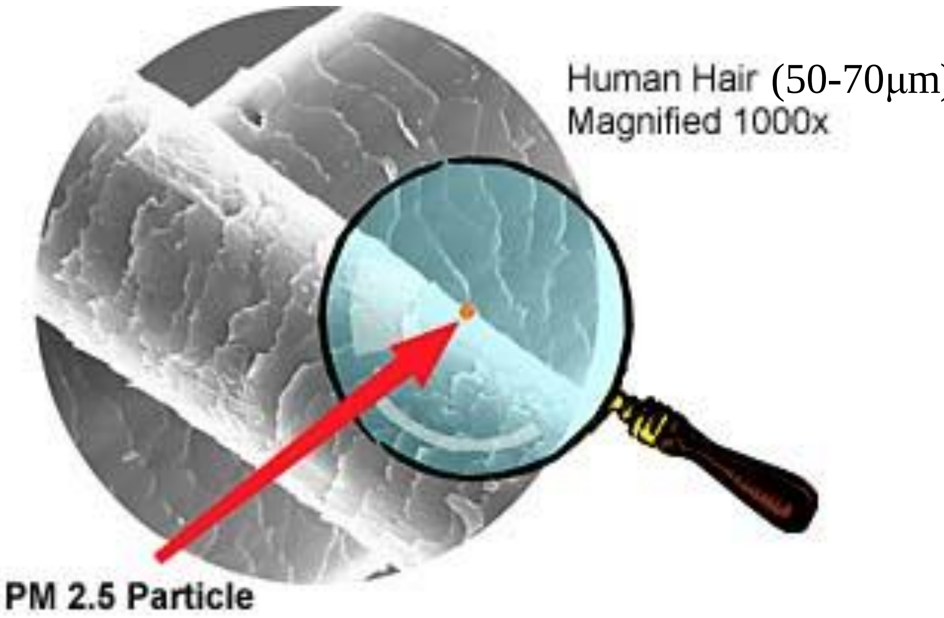
- Smoke PM acts as a vehicle to carry absorbed hazardous compounds into the respiratory tract.
  - VOCs
  - SVOCs
  - Toxic metal elements
- PM under the influence of fire smoke could be more damaging to human health than normal urban particles.

Composition of smoke PM



Size of smoke PM

- ~90% of PM in smoke is PM_{10}
- ~70–90 % 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.



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.

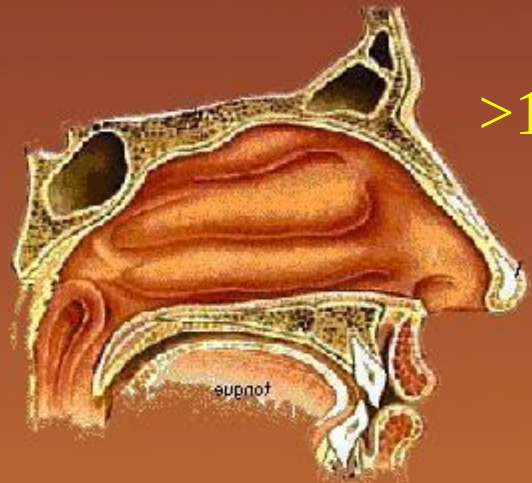
Lifetime

- 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.

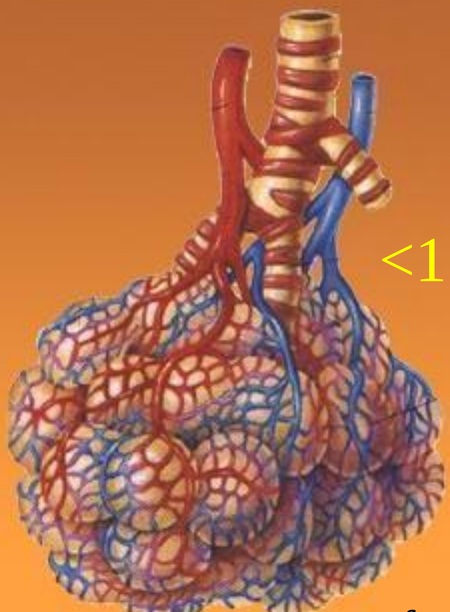
Where are particles removed or deposited?



