Wildland Fire Emission Factors - Latest Research

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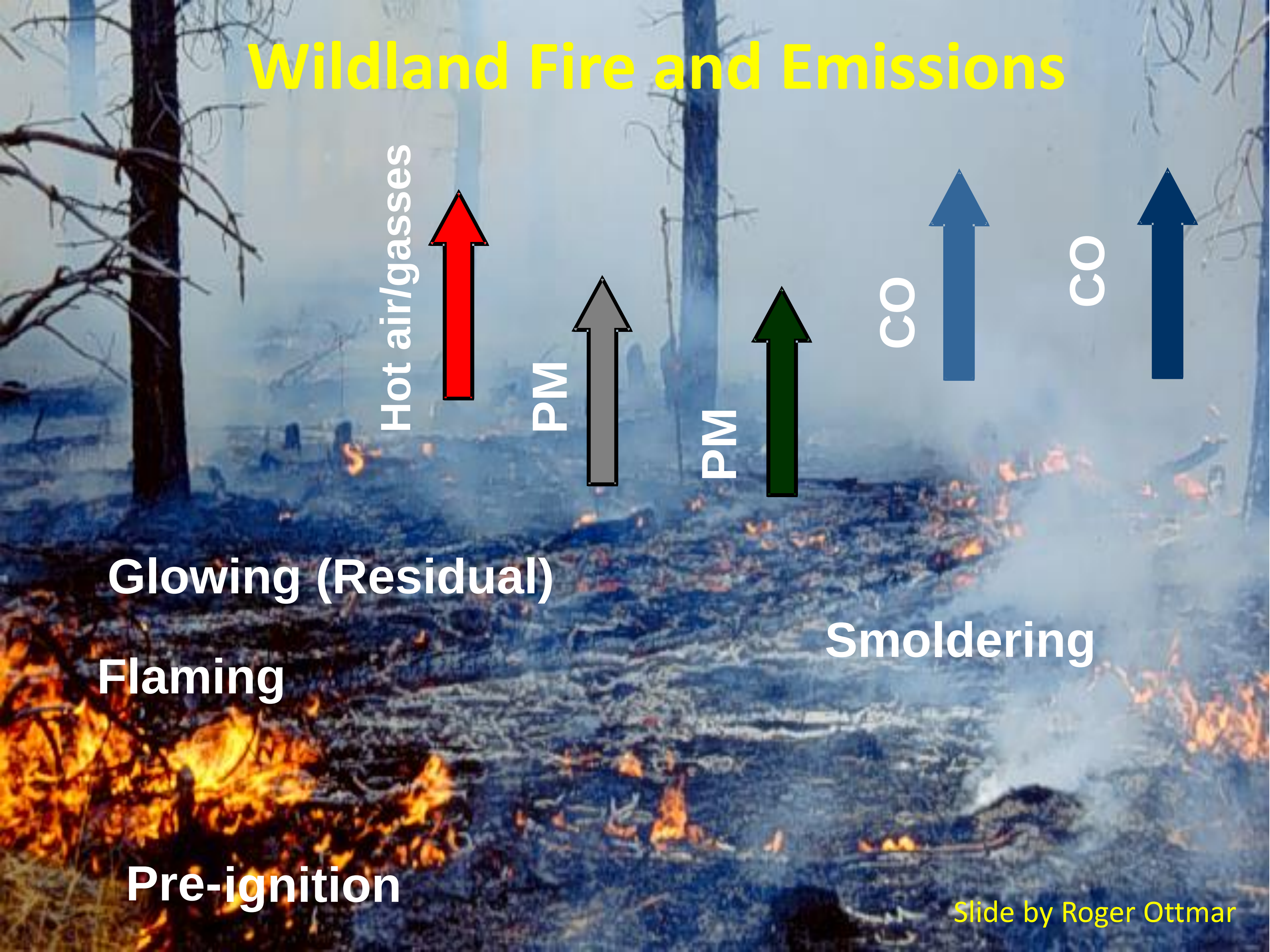
Outline

- Wildland Fire and Emissions
- Emission Characterization – General
- Laboratory Measurements
- Field Measurements
- Recent Efforts in Emission Characterization
- Emission Factor Synthesis
- Implementation of Updated Emission Factor
- Impact of Updated Emission Factors


Wildland Fire and Emissions
Hot air/gasses
PM
PM
CO
CO
Glowing (Residual)
Smoldering
Flaming
Pre-ignition
Slide by Roger Ottmar

Fuels and the Combustion Process

The combustion process depends on the fuels and environmental conditions

Flaming → **Smoldering**

Fuel Particle

High surface to volume ratio → Low surface to volume ratio

Blade grass, conifer needle — Log

Fuel Bed

Low bulk density → High bulk density

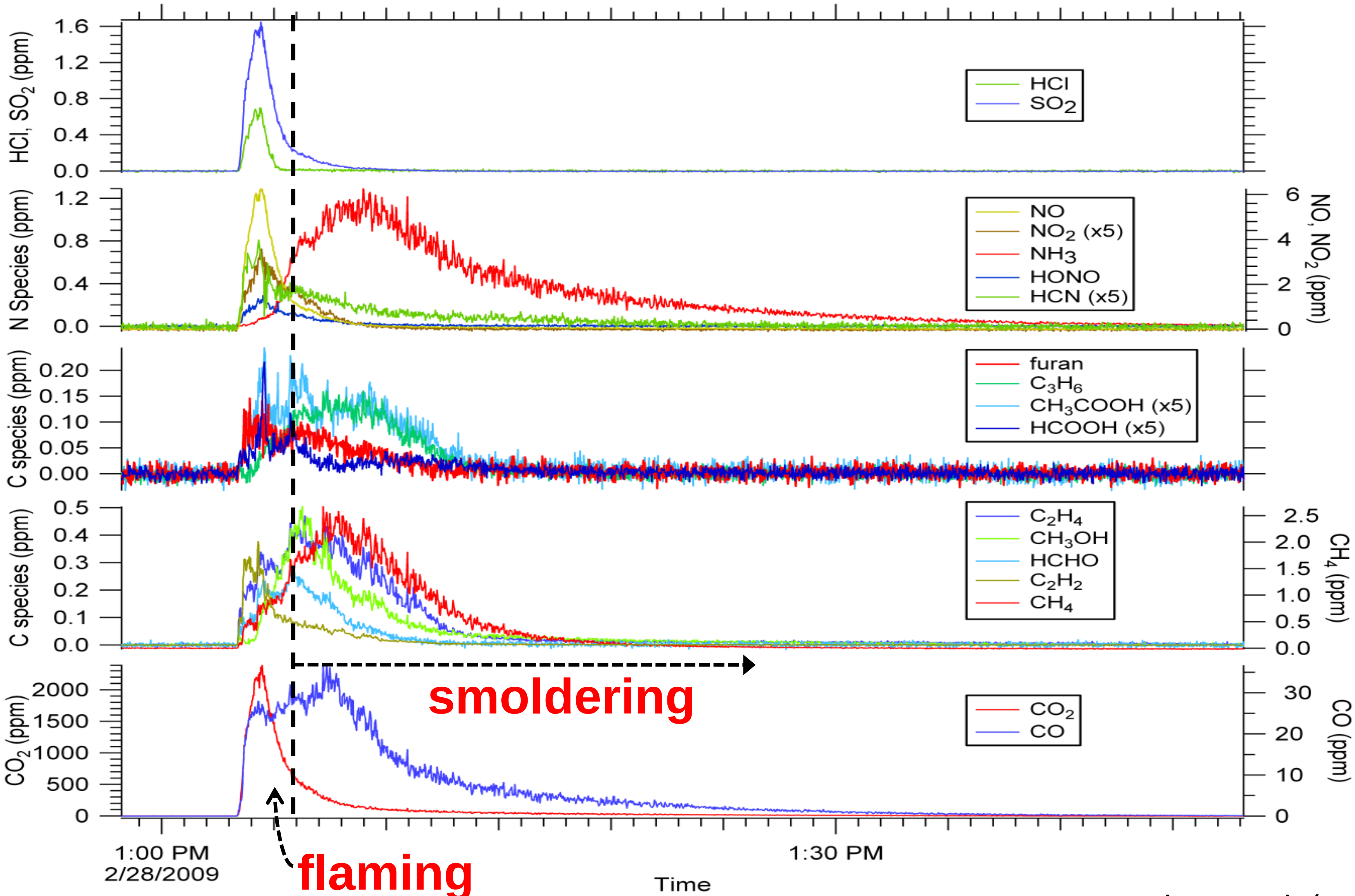
Moisture

Dry (low moisture content) → Wet (high moisture content)

Chemistry – e.g. sound vs. rotten wood, mineral content, carbohydrate & oils?

Flaming is more complete combustion compared with smoldering
Flaming is more efficient in converting biomass C to CO_2 and produces less incomplete products – CO, VOC, PM

Emissions by Combustion Phase



Burling et al. (2010)

Smoke Composition and the Combustion Process

Flaming Combustion:

CO_2, NO, NO_2, HCl, SO_2, HONO, 'black carbon' $PM_{2.5}$

Smoldering Combustion:

CO, CH_4, organic $PM_{2.5}$, NH_3, and many VOC (C_3H_6, CH_3OH, CH_3COOH, C_4H_4O)

Both Processes:

C_2H_2, C_2H_4, HCOOH, HCHO

Emissions are Characterized Through Laboratory and Field Studies

- Identify the components of smoke
- Quantify emissions of different species with emission factors (EF)
- Characterize the dependence of emissions factors on:
  - fuel type and condition
  - combustion phase
  - fire type (under story broadcast burn, wildfire, …)

Emission Factors

An Emission Factor, EF, is the mass of a particular emission product produced per mass of fuel consumed by fire,

e.g. 5 g CH4 per kg of fuel burned, EFCH4 = 5 g kg^{-1}

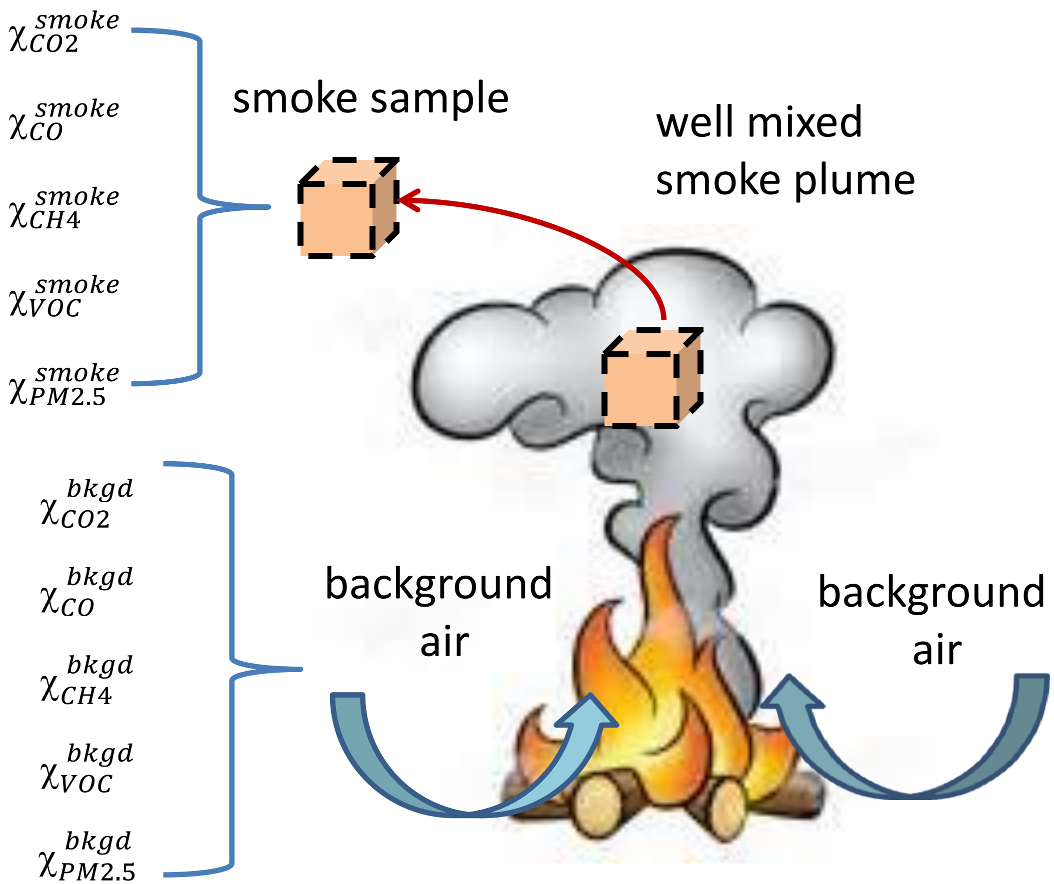
EF are used to estimate fire emissions

Methane emissions:

$$ECH_4 = A \times FL \times FC \times \mathbf{EFCH4}$$

- A – area burned
- FL – fuel load
- FC – fraction of fuel consumption
- **EFCH4** –EF for CH4

