Emission Factors for Fire

National Fire Emissions Technical Workshop

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Ron Babbitt, National Fire Sciences Laboratory

Bill Battye, EC/R Incorporated

Agenda

- Background on emission factor measurement
- Recent measurements on existing emission factors and equations for $PM_{2.5}$, CO and VOC
- Standard emission factors and equations
- Additional required emission factors and potential data sources
- Speciation factors
- Recap of questions and general questions

Background on emission factor measurement

Byram's Chemical Model for Wood

$$C_6H_9O_4$$

By weight, Byram's model is 49.6% carbon - this ~50% carbon composition seems to hold for all woody fuels.

Complete Combustion

$$4(C_6H_9O_4) + heat + 25(O_2)$$

$$= 24(CO_2) + 18(H_2O)$$

we never achieve complete combustion in nature and always get products of incomplete combustion such as CO, CH_4, C_3H_6, PM + hundreds of other compounds

Combustion Efficiency (CE)

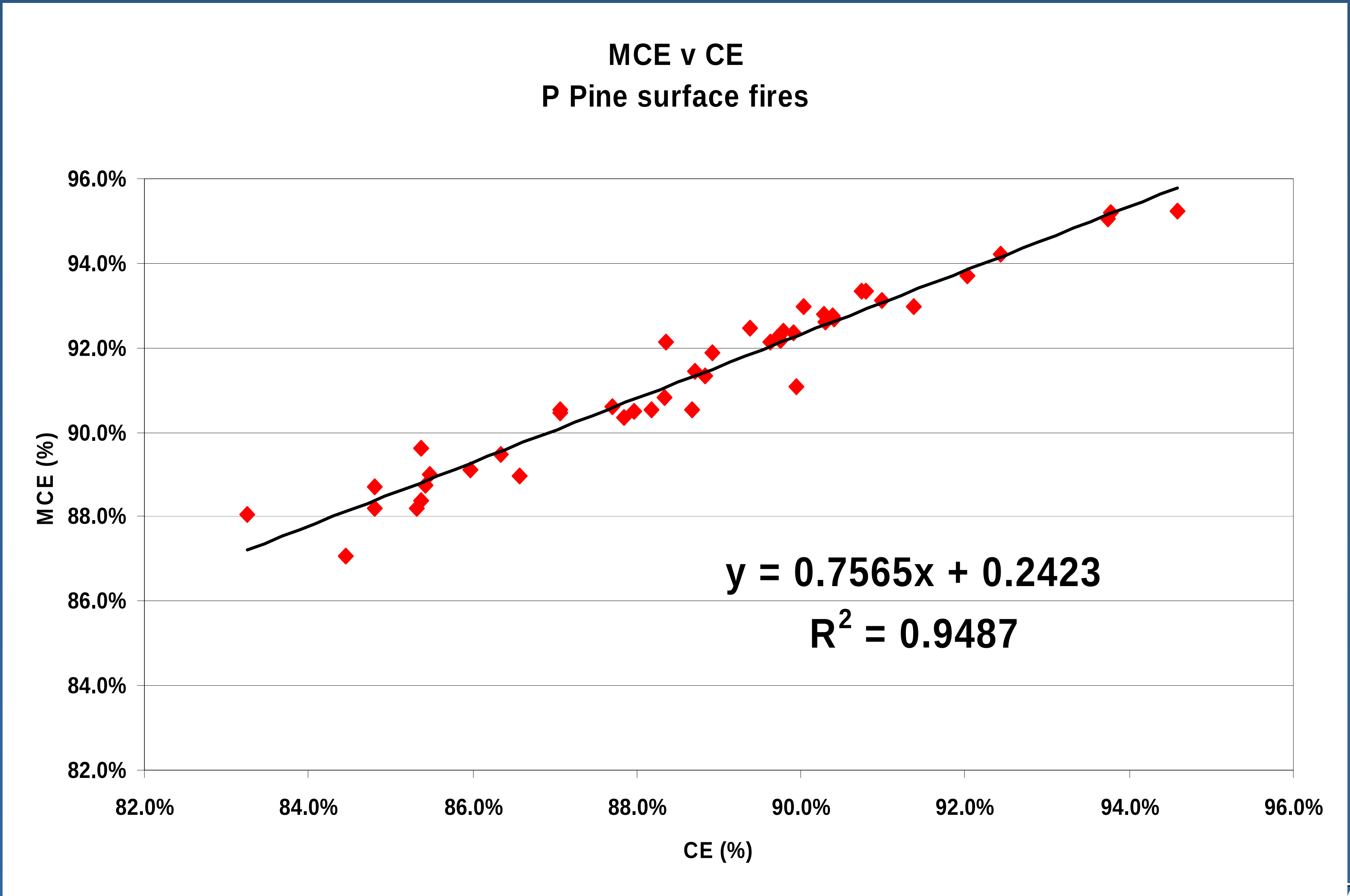
$$CE = \frac{CO2}{CO2 + CO + CH4 + C2H4 + \ldots\ldots}$$

Modified Combustion Efficiency (MCE)

$$MCE = \frac{CO2}{CO2 + CO}$$

MCE is a good estimate of CE as CO_2 & CO account for about 95% of the carbon

CE and MCE Relationship



Emission Factor

- The amount of a particular emission produced per amount of fuel consumed
  - e.g. EF_{CO} 150 lbs CO/ton fuel

Expressed in:

pounds/ton

grams/kilogram

- Emission Factors usually increase as CE decreases

Emission Factor

- Emission Factors may be calculated directly from field/lab measurements (CO_2, CO, CH_4, NMHC)
- Or an Emission Factor may be estimated through a known relationship to CO or CE
- $EF_{PM2.5} = 67.4 - (66.8 \times CE)$
- $EF_{NH4} = 0.014 \times CO$

Emission Factors are used to estimate total emissions for a specific compound from a site by:

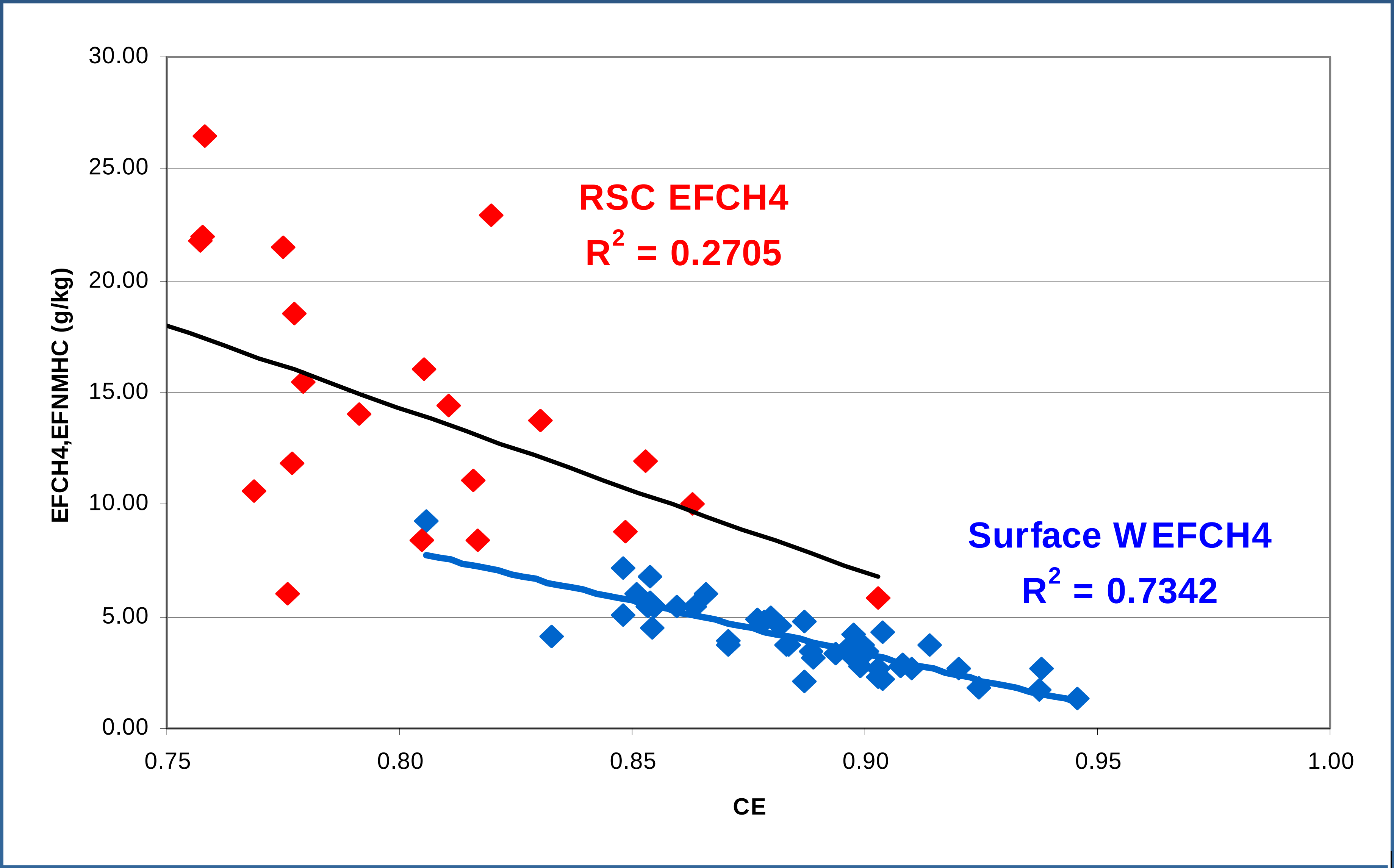
$$Emission_{total}(z) = FuelConsumption_{total} \times EF(z)$$

We also need fuel consumption from a site to predict total emissions!

Residual Smoldering Combustion (RSC) EFs by Fuel Type

Fuel Catergory	No. samples	EFCO2 (g/kg)	EFCO (g/kg)	EFCH4 (g/kg)	EFNMHC (g/kg)	MCE
Large Woody AVE	28	1426	237	17.2	3.5	79%
Stump AVE	10	1353	283	11.6	2.4	75%
Duff AVE	14	1437	233	11.3	3.9	80%
Alaska Duff AVE	12	1437	246	9.2	1.4	80%
Basal Duff AVE	8	1347	299	5.2	0.9	74%
Rotten Wood AVE	7	1352	295	6.6		74%
Rotten Stump AVE	2	1381	266	12.5		77%

RSC emissions are more variable than those from surface fires



Comparing Flaming, Smoldering and RSC (by Region)

Western Emission Factors - Averaged by Phase (primarily P. Pine understory burns)						
Phase	EFCO2	EFCO	EFCH4	EFNMHC	EFPM2.5	MCE
Flaming	1648	91	3.5	2.9	13.4	92%
Smoldering	1563	133	5.8	3.9	15.6	88%
RSC	1464	217	14.3	3.7		81%

Alaska Emission Factors - Averaged by Phase						
Phase	EFCO2	EFCO	EFCH4	EFNMHC	EFPM2.5	MCE
Mixed (aircraft)	1660	89	2.8	2.3		92%
RSC	1437	246	9.2	1.4		80%

Southern Emission Factors - Averaged by Phase						
Phase	EFCO2	EFCO	EFCH4	EFNMHC	EFPM2.5	MCE
Flaming	1681	73	2.0	2.4	11.7	94%
Smoldering	1605	116	3.3	4.0	11.6	90%
RSC	1338	295	10.6	2.1		74%

FTIR Derived EFs

Fire Name	CO_2 g kg^{-1}	CO g kg^{-1}	CH_4 g kg^{-1}	C_2H_4 g kg^{-1}	C_3H_6 g kg^{-1}	NMHC g kg^{-1}	MCE	PM 2.5 g kg^{-1}
Lolo 1	1454	128	10.4	2.06	2.03	4.09	0.879	11.3
Lolo 2	1460	153	8.2	1.71	1.03	2.74	0.858	6.6
Lolo 3	1478	157	4.0	0.99	1.37	2.37	0.857	
NWT 1	1436	112	9.0	1.13	0.39	1.51	0.891	
NWT 2	1448	165	6.3	1.32	1.08	2.41	0.848	15.1
Stump	1612	109	7.4	1.53	0.53	2.06	0.904	15.8
Cwd 2	1469	155	16.2	2.36	2.36	4.71	0.856	
Zambia Log	1454	158	23.2	2.11	2.04	4.15	0.854	
Plum Creek 1	1570	162	2.4	0.30		0.30	0.861	
Plum Creek 2	1558	160	6.2	0.33		0.33	0.861	
ave	1494	146	9.3	1.38	1.35	2.47	0.867	12.2

Emissions estimation tools

- FOFEM
  - First Order Fire Effects Model
  - US Forest Service Fire Sciences Laboratory, Missoula, MT
- Consume
  - Primarily for predicting fuel consumption
  - USFS Fire and Environmental Research Applications (FERA) team, Corvallis, OR
- FEPS
  - Fire Emission Production Simulator – replaces the Emission Production Model (EPM)
  - Estimates consumption, emissions, heat production
  - USFS FERA team, Corvallis, OR
- Other integrated models incorporate emission algorithms from the above
  - BlueSky
  - CSEM – Community Smoke Emissions Model

Standardization of emission factors

- Comparability of model results
- Current status
  - FOFEM and Consume factors are closely tied
  - Main differences are in format
    - Consume: Flaming and smoldering factors
    - FOFEM and FEPS: equations based on combustion efficiency (CE)
  - Consume developers are also considering CE based emission relationships

Questions on standardization

- Is a standard factor set needed for those not using fire emission models?
- What is the preferred format for a standard factor set?