>10 μm: nasal passages

5 μm: trachea, bronchi

<2 μm (smoke): bronchioles



<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)

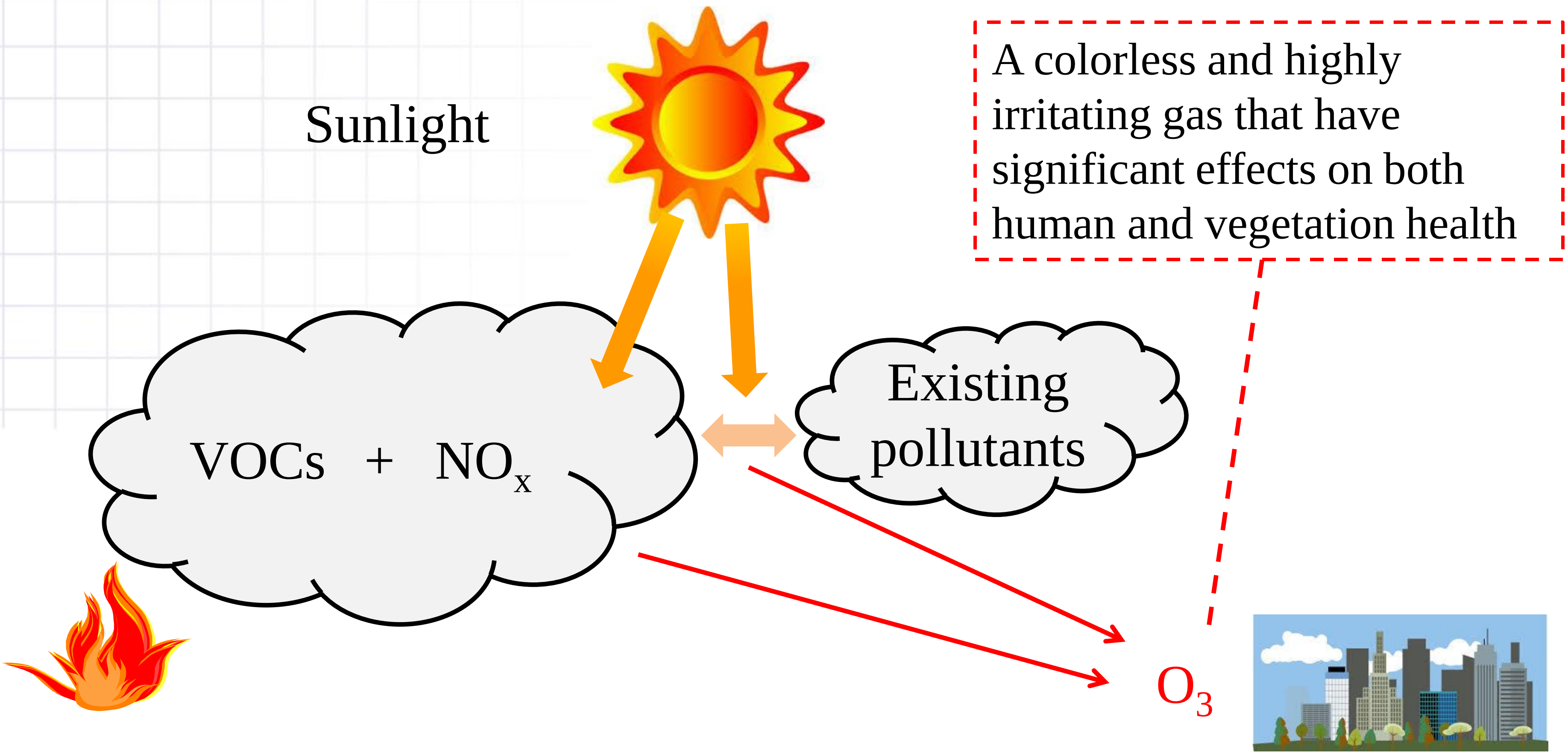
- Complex molecules such as polycyclic aromatic hydrocarbons (PAHs).
  - Benzo(a)pyrene (BaP), naphthalene, and anthracene, …
  - Can be adsorbed onto fine particles or as volatiles in the vapor phase; can be transported long distances.
  - Potentially carcinogenic and mutagenic.