Measurement of Emission Factors
Carbon Mass Balance Method



All the volatized carbon species are measured

Emissions are well mixed

Emission of species i is:

$$\chi_i^{emitted} = \Delta\chi_i = \chi_i^{smoke} - \chi_i^{bkgd}$$

Emission Factor Calculation
Carbon Mass Balance Method

$$EF_X = F_C \times 1000\ (g\ kg^{-1}) \times \frac{MM_X}{12} \times \frac{\Delta X}{C_T}$$

$$C_T = \Delta C_{CO_2} + \Delta C_{CO} + \Delta C_{CH_4} + \Delta C_{PM} + \Delta C_{NMOC}$$

NMOC =
non-methane
organic compounds
(VOC excluding CH_4)

Where:
$\Delta X = X_{smoke} - X_{background}$
MM_X = molar mass of X
F_c = carbon fraction of fuel (~ 0.50)
ΔC_{CO2} carbon in excess CO_2, ……
$\Delta C_{CO2} = C_{CO2}(smoke) - C_{CO2}(background)$

CO_2, CO, and CH_4 ≥ 90% of carbon emitted

(Ward & Radke, 1993; Yokelson et al., 1999; Akagi et al., 2011)

Emission Measurements

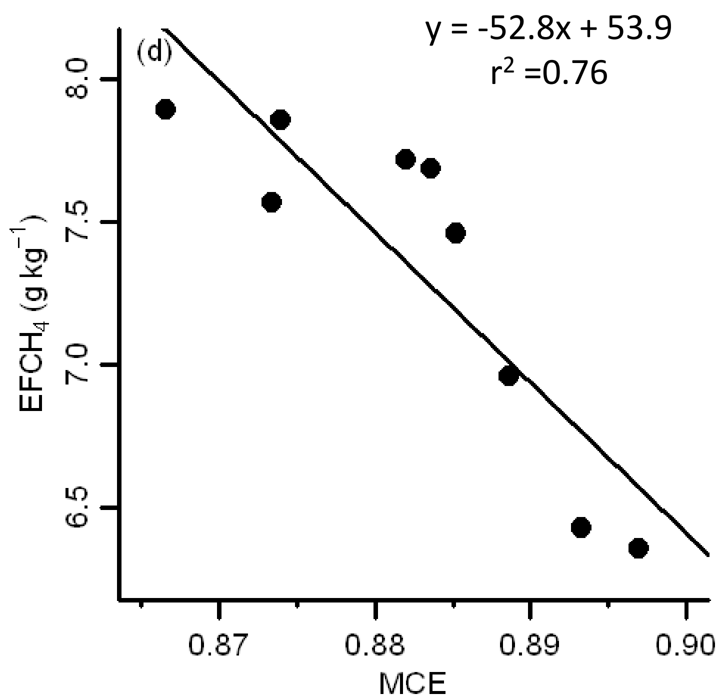
Modified Combustion Efficiency, **MCE**, quantifies the relative amount of flaming or smoldering combustion :

$$MCE = \frac{\Delta CO_2}{\Delta CO_2 + \Delta CO}$$

EF of many species are highly correlated with MCE

MCE may be used to predict EF

Dependence of $EFCH_4$ on MCE



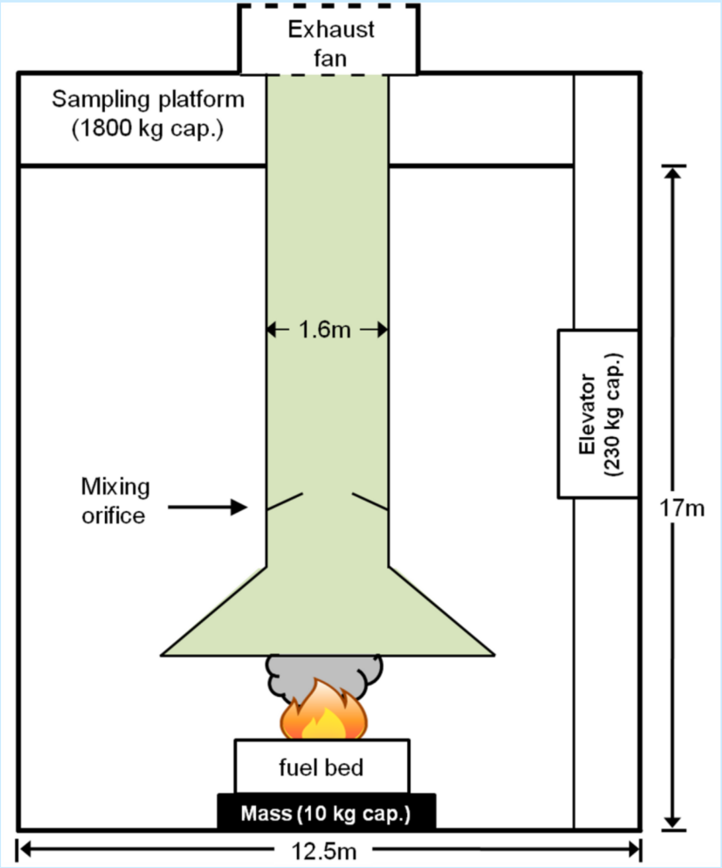
(Urbanski, 2013)

(Ward & Radke, 1993; Yokelson et al., 1999)

Laboratory Experiments

Advantages of Lab:

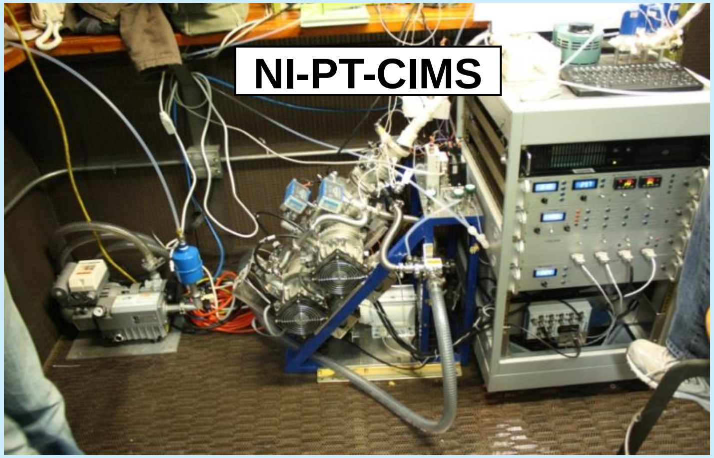
- Controlled conditions
- Replicate burns
- Concentrated Smoke
- Many instruments
- Lots of scientists!

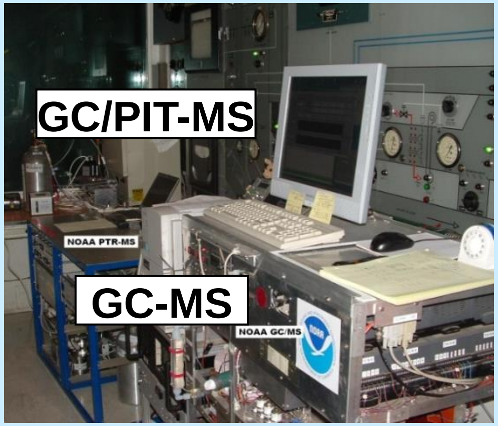


Missoula Fire Lab combustion chamber

Diagram from Burling et al. (2010)

Laboratory on Platform





Photos by Bob Yokelson

Measuring Emissions

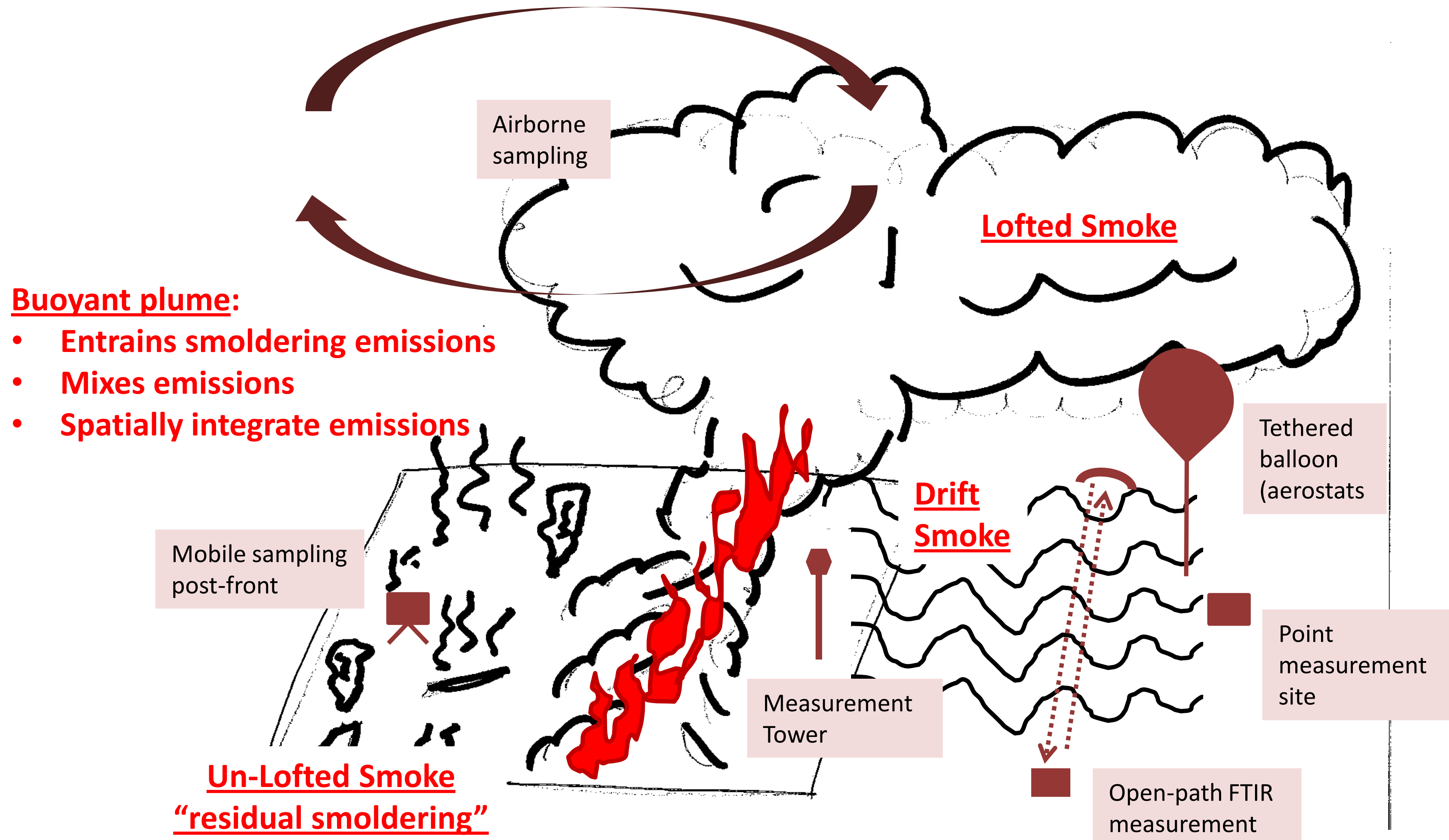
Lab fires are very useful……..