Pollutant categories

- Criteria pollutants
  - $PM_{2.5}$, SO_2, NO_2, O_3, Lead
- Precursors of O_3, $PM_{2.5}$, and Regional Haze
  - VOC, NO_X, NH_3, SO_2, CH_4
- Bulk components of $PM_{2.5}$ - useful for source apportionment
  - EC, OC, SO_4^{-2}, NO_3^-
- HAPs and air toxics
  - VOC species
  - Particulate organics (e.g. PAH)
  - Metals
- Global warming gases
  - CO_2, CH_4, N_2O, halogenated species

Standard emission relationships

Pollutant	Emission factor (kg/Mg of fuel consumed)
CO_2	1833 x CE[a]
CO	961 – (984 x CE)[a]
$PM_{2.5}$	67.4 – (66.8 x CE)[a]
PM_{10}	1.18 x $PM_{2.5}$[a]
VOC	(0.18 to 0.28) x CO[b]
NO_X	3.27 – 0.011 x CO[a]
SO_2	~0.98[a]

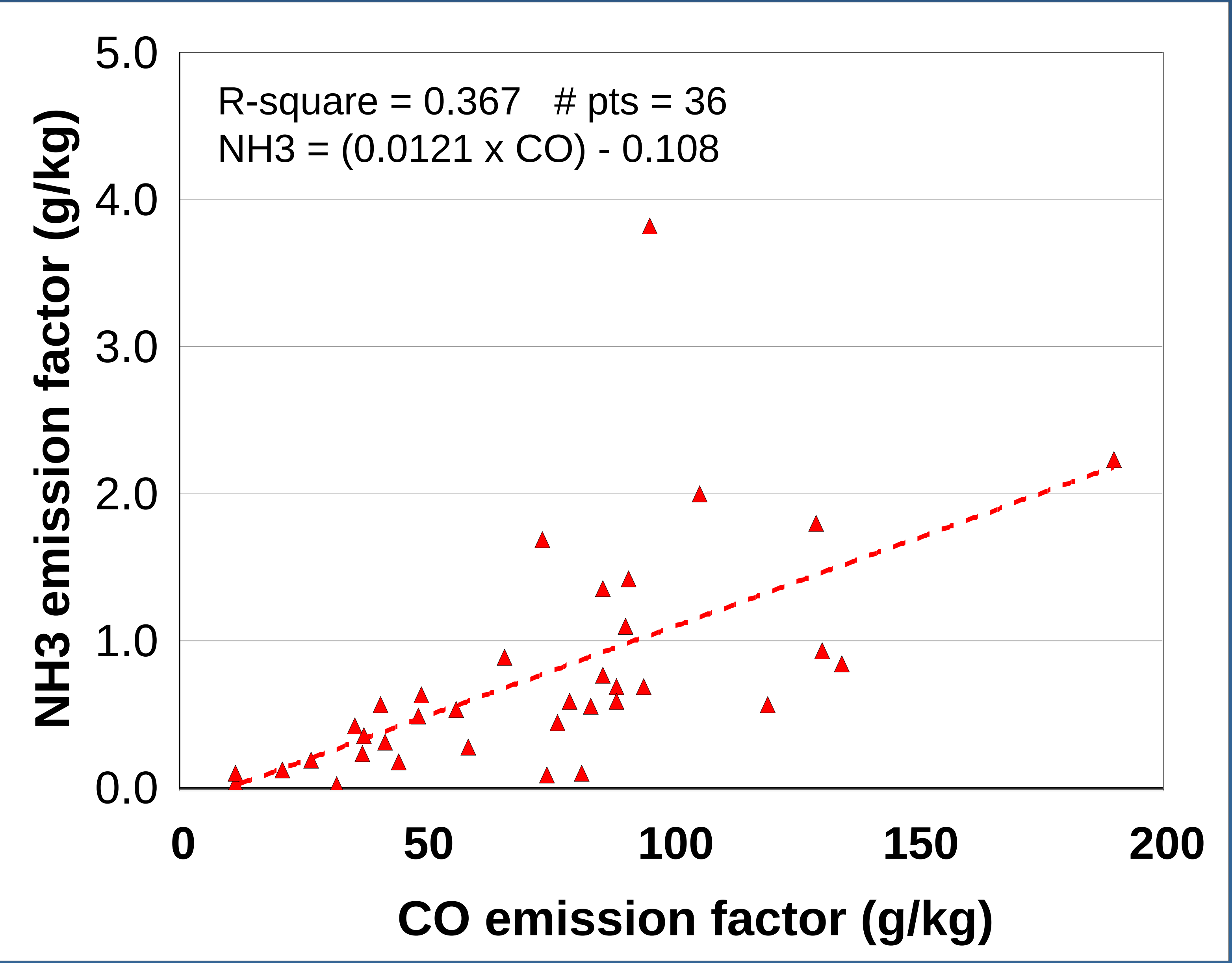
[a] FOFEM

[b] Communication with R. Yokelson, Fire Sciences Lab

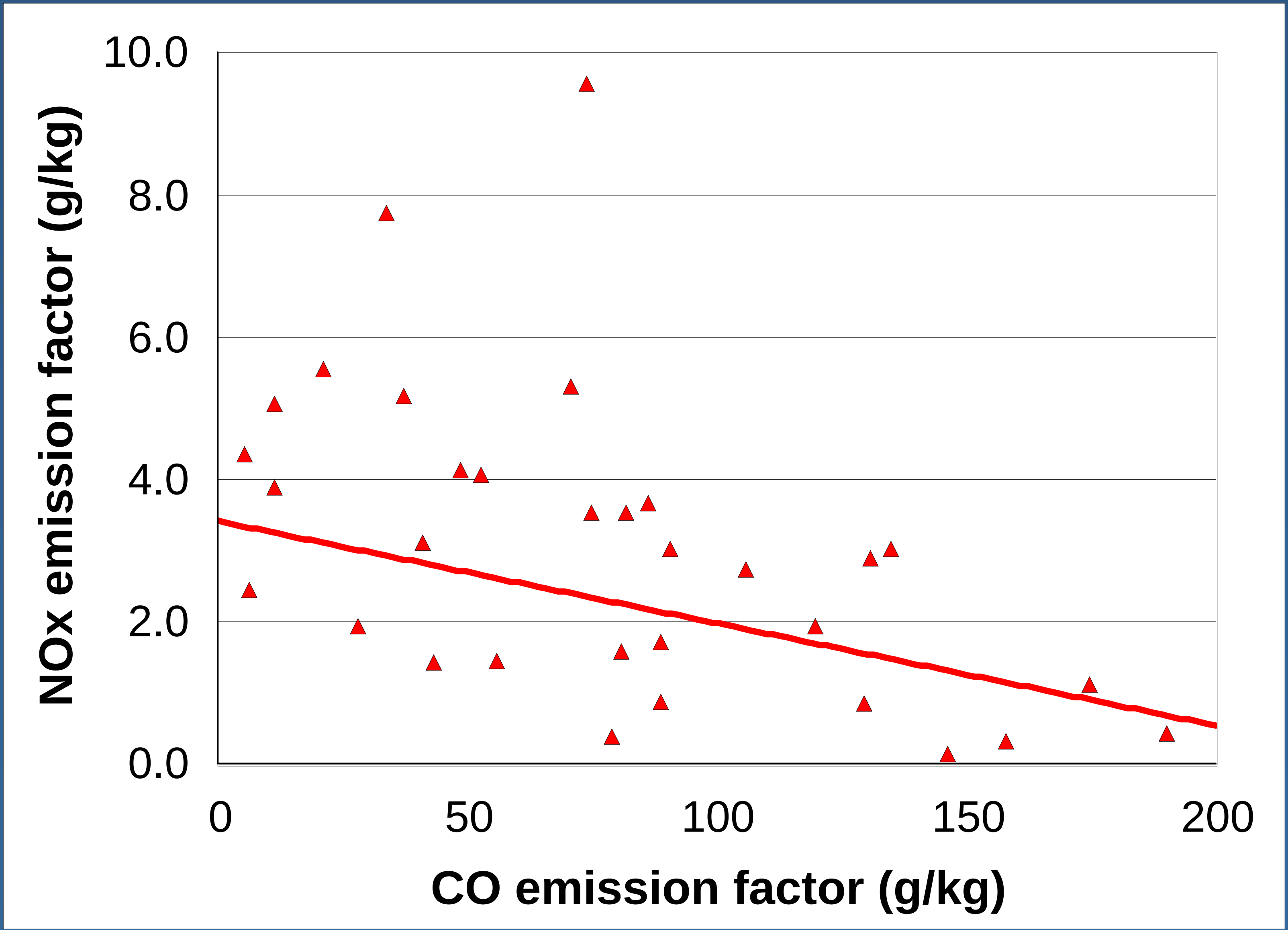
Relations of pollutant species to CO, CE, MCE, or $PM_{2.5}$

- Influence of flaming / smoldering
  - Some pollutants are enhanced in flaming conditions
  - Others (most) are enhanced in smoldering
- CO emissions are a key indicator of smoldering
- Many pollutant species can be related to CO
  - Facilitates calculation from an existing inventory
  - CE or MCE can also be used, but aren't generally reported
- $PM_{2.5}$ species can be related to total $PM_{2.5}$