- 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

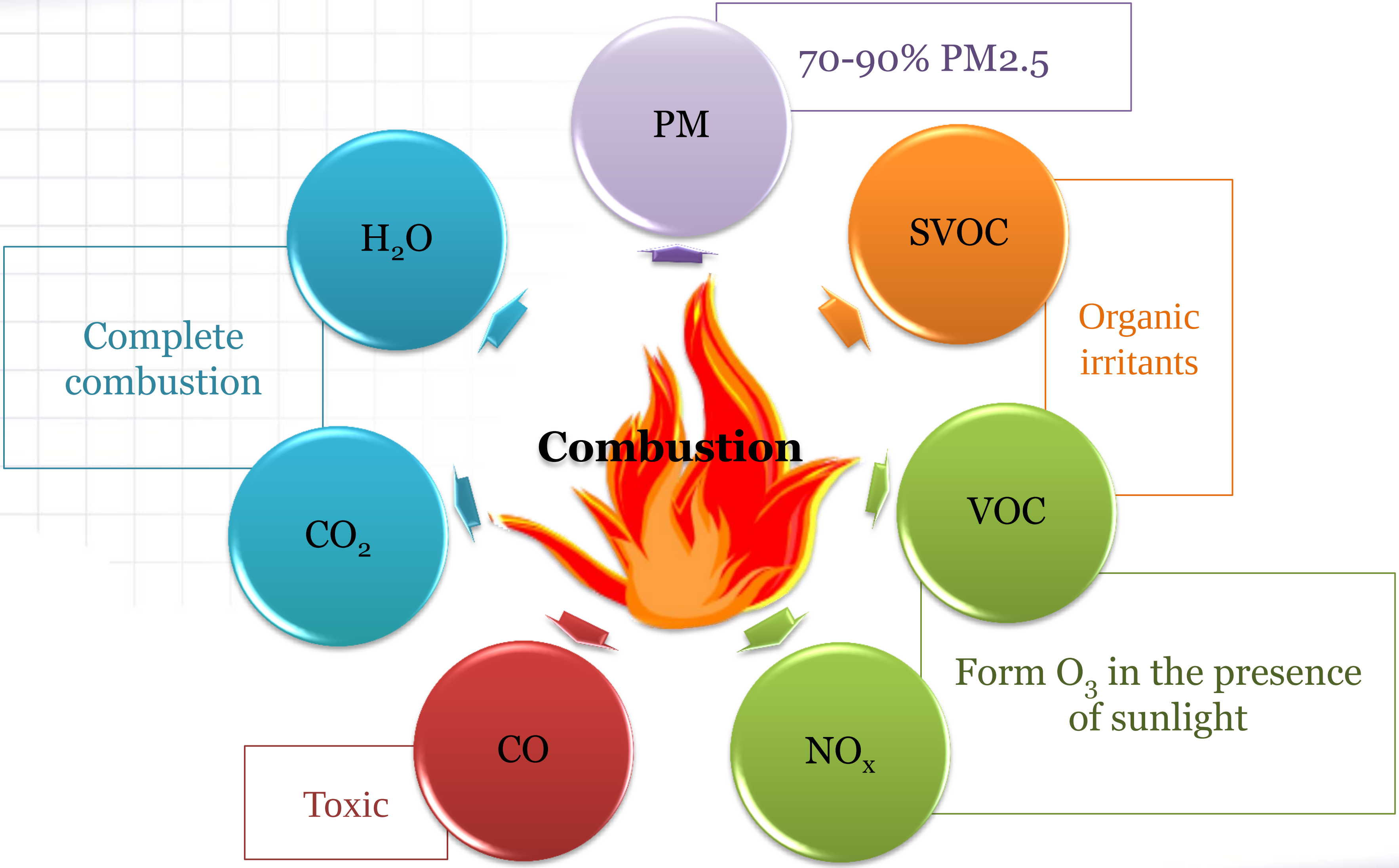
Secondary pollutants of the smoke plume



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

Summary of smoke composition



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

- Many hazardous compounds in smoke such as CO are present only in significant quantities in the immediate vicinity of the fire.
- However, $PM_{2.5}$ can be transported long distances. $PM_{2.5}$ and O_3 can be present in the smoke plume far away from the source.

Estimation of smoke emissions

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

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

- A is burned area, ha;
- FL is fuel load, kg DM/ha;
- CC is combustion completeness, %;