but are not real fires

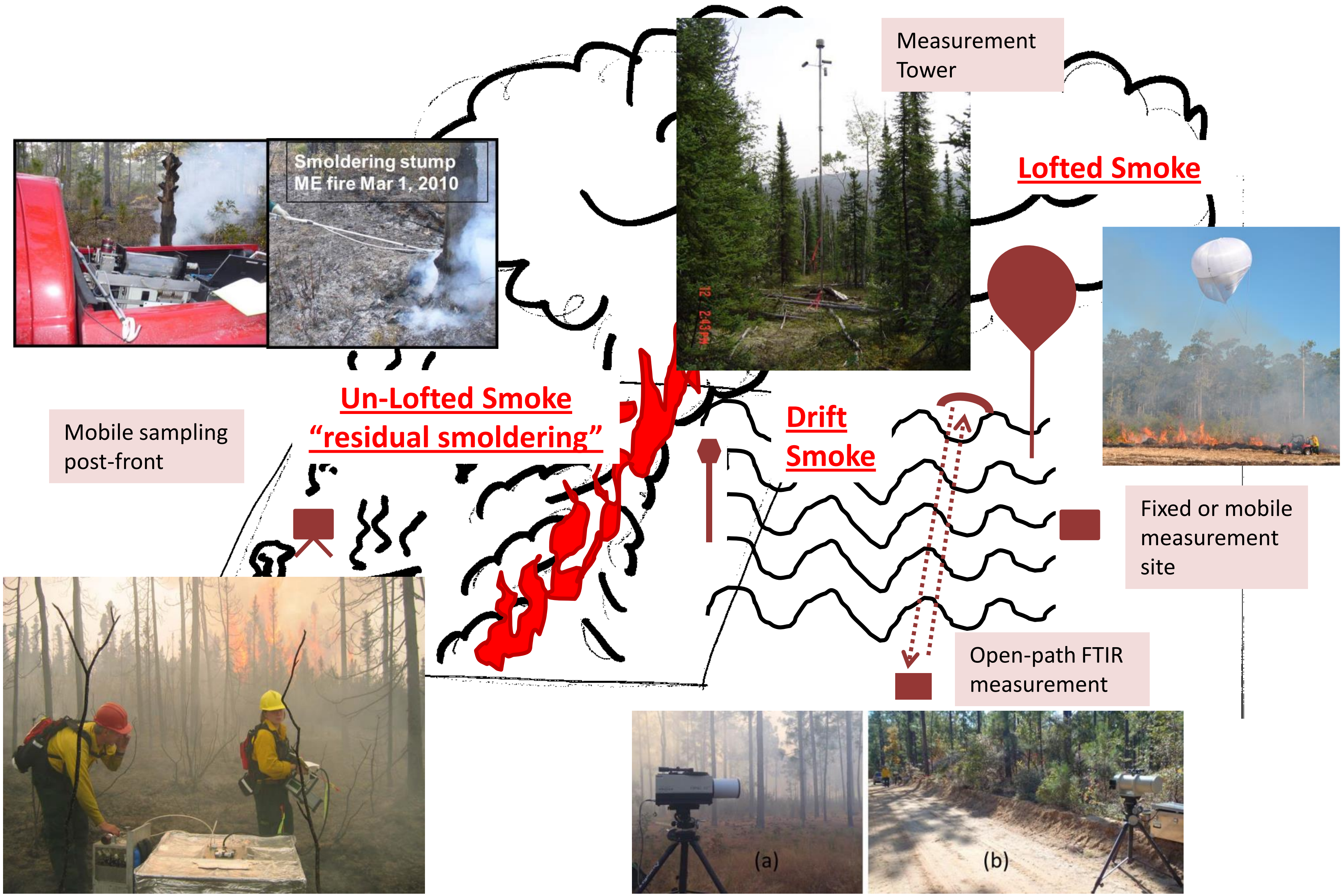
Field Measurements

- Validate laboratory experiments
- Measure EF for ***"real"*** fires
- Characterize natural variability of fire emissions

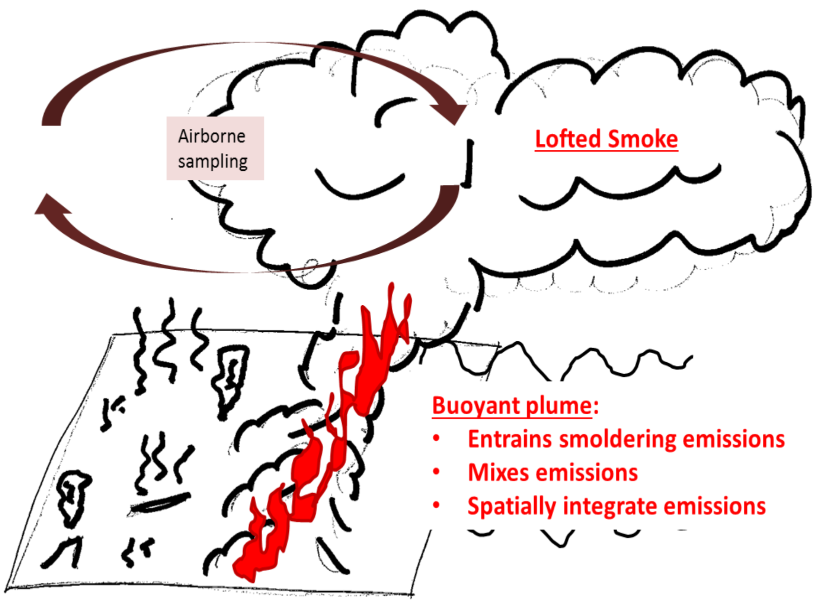
Field Measurements



Ground-based Measurements



Airborne Measurements



Airborne Laboratory
USFS Smoke Jumper Twin Otter

Inlets on Twin Otter roof

Instruments inside

20^{th} Century Emission Factors – Pre-Update

Summary of EF in Smoke Management Guide (SMG), EPA AP-42 (AP-42), and Andreae and Merlet (A&E)

Fire Type	CO_2	CO	PM_{10}	$PM_{2.5}$	CH_4	VOC	NO_X	Additional Species
Smoke Management Guide (2001) Table 5.1 (SMG)								
Broadcast burned slash (5 forest types)								
Pile & burned slash (2 pile types)								
Broadcast burn - brush (sage & chaparral)								
Wildfire in forest								
AP-42 / Battye & Battye (2002) Tables 38 and 39 (AP-42)								
Broadcast burned slash (5 forest types)								
Pile & burned slash (2 pile types)								
Broadcast burned brush (sage & chaparral)								
Wildfire in forest								
General								NH_3 and 20 HAPs (overall)
Andreae and Merlet (2001) (A&M)								
Savanna & Grassland								NH_3 and 66 NMVOC
Extratropical Forest								NH_3 and 66 NMVOC
Tropical Forest								NH_3 and 66 NMVOC

Slash burns – All 5 forest types measured in OR & WA

Red = Fire average EF only **Gray = EF by flaming / smoldering**

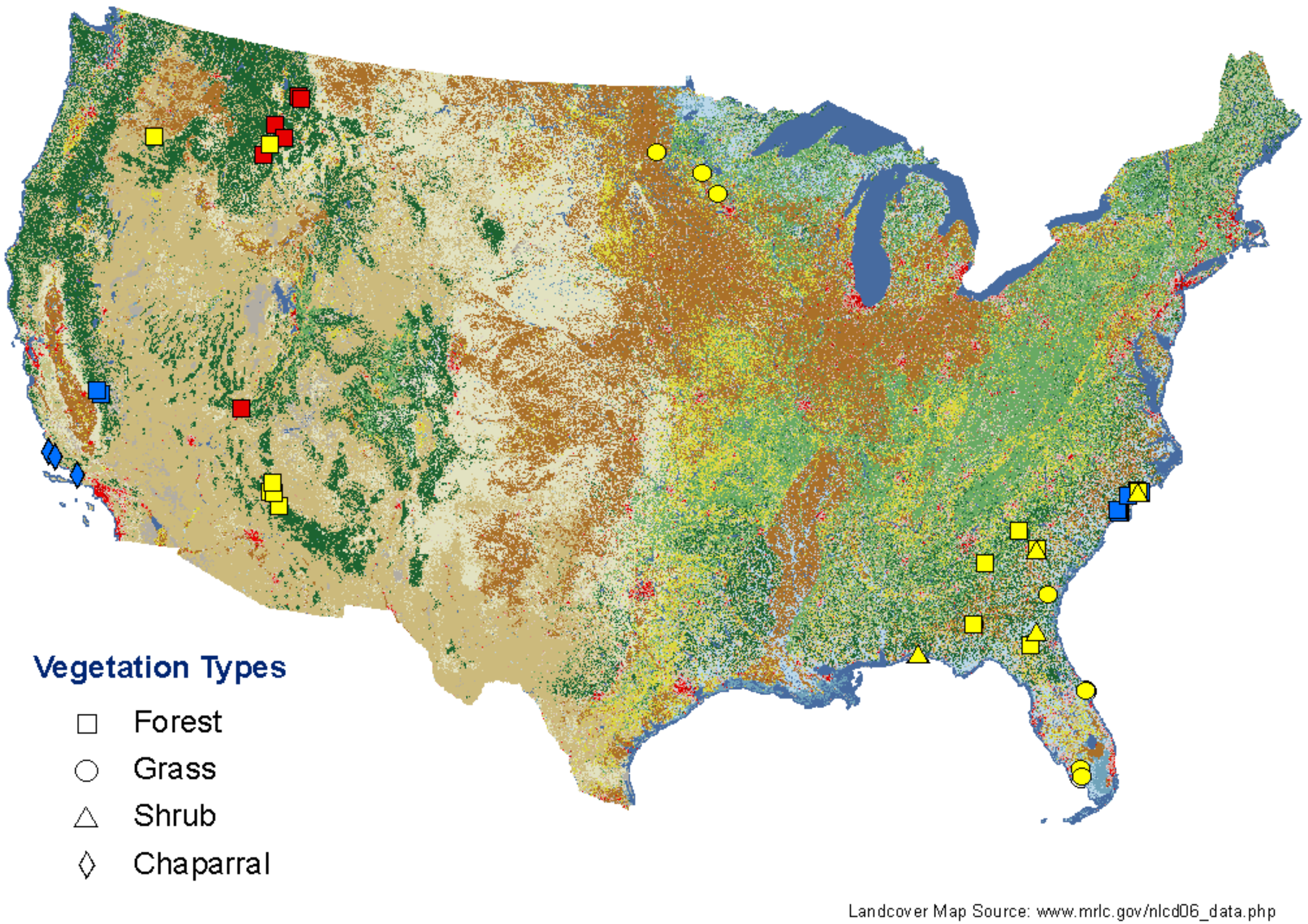
Emission Factors – Some Recent Efforts

	EF Reviews/Synthesis	Laboratory Studies	Field Studies
2001	SMG; A & M		
2002	AP-42		**FiSL Southeast Rx (2002)**
2003			
2004			
2005			
2006		FLAME I (2006)	**JFSP 98-1-9-01 (2007)**
2007		FLAME II (2007)	NASA ARCTAS (2008)
2008		**FLAME III (2009)**	**SERDP RC-1648 (2009)**
2009	Urbanski (2009)	**SERDP RC-1648 (2009)**	**SERDP RC-1649 (2009-2011)**
2010		**SERDP RC-1649 (2009)**	
2011	Akagi (2011)		**JFSP 08-1-6-09 (2011)**
2012		FLAME IV (2012)	JFSP RXCADRE (2012)
2013	Yokelson (2013)		NASA SEAC4RS (2013)
2014	Urbanski (2014)		DOE BBOP(2013)