Example relation to CO



Example inverse relation to CO



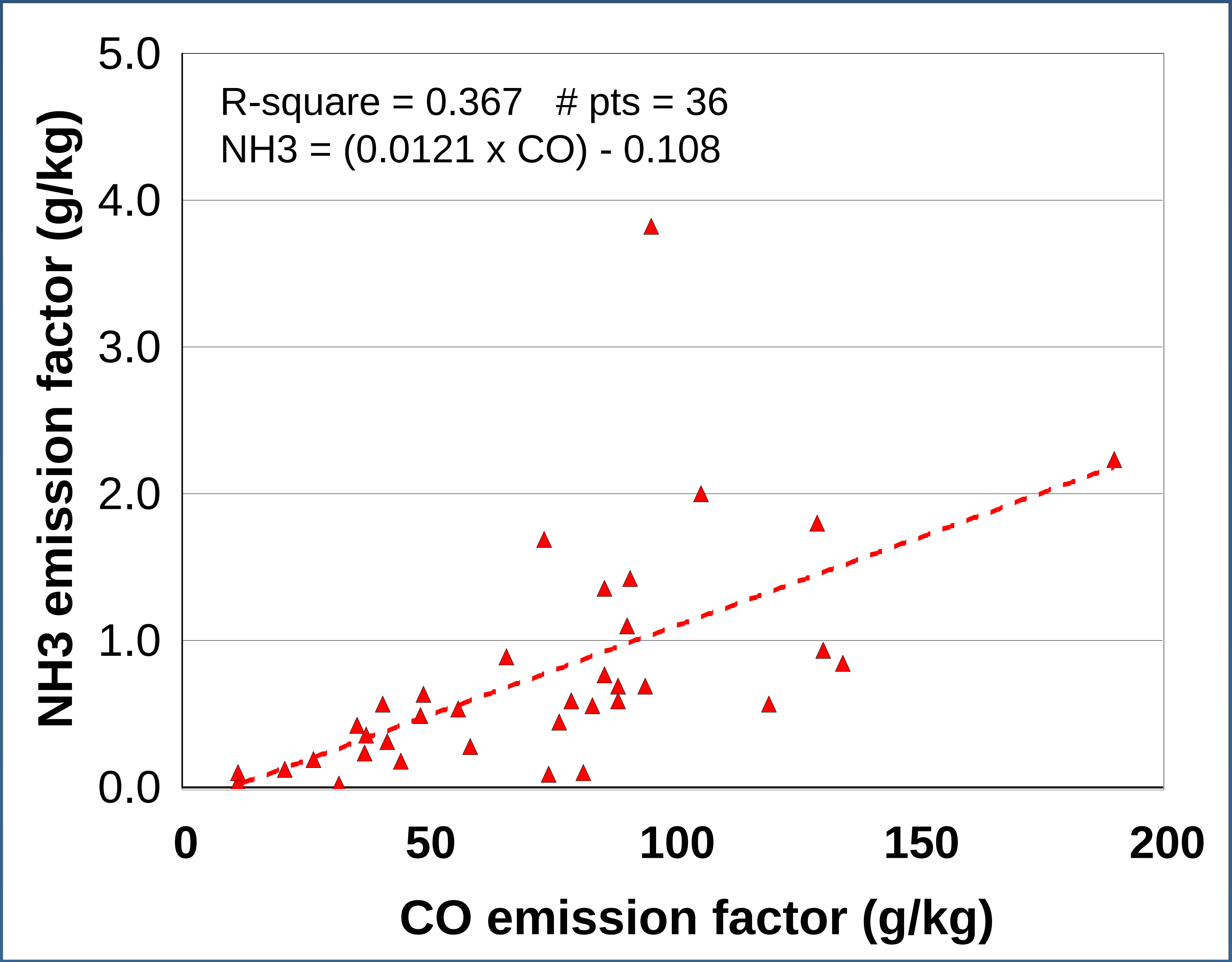
Other pollutants

- Regional $PM_{2.5}$ and haze modeling
  - NH_3
  - EC
  - OC
- National-scale Air Toxics Assessment (NATA)
  - HAPs
- Regional ozone modeling
  - VOC speciation

Sources of data for NH_3

Study	Locations
LeBel, 1988	Florida
Hegg, 1990	Various, US & Canada
Griffith, 1991	Montana, Wyoming
Laursen, 1992	Various, US & Canada
Nance, 1993	Alaska
Worden, 1994	Oregon, California
Yokelson, 1996/99/2003	Lab / North Carolina / Africa & Indonesia
Goode, 1999 / 2000	Lab / Alaska

NH_3 in relation to CO



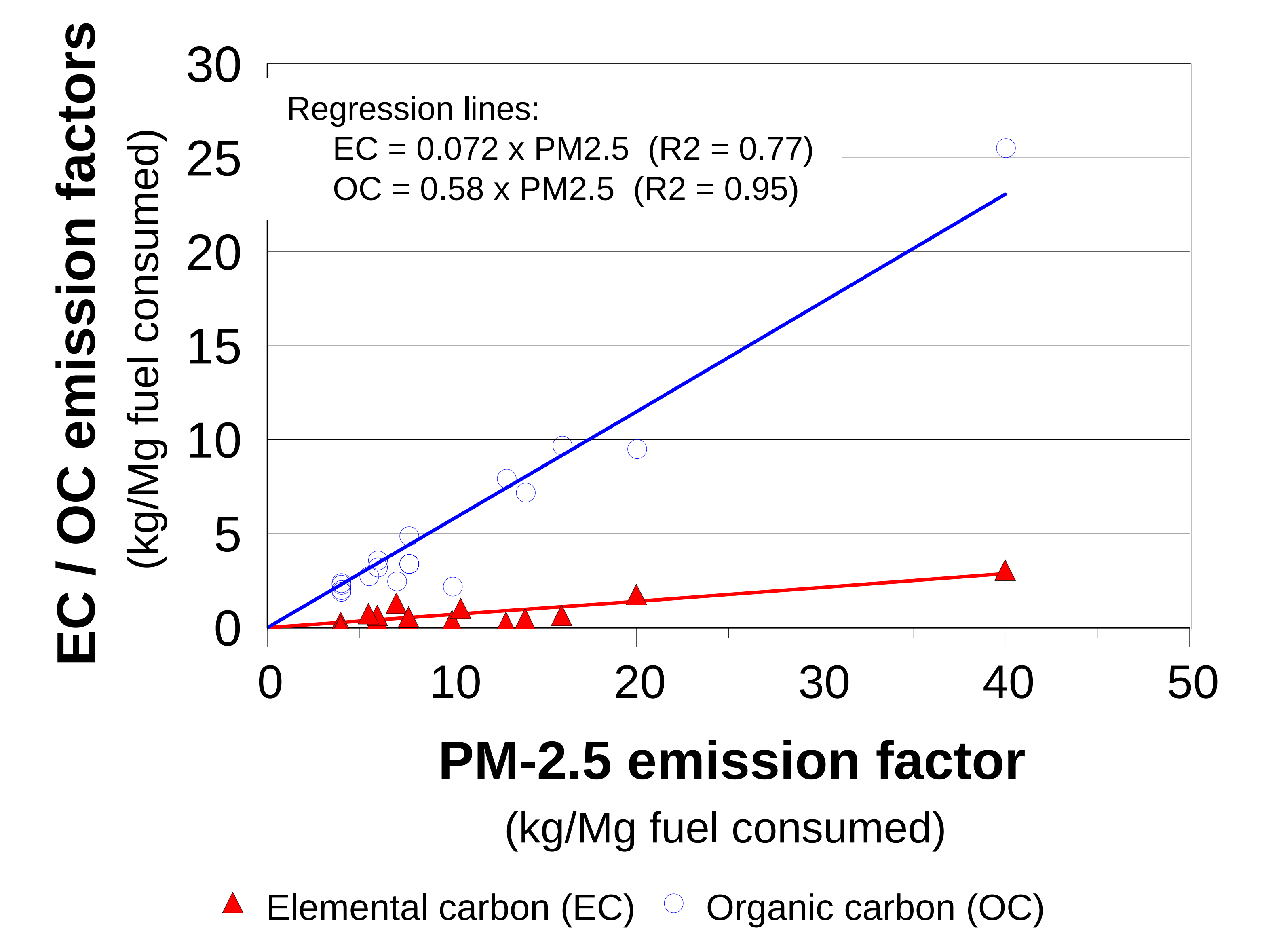
Questions on NH_3 emissions

- Additional relevant data sets?
- Data sets that should not be included?
- Is the form of the relationship appropriate?