- 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)

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

~35 kg $PM_{2.5}$

Burned area: 1 ha

Assuming 5000 kg DM/ha fuel load.

≈

~35 kg $PM_{2.5}$

Run: 5,000,000 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

~15 kg NO_x

↑

Burned area: 1 ha

↑

Assuming 5000 kg DM/ha fuel load.

≈

~15 kg NO_x

↑

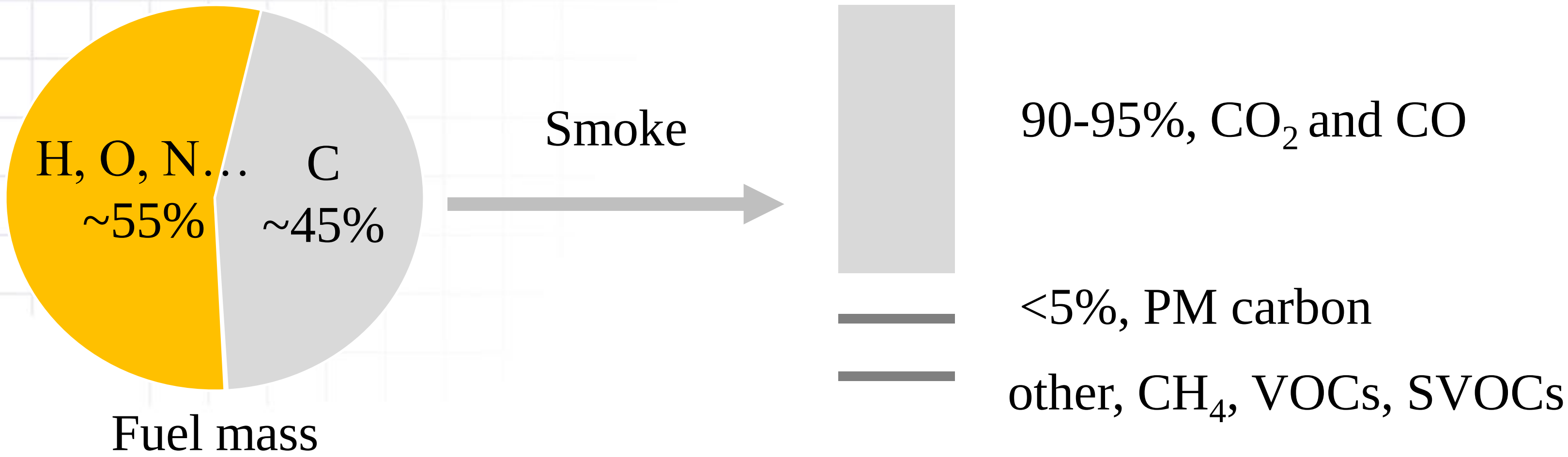
Run: 125,000 miles

↑

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

Carbon balance of fire smoke

A carbon balance method is often used to determine carbon mass in a smoke component as a fraction of the carbon mass in the total combustion products (CO_2, CO, PM carbon, CH_4, VOCs, and SVOCs).



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.

How do weather conditions affect dispersion of smoke?