Used in Urbanski (2014). Table does not include all studies used in Urbanski (2014)

Emission Factors – Some Recent Field Efforts

Include only field measurements used in Urbanski 2014

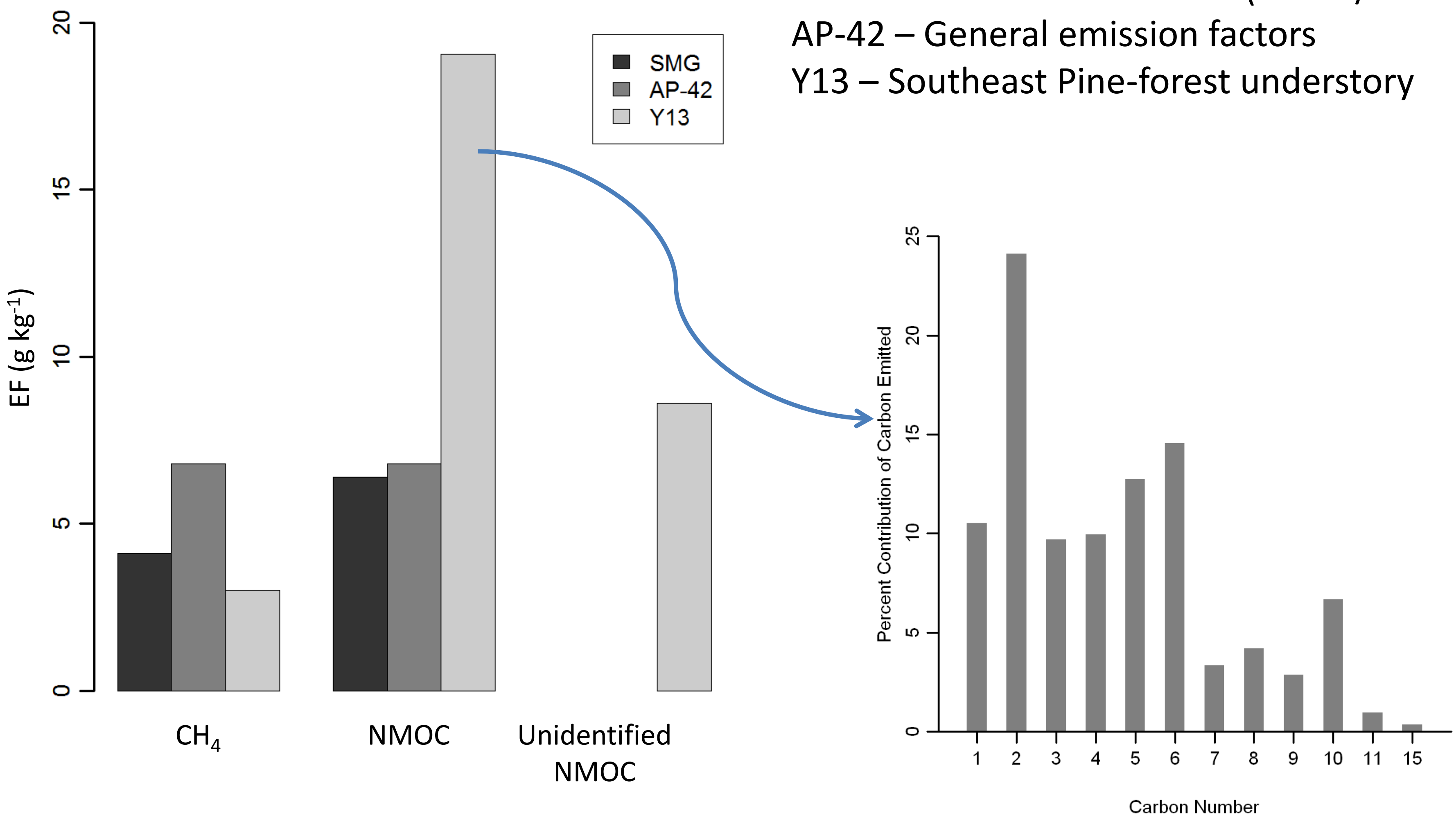


Results

- Hundreds of gases identified
- Emission factors (EF) measured for 100’s species --- *used to predict fire pollutant source strength*
- Relationship of emissions to combustion processes characterized
- Particle properties characterized – size, composition, morphology, optical properties

Fire Average VOC EF for SMG and AP-42 vs. Yokelson et al. 2013 lab/field synthesis

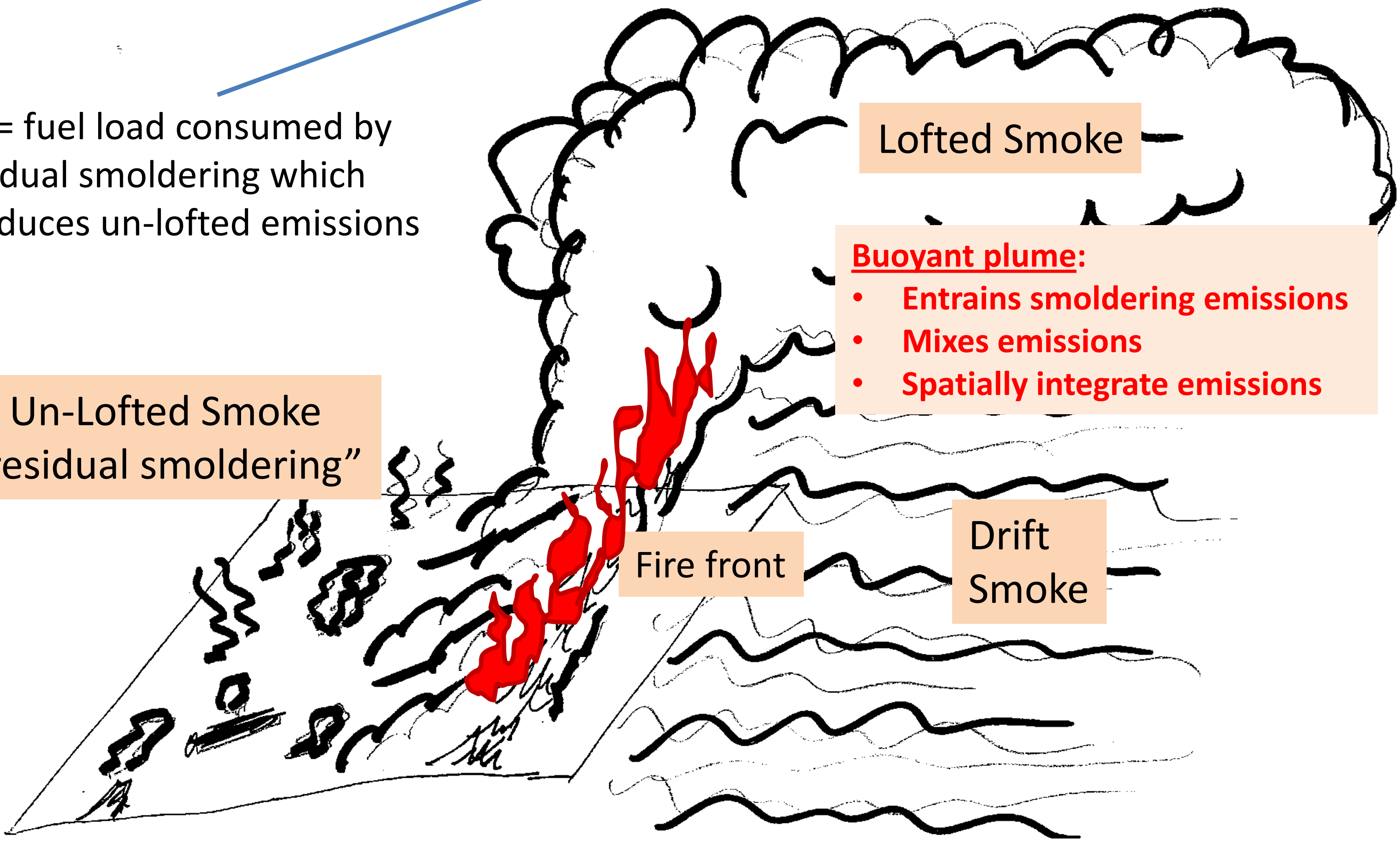
SMG – broadcast burn slash (PPine /LPine)
AP-42 – General emission factors
Y13 – Southeast Pine-forest understory