Data sources for EC/OC speciation

Study	**Location**
Ward and Hardy, 1984	Western Oregon
Einfeld, 1989	Los Angeles Basin
Nance, 1993	Alaska
Babbitt, 1994	Oregon, Idaho
Jenkins, 1996	Lab
Yokelson, 1996 / 2003	Lab / Africa & Indonesia
Sinha, 2003	Africa

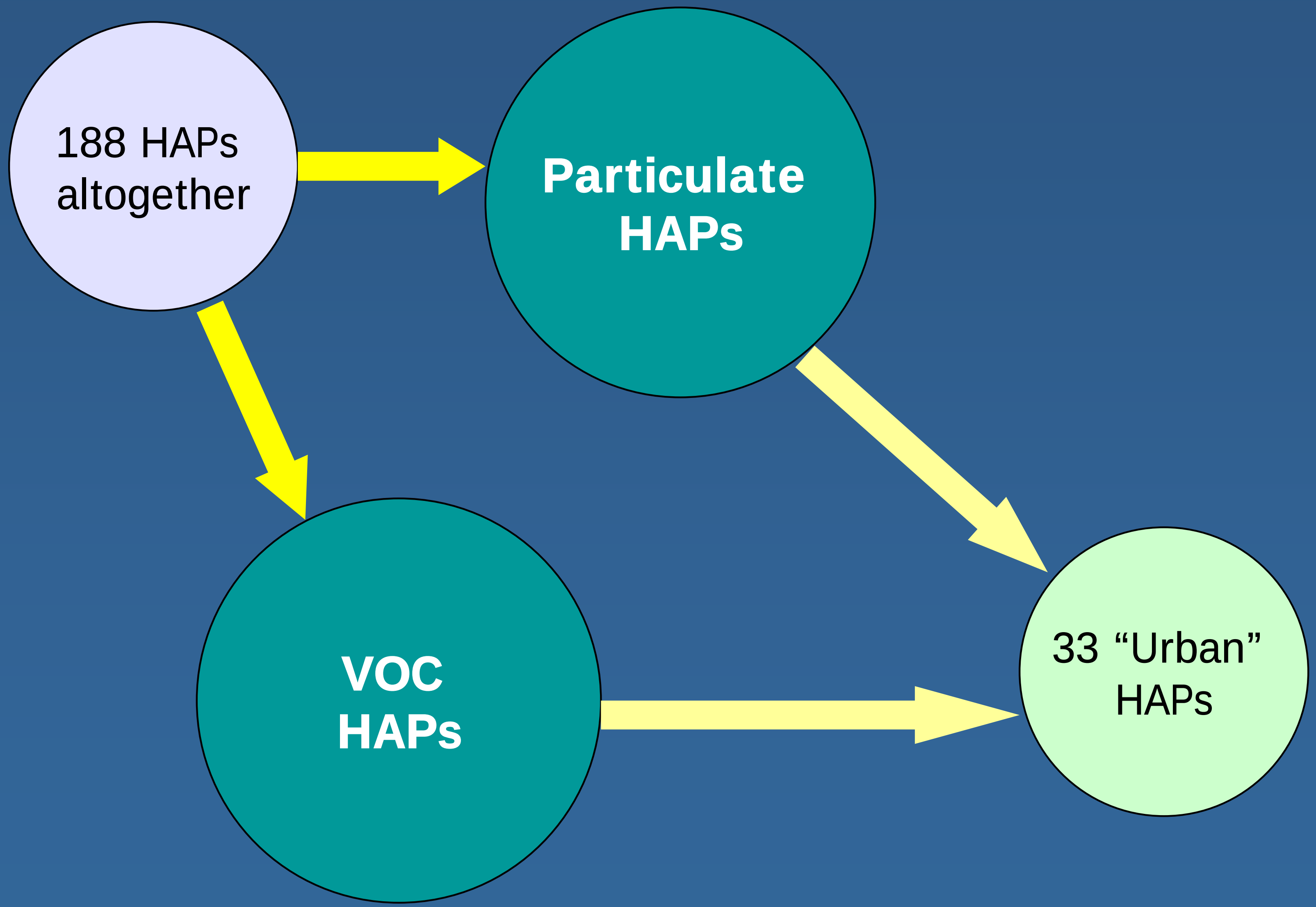
EC / OC in relation to $PM_{2.5}$



Questions on EC and OC emissions

- Additional relevant data sets?
- Data sets that should not be included?
- Is the form of the relationship appropriate?

HAPs


188 HAPs altogether
Particulate HAPs
VOC HAPs
33 "Urban" HAPs

Data sources for particulate HAPs

PAH	Location
McMahon, 1979	Lab
Ward and Hardy, 1984	Western Oregon
Jenkins, 1996	Lab
Metals	**Location**
Ward and Hardy, 1984	Western Oregon
Friedli, 2003 (?)	Washington / Oregon

Particulate HAP emissions

Pollutant	Emission Factor (kg/Mg of fuel consumed) or Relationship	"Urban" 33
Total PAH	0.01	✓
Benzo(a)pyrene	0.00013	✓
Benz(a)anthracene	0.0031	✓
Dioxins (2,3,7,8,-TCDD TEQ)	1×10^{-9}	✓
Cadmium compounds	$0.00049 \times PM_{2.5}$	✓
Chromium compounds	$0.00014 \times PM_{2.5}$	✓
Lead compounds	$0.0017 \times PM_{2.5}$	✓
Manganese compounds	$0.00018 \times PM_{2.5}$	✓
Mercury compounds	$14\text{-}112 \times 10^{-6}$ (??)	✓
Nickel compounds	$0.00006 \times PM_{2.5}$	✓

Questions on PAH emissions

- Additional relevant data sets?
- Data sets that should not be included?

Questions on HAP metal emissions

- Additional relevant data sets?
- Data sets that should not be included?
- Suggestions for approach to accounting for past deposition?

Data sources for VOC HAPs

Study	Location
Griffith, 1991	Montana, Wyoming
Lobert, 1991	Lab / U.S.
McKenzie, 1995	Lab
Jenkins, 1996	Lab
Yokelson, 1996/99/2003	Lab / North Carolina / Africa / Indonesia
Goode, 1999, 2000	Lab / Alaska

VOC HAPs

Pollutant	Emission Factor (kg/Mg of fuel consumed) or relationship	"Urban" 33
Acetaldehyde	0.76 -3.09[b]	✓
Acrolein	0[b]	✓
Acrylonitrile	0[b]	✓
Benzene	0.21 – 0.94[b]	✓
1,3-Butadiene	0.073[b]	✓
Carbon tetrachloride	0[b]	✓
Carbonyl sulfide	0.00027[a]	
Formaldehyde	1.12 – 1.9[b]	✓
n-Hexane	0.013[b]	
Methanol	1.18 – 3.79[b]	
Methylene chloride	0.0073[a]	✓
Methyl chloride	0.053	
Perchloroethane	0.00001[a]	✓
Phenol	0.83 – 2.10[b]	
Toluene	0.18 – 0.79[b]	
Trichloroethane	0.0009[a]	✓
Xylenes	0.00096 × CO	