Vertical dispersion

High **mixing height** = gets smoke up, up, and away

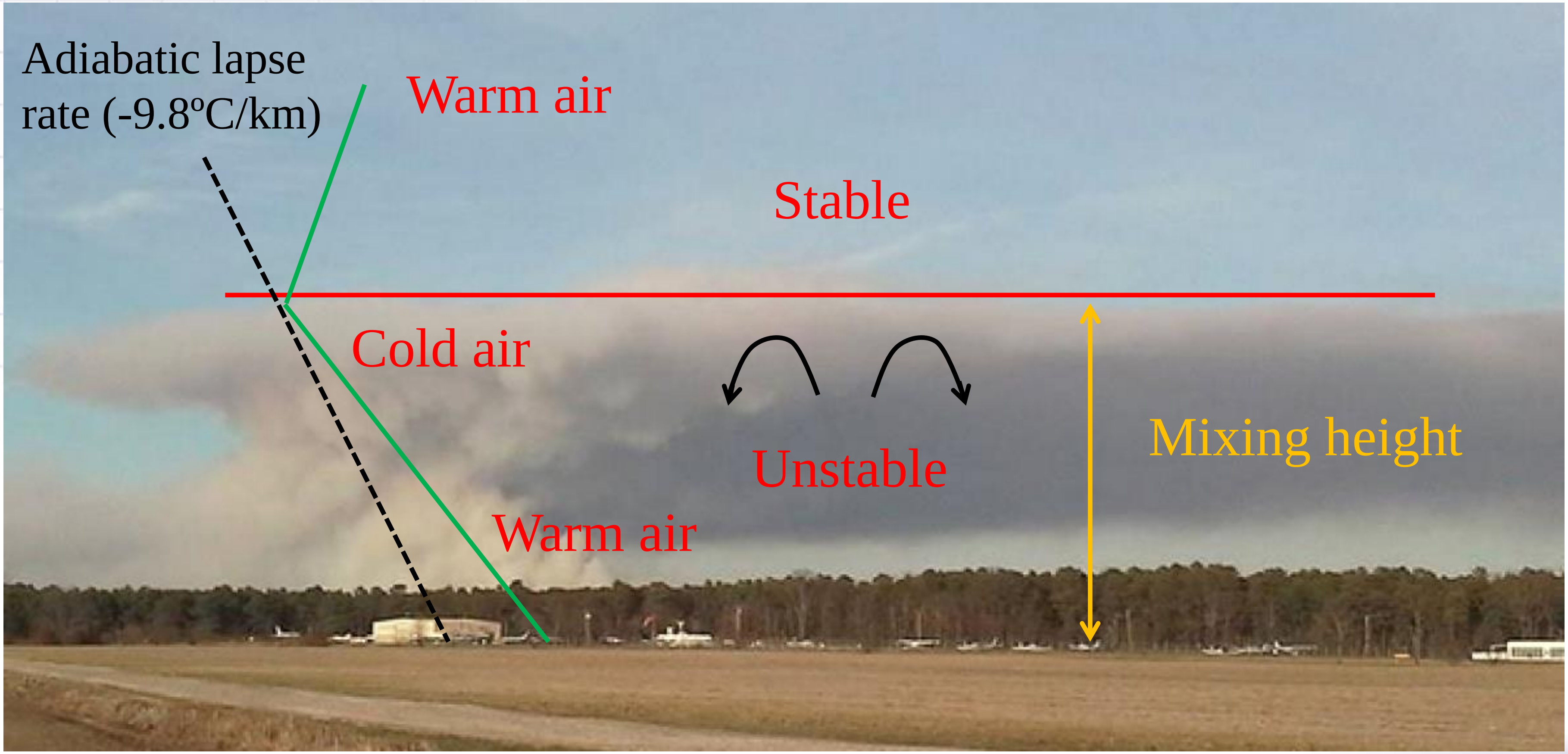
Horizontal dispersion

Good **transport wind** = smoke goes away

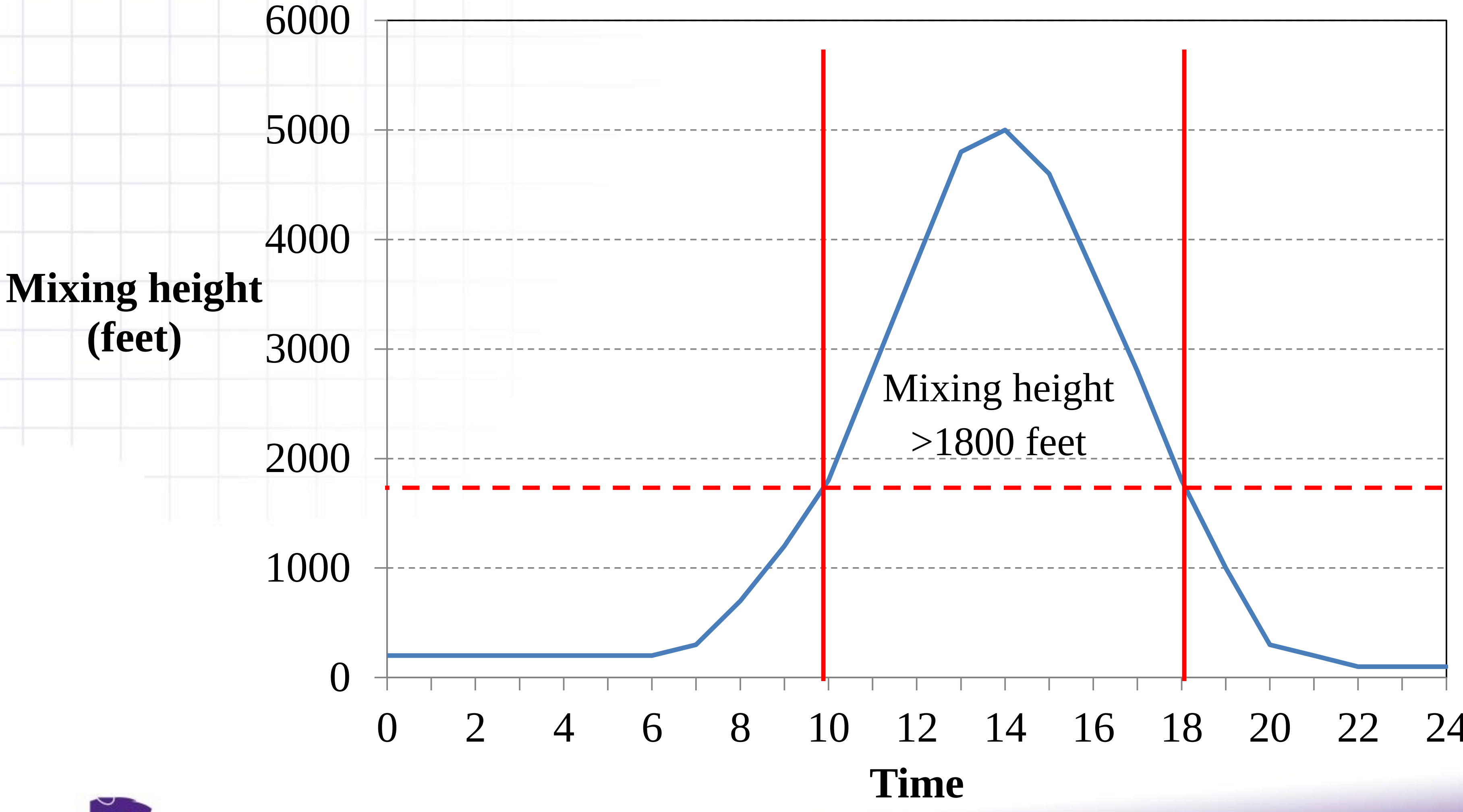
Good wind direction = less smoke on sensitive spots

Mixing height

Mixing height defines the height above the ground through which the air is under turbulent mixing. It is the height at which smoke stops rising.



Ideal burning hours



Transport Wind

Transport wind generally refers to the average rate of the horizontal transport of air within the mixing layer. Transport wind at 8-20 mph is desired for burning.