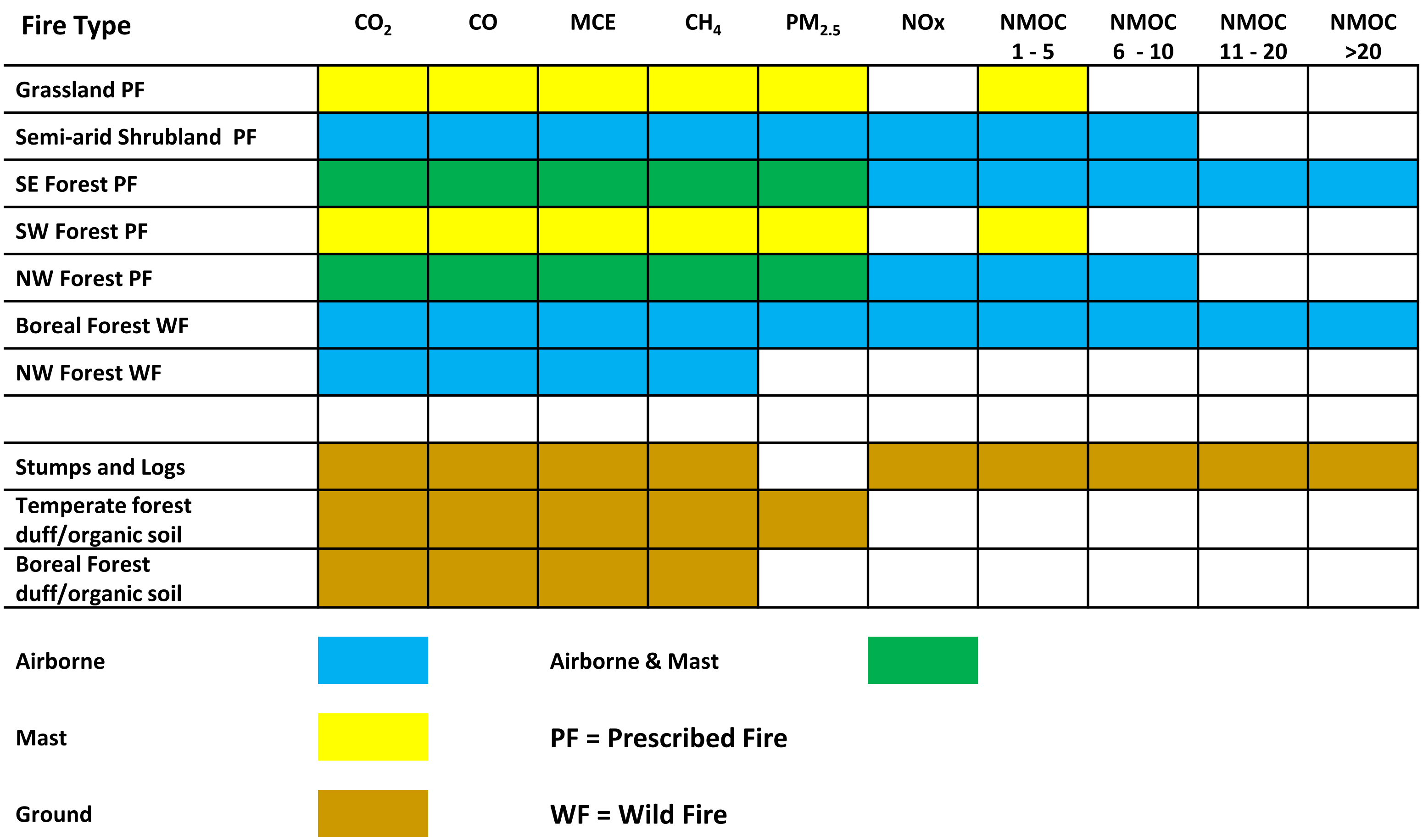
EF Synthesis Framework

$$EF_{TOTAL} = EF_{LOFTED} \times (1 - F_{RS}) + EF_{UN\text{-}LOFTED} \times F_{RS}$$

F_{RS} = fuel load consumed by residual smoldering which produces un-lofted emissions



Field Study Data Inventory



Synthesis of Field and Lab Data

EF field measurements identified as suitable assigned to generalized fire types

Fire Types – life form, fuel components, knowledge of MCE, limited by availability of emissions data

Favored data source is field measurements of fresh emissions

- Lofted EF employ airborne and mast measurements
- Un-lofted EF ground-based measurements of independently smoldering fuel components

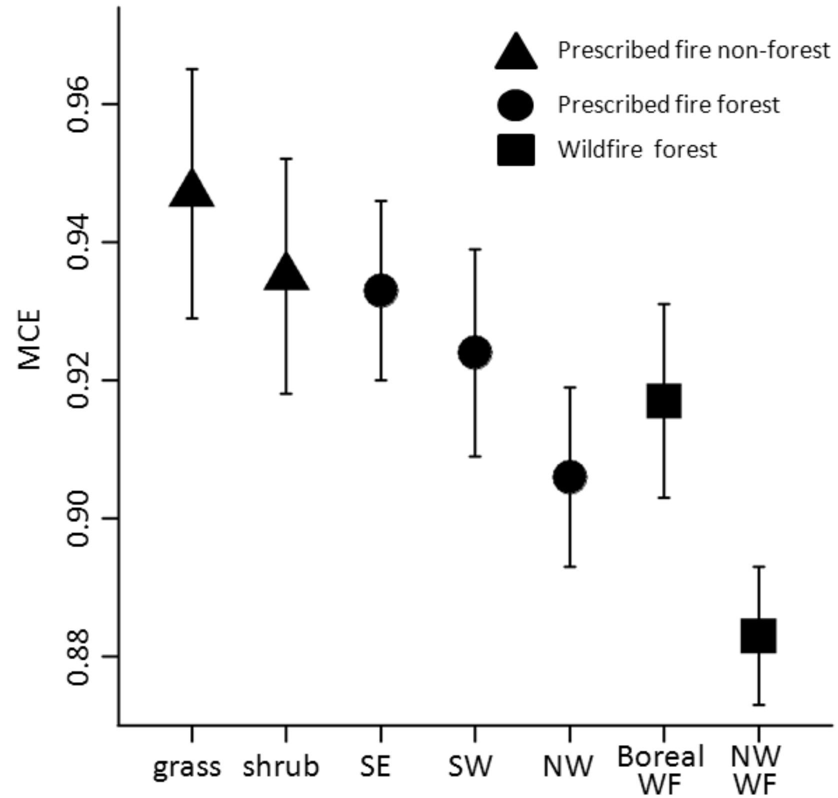
Case A: field measurements are available from multiple studies for a particular fire type - average taken as best-estimate EF (and their standard deviation taken as the uncertainty)

Case B: field measurements available from only one study; its average and standard deviation taken as the best-estimate EF and uncertainty, respectively

Case C: field measured EF for a specific species - fire type combination is not available, EF estimated from an MCE-based synthesis of available laboratory and field data

Synthesis of Field and Lab Data
Forest

Mix of flaming & smoldering combustion, measured by MCE, varies by fire type / location



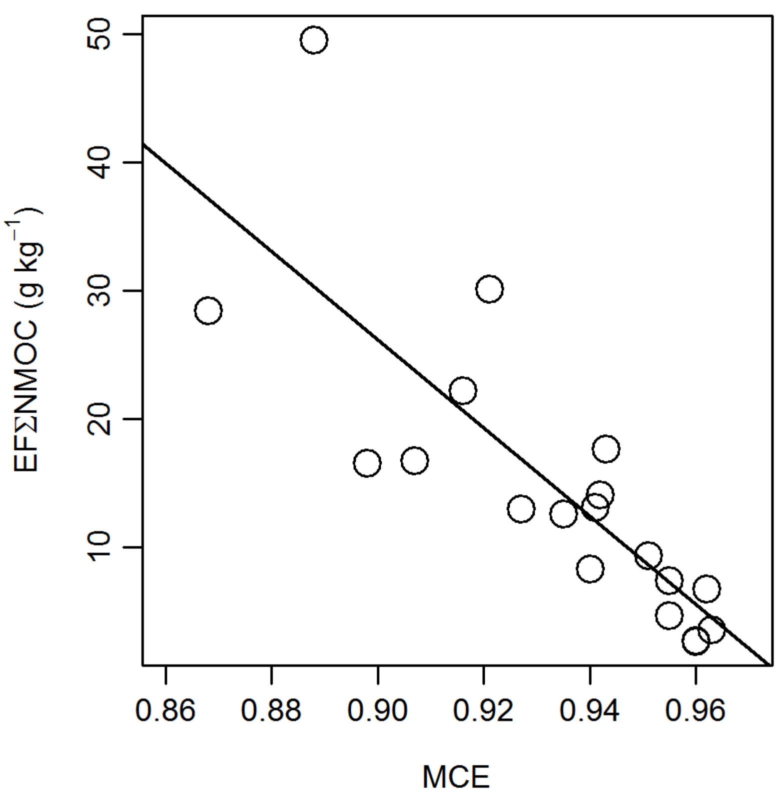
Majority of field measurements are from prescribed fires in the Southeast forests

Most EF for western forests must be extrapolated from lab/field data:

$$EF = a + b * MCE$$

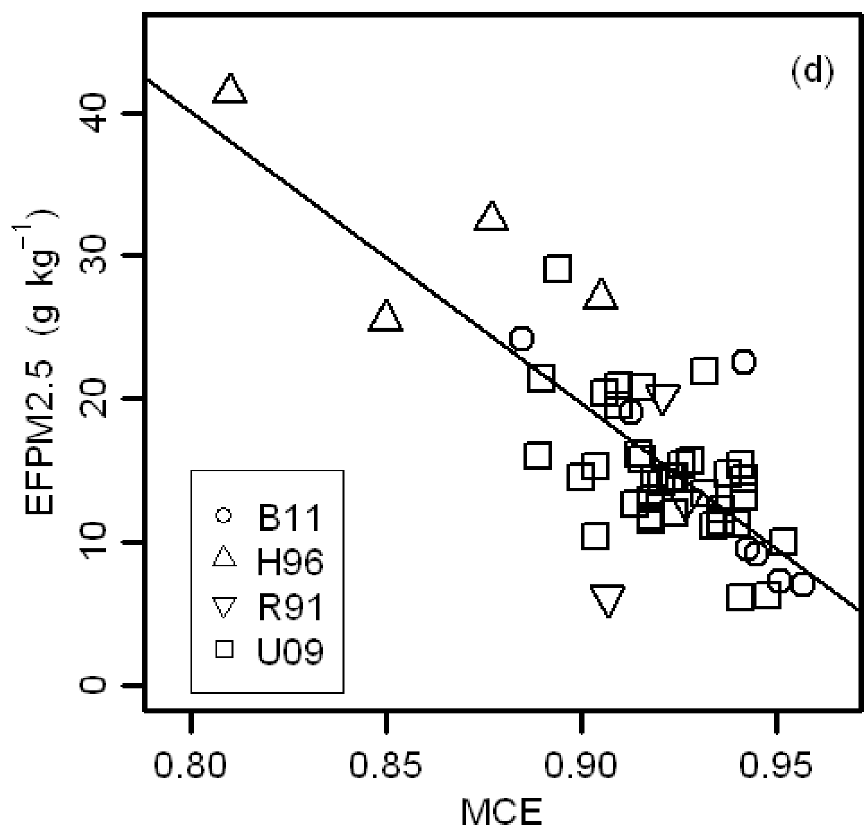
Forest Fire Emissions – Lofted (EF_{LOFTED})

EFΣNMOC = a + (b*MCE)
lab studies
Fine fuels



Data from Yokelson et al. (2013)

EFPM2.5 = a + (b*MCE)
field studies
Airborne & Mast



Urbanski (2013)

Forest Fire Emissions – Lofted (EF_{LOFTED})

Estimate the sum of NMOC (192 species) based on MCE:

$$EF\Sigma NMOC = -343.9*MCE + 335.7 \quad (R^2 = 0.65)$$

EF of individual NMOC species estimated by assuming relative contribution of each equals the average of lab burns (n=19):

$$EF_j = (a + b * MCE) * \beta_j$$

$$\beta_j = \frac{\overline{EF_j}}{\overline{EF \sum NMOC}}$$

- Actual dependence of individual EF varies among species
- EF for some species not well correlated with MCE
- Dataset does not include coarse woody debris or duff

Forest Fire Emissions – Residual Smoldering ($EF_{UNLOFTED}$)

$EF_{UNLOFTED}$ (residual smoldering) – emissions from residual smoldering of coarse woody debris and duff/organic soil

EFNMOC

Coarse woody debris and duff/organic soil - Assume it follows MCE dependence observed in lab

EFPM2.5

Coarse woody debris – Assume $EFPM_{2.5}$ follows MCE dependence observed in field studied (airborne/mast)

Duff / Organic Soil – Average of limited ground-based field and lab measurements

Emissions from Fires in Non-forest Vegetation

No consistent EF - MCE relationship for VOC emissions:

Semi-arid shrubs

- Laboratory measurements – Burling et al. (2010)
- Field measurements – Burling et al. (2011)

Grassland

- Field measurements – Urbanski et al. (2009)

Due to the lack of EF – MCE relationship for rangeland fuels EF were taken directly from synthesis of Yokelson et al. (2013).