Sources:
[a] EPA
[b] R. Yokelson, FSL

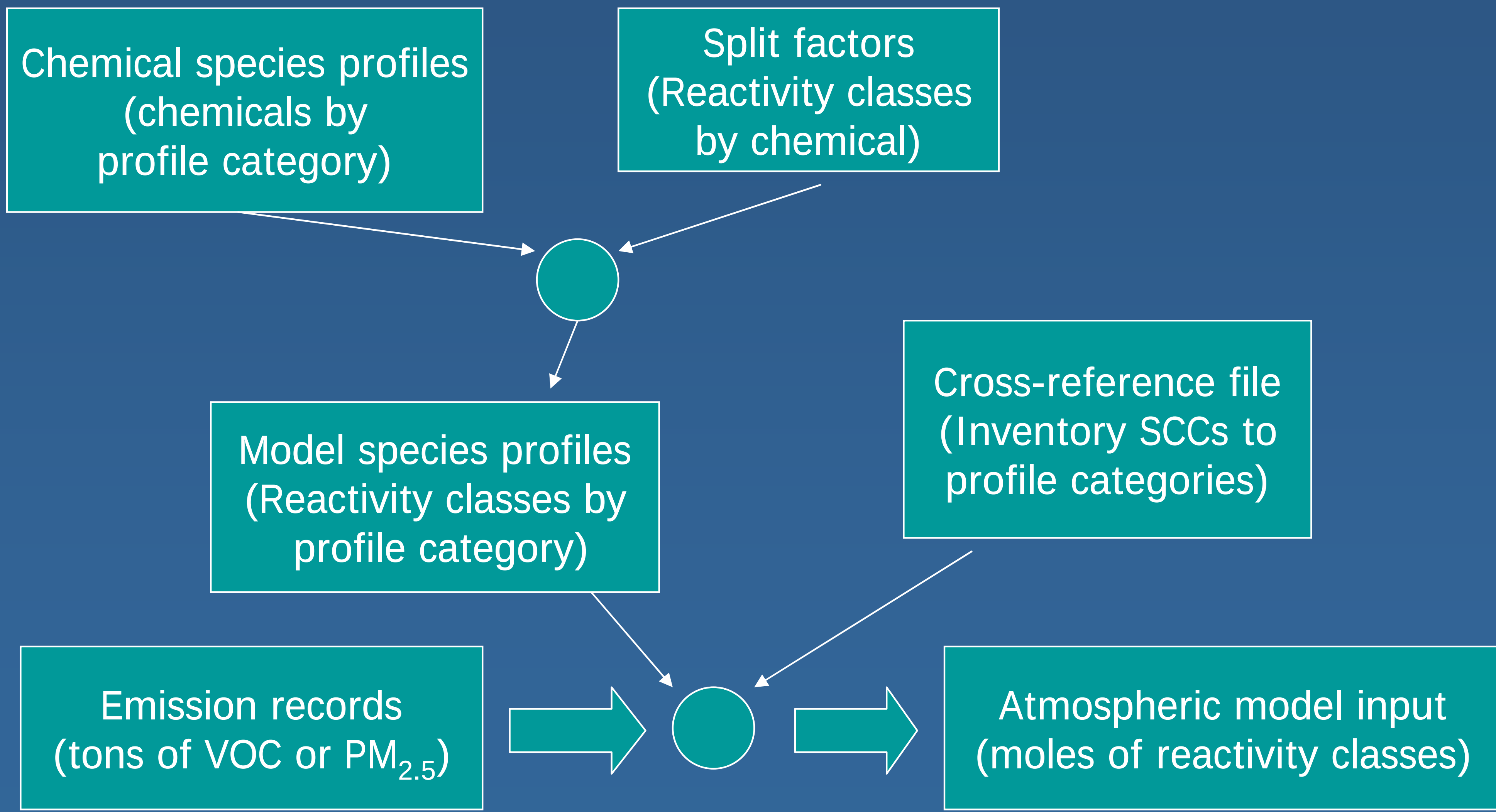
Questions on VOC HAP emissions

- Additional relevant data sets?
- Data sets that should not be included?