Species measured in the lab and without comparable field measurements were extrapolated to field conditions using the average ratio of EF for all species with both field and lab measurements

Implementation of Updated EF

Fire Effects Models

Allocate simulated fuel consumption to combustion phases

CONSUME

Empirical model

Allocates fuel consumption:

Flaming
Smoldering
Residual Smoldering

Depends on fuel component

Emissions:
Designed for phase specific EF

First Order Fire Effects Model (FOFEM)

Employs physical model (BURNUP)

Allocates fuel consumption:

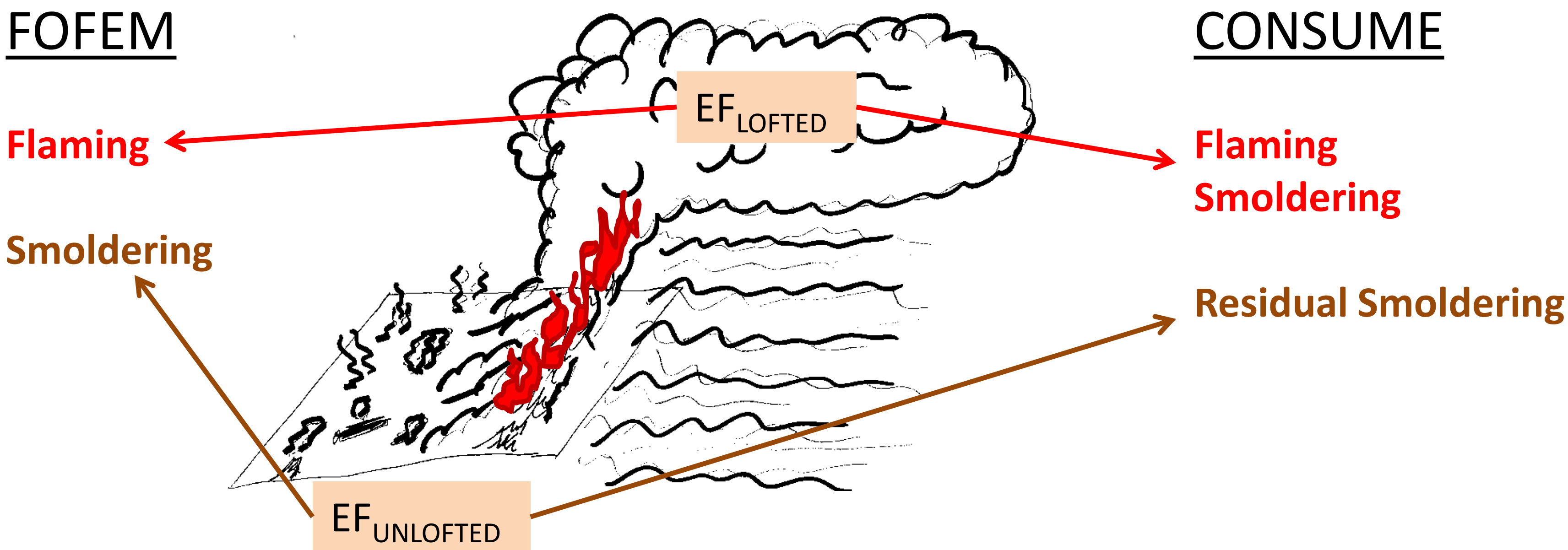
Flaming
Smoldering

Flaming assumed to cease when intensity < 15 kW m^{-2}

Emissions:
Applies EF = f(CE) (circa 1989)
CE = 0.97 for flaming
CE = 0.67 for smoldering

Implementation of Updated EF

How to reconcile mismatch between the emission measurements and fuel consumption models?



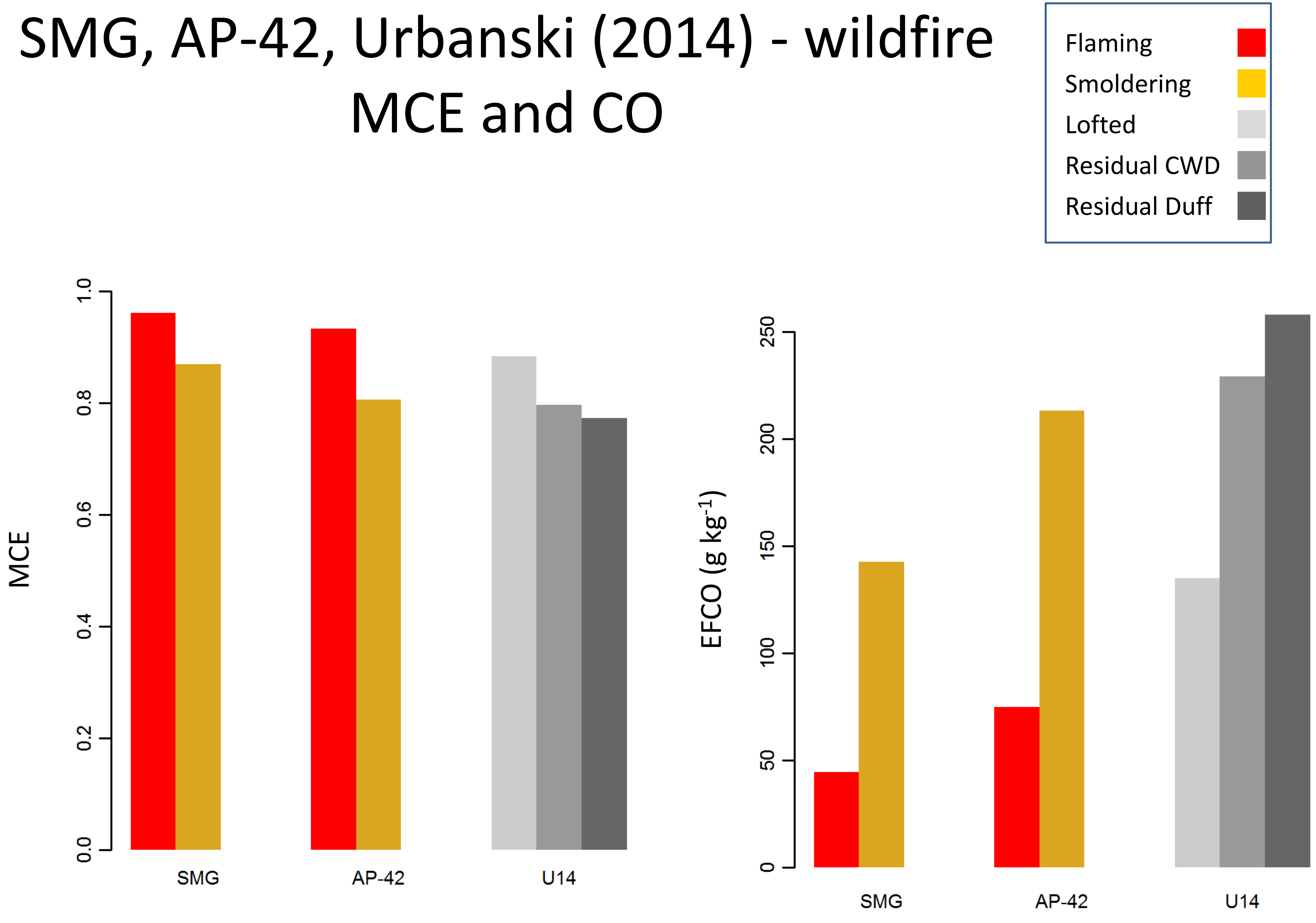
Some unknown and variable fraction of FOFEM smoldering emissions are entrained and lofted in buoyant plume!

Impact of Updated EF

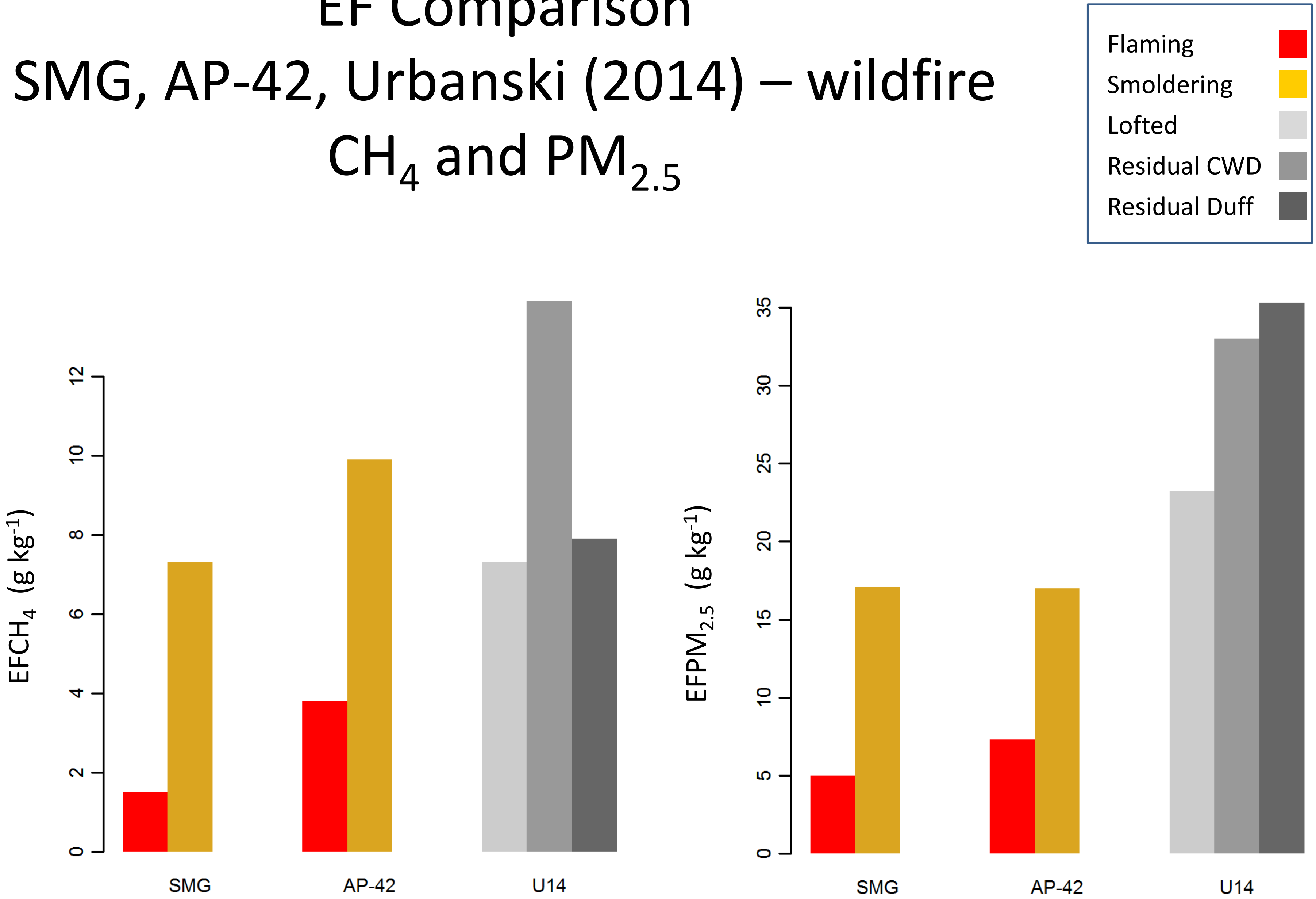
Give examples of the impact of updated EF on emissions for a couple scenarios using CONSUME

What scenarios?
SE prescribed fire long-leaf pine
Western Ponderosa Pine or Doug-fir
RXCADRE L2F and L1G how do we compare?

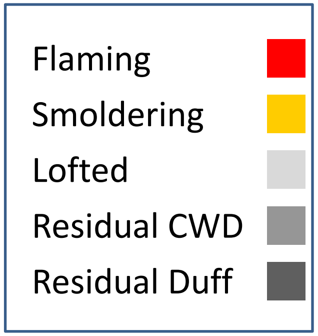
EF Comparison
SMG, AP-42, Urbanski (2014) - wildfire
MCE and CO

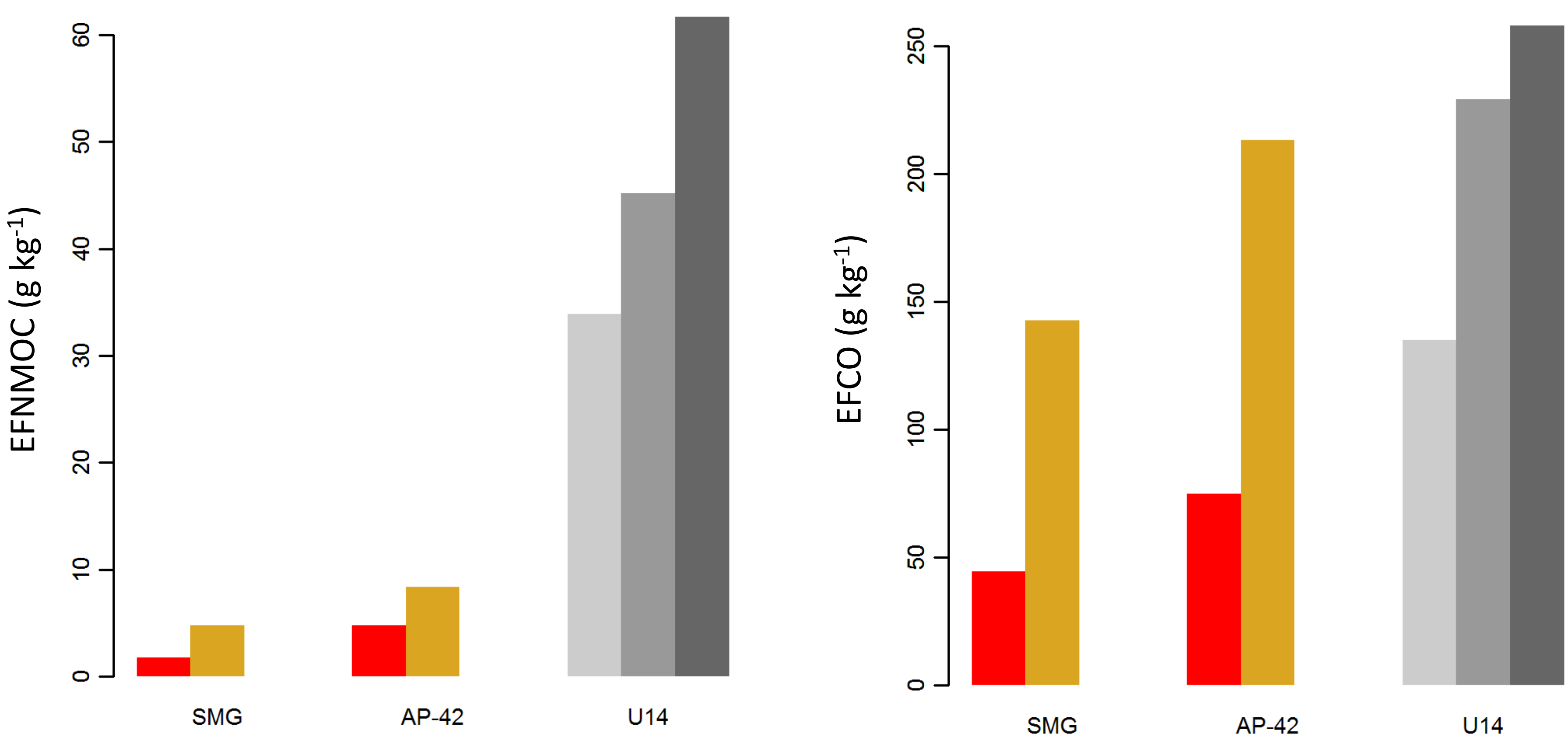


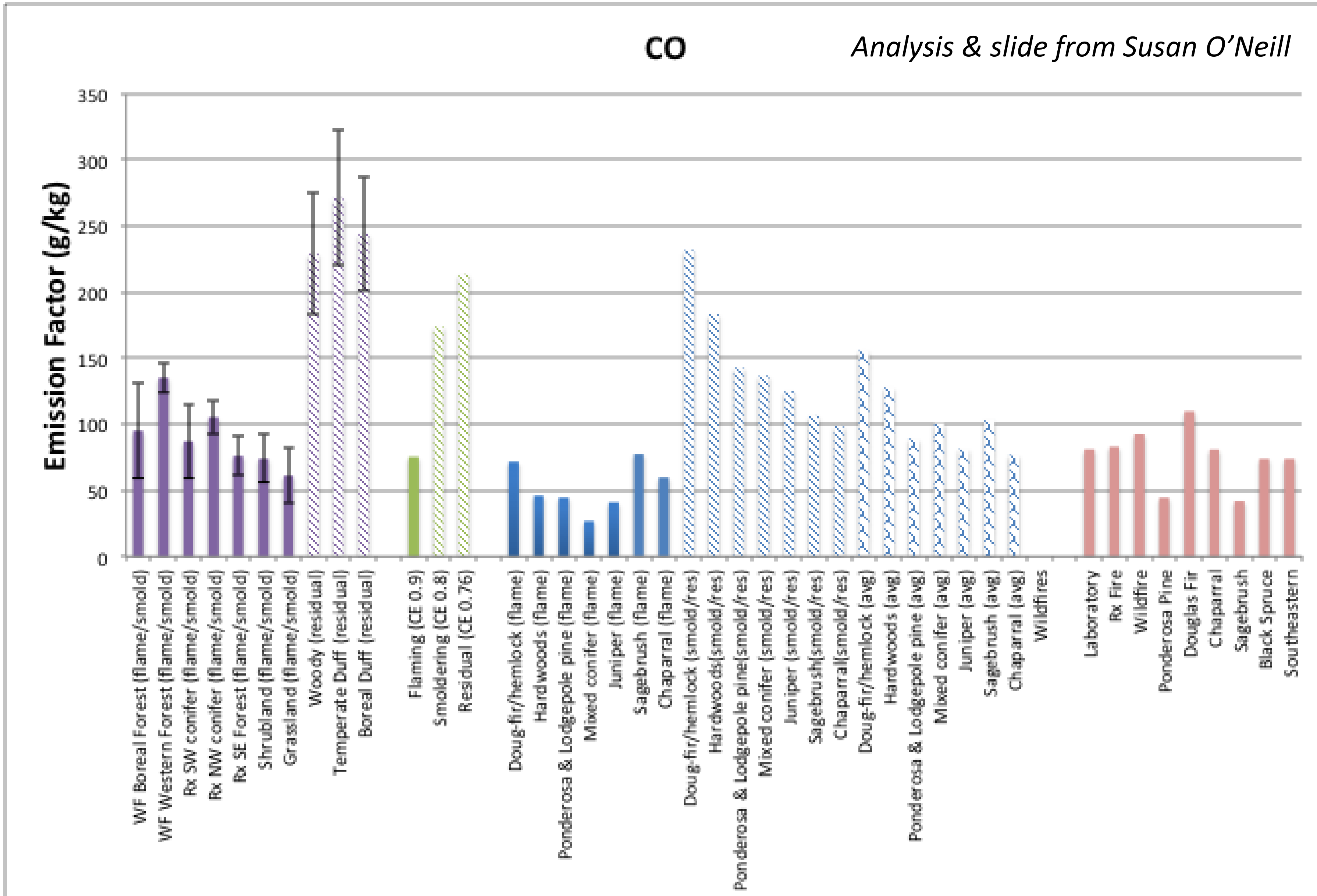
EF Comparison
SMG, AP-42, Urbanski (2014) – wildfire
CH_4 and $PM_{2.5}$



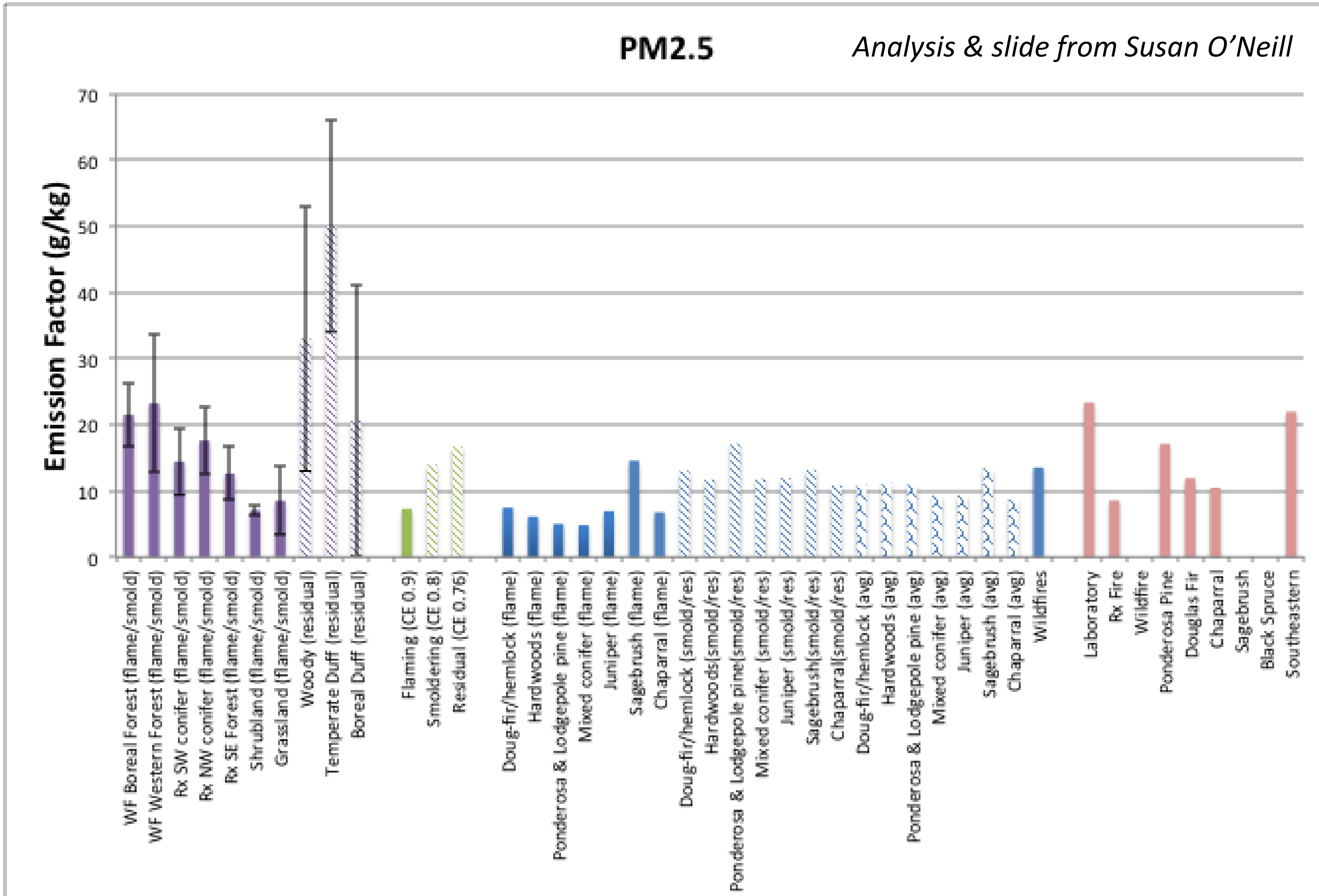
EF Comparison
SMG, AP-42, Urbanski (2014) – wildfire
NMOC and CO