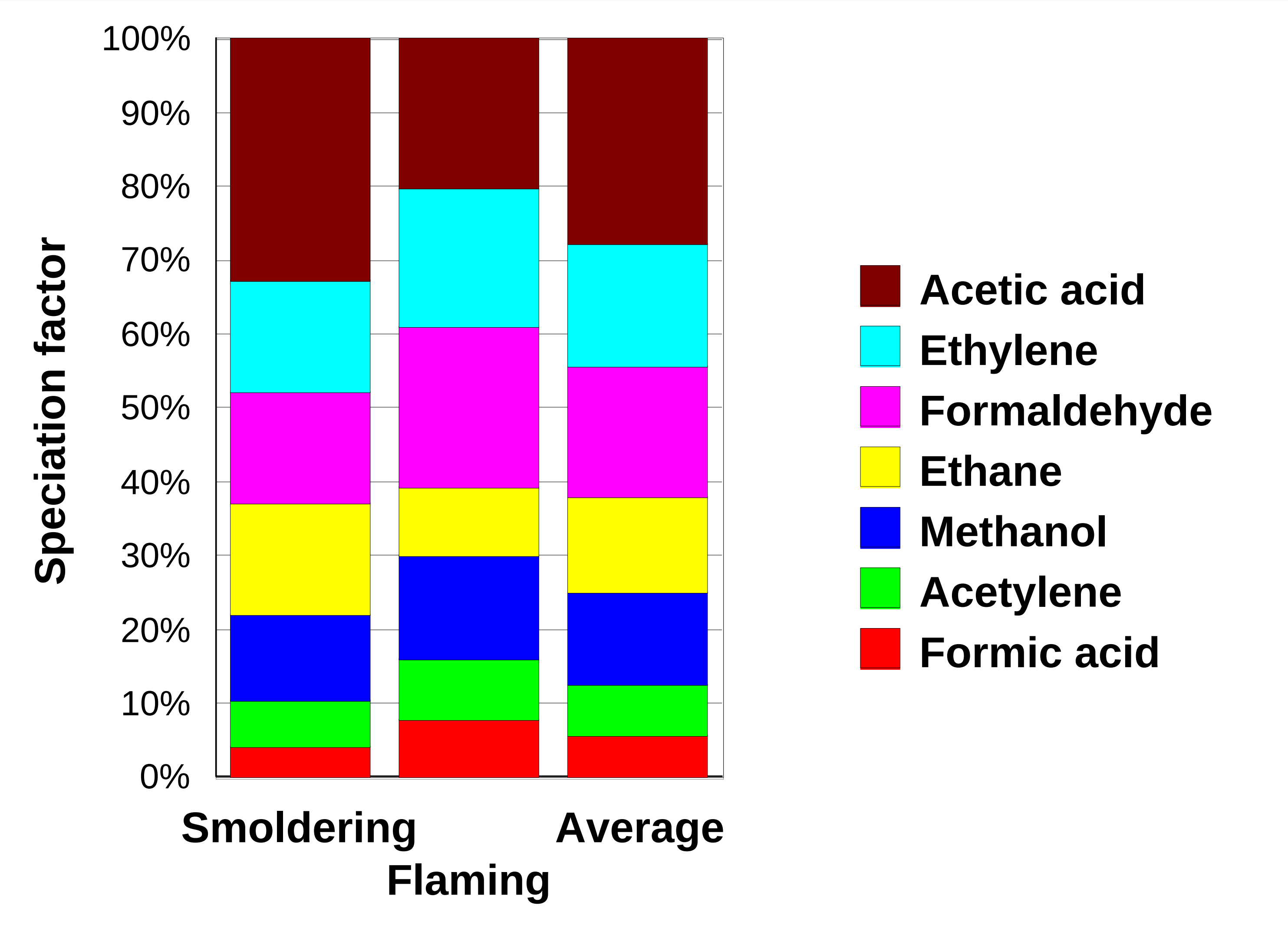
Speciation factors

- Used for VOC and $PM_{2.5}$
- Quantify component fractions or chemical species as % of total
- Used in atmospheric chemistry modeling
- Also can be used to quantify HAP emissions

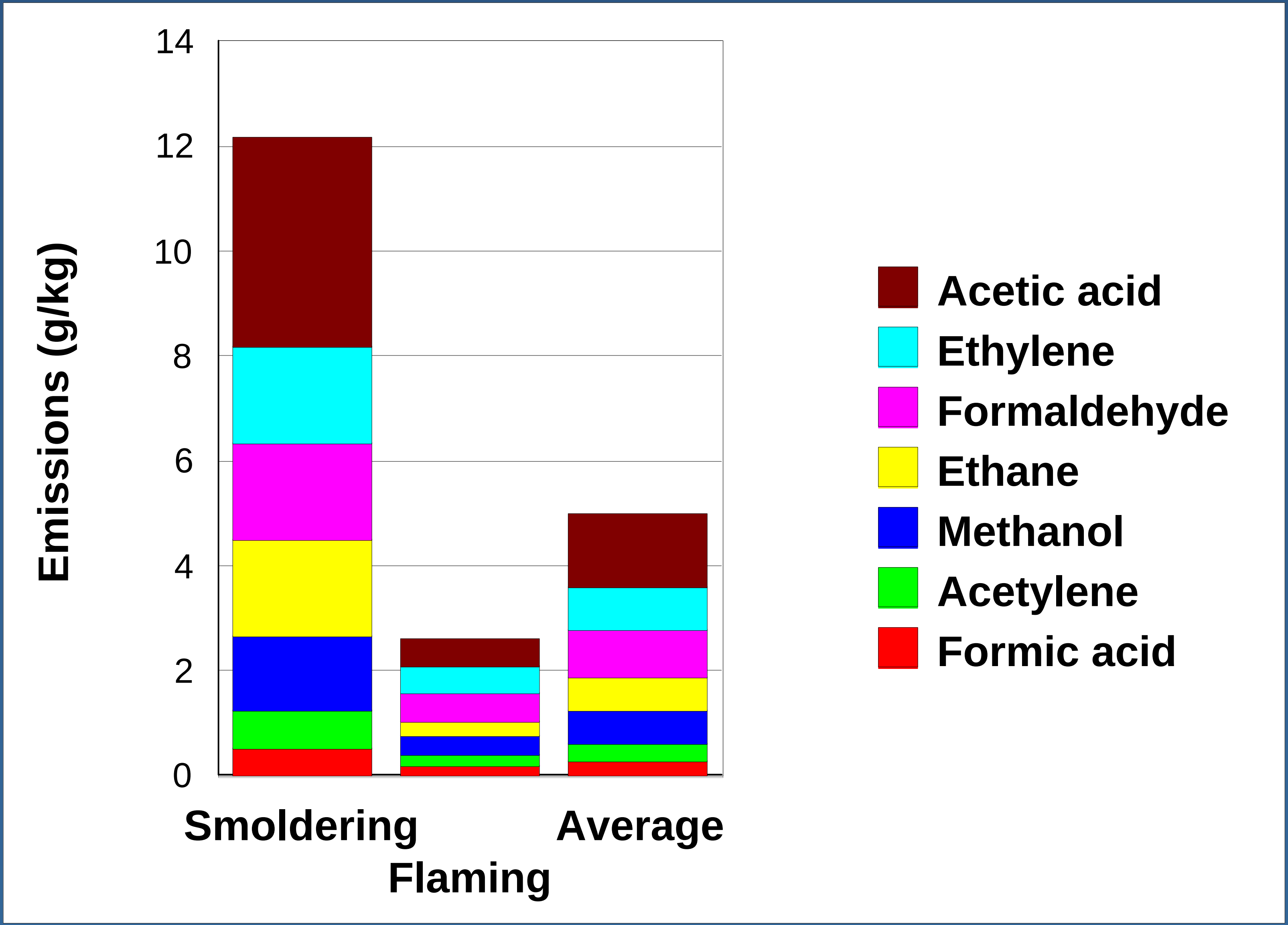
Use of speciation factors



Variation of VOC speciation factors for fire



Speciated VOC emissions for fire



Questions on speciation factors - VOC

- How to reflect different speciation for flaming and smoldering?
  - Options
    - Separate flaming and smoldering emissions within the inventory
    - Use equations for speciation
    - Recognize uncertainty in speciation factors
- How to handle unidentified VOC

Questions on speciation factors - $PM_{2.5}$

- Should EC and OC be handled as separate pollutants or $PM_{2.5}$ species?
- How should "tracers" of fire emissions be handled?

General questions

- What pollutants should be added to fire emission models?
- Is there a need for a standard table of factors outside of the models?
- Next steps for developing a standard set of factors and equations.
- Longer term needs.