Urbanski 2014 = purple, FEPS = green, CONSUME = blue, Strand et al. = peach



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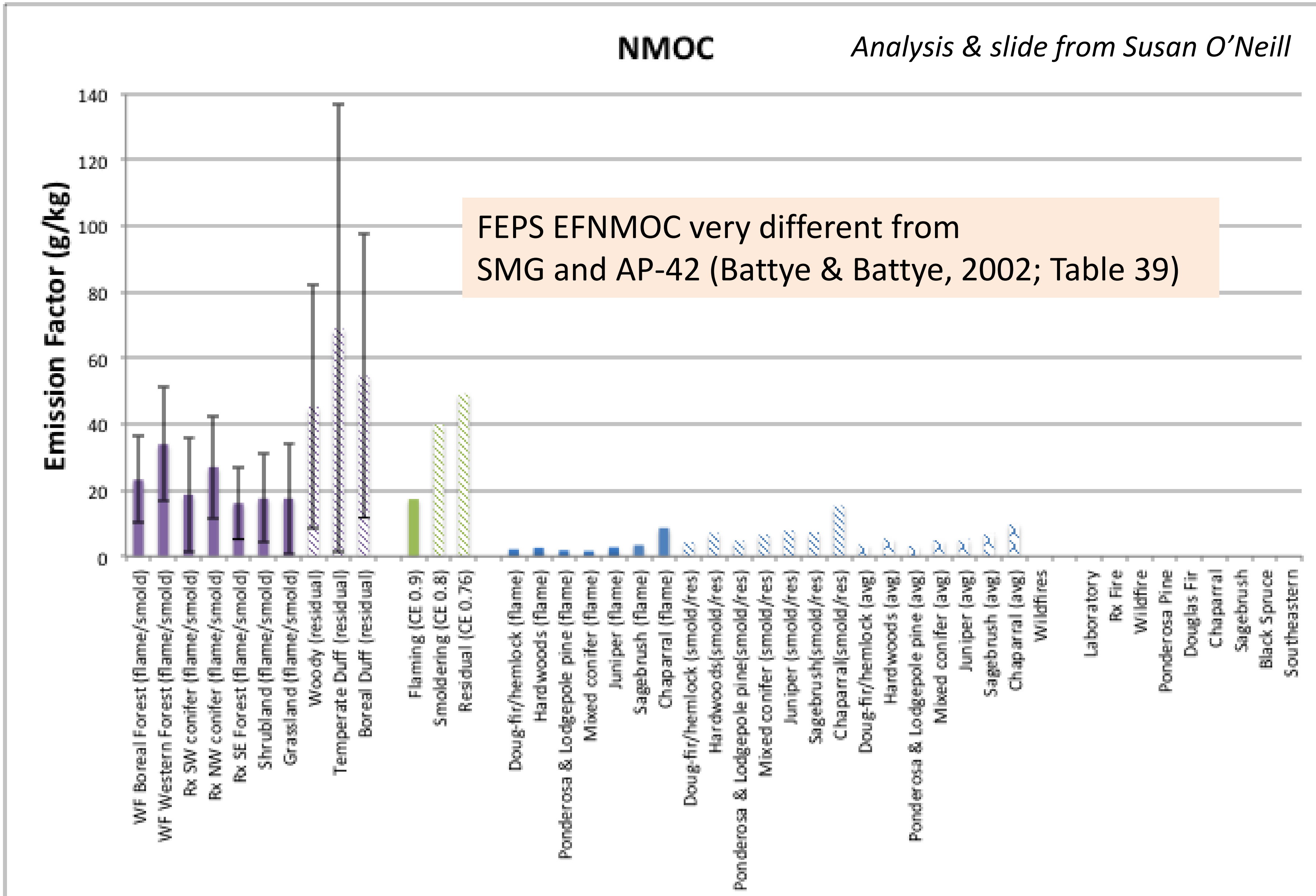
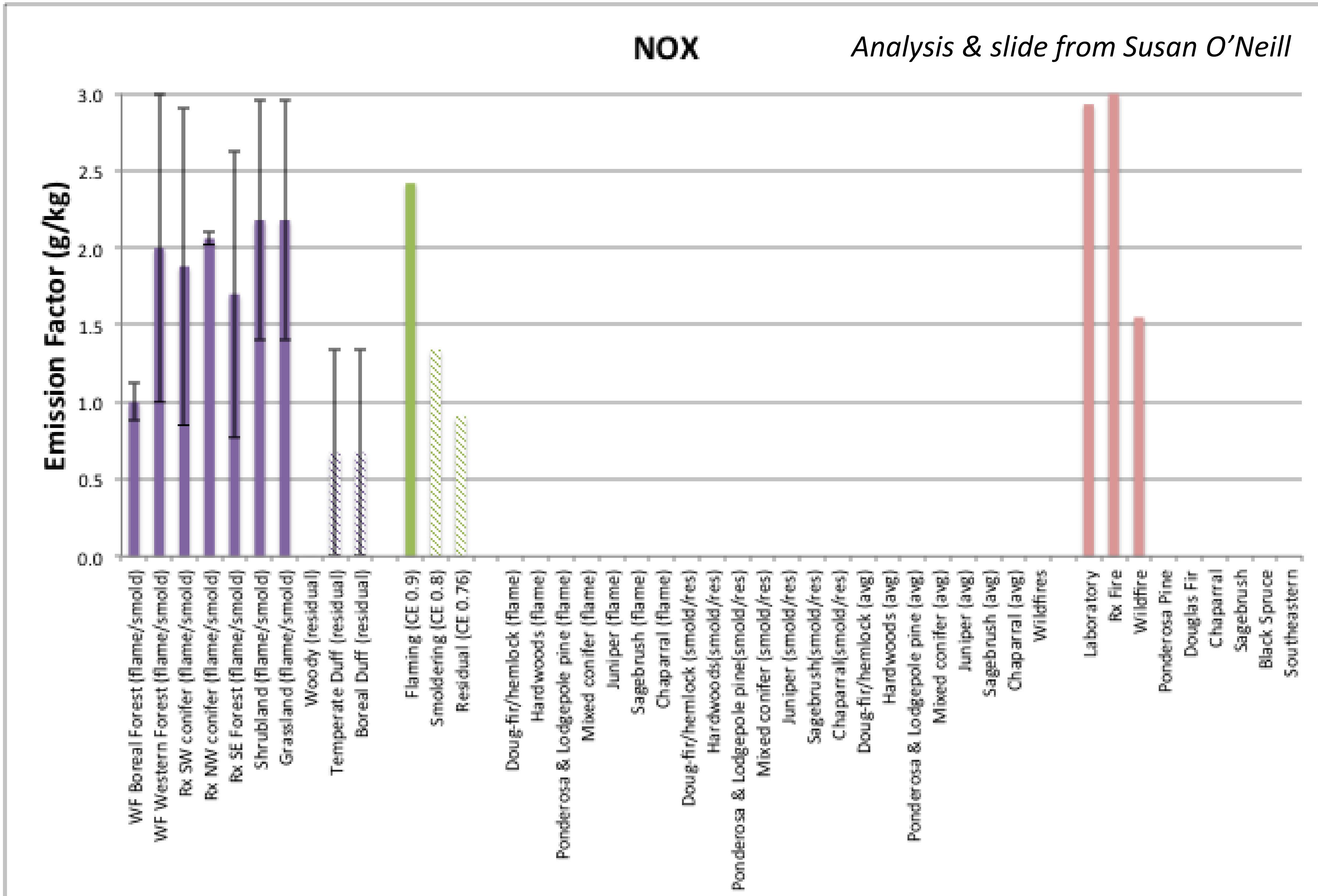


Urbanski 2014 (NMOC) = purple, FEPS (VOC) = green, CONSUME (NMHC) = blue, Strand et al. = peach



Urbanski 2014 = purple, FEPS = green, CONSUME = blue, Strand et al. = peach

Impact of Updated EF

Four Fire Scenarios

- Broadcast rx burn in long leaf pine (LLP)
- Wildfire in California mixed conifer (CMC)
- Wildfire in Lodgepole pine (LP)
- Wildfire in Ponderosa Pine (PP)

Simulate fuel consumption using CONSUME

Emission Factors

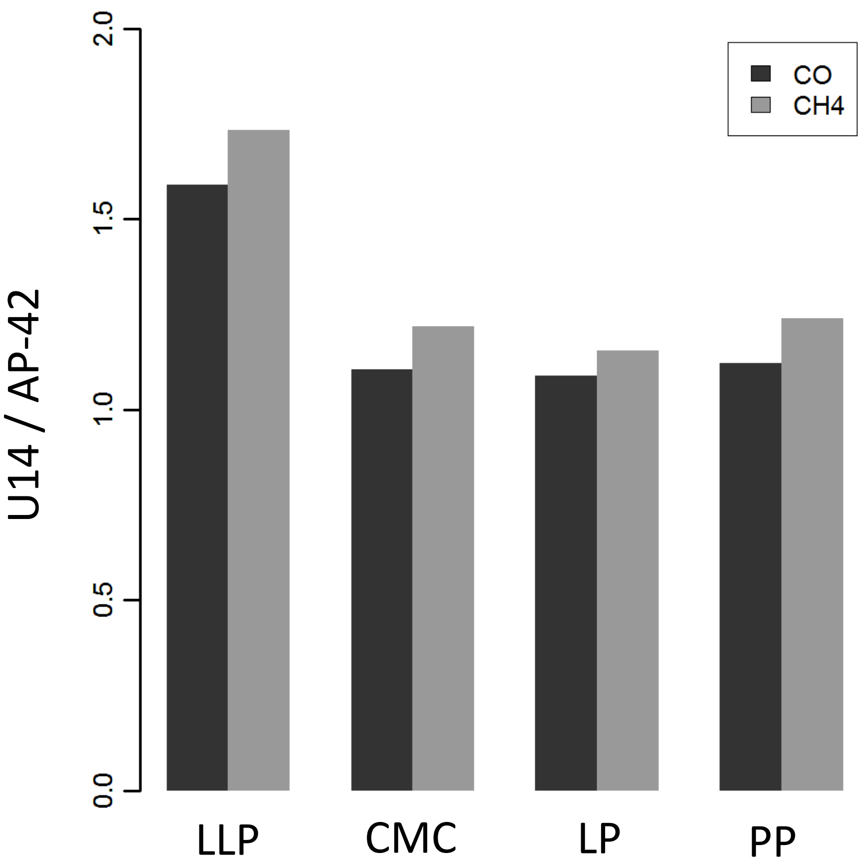
AP-42 / Battye & Battye (2002) Table 39 (AP-42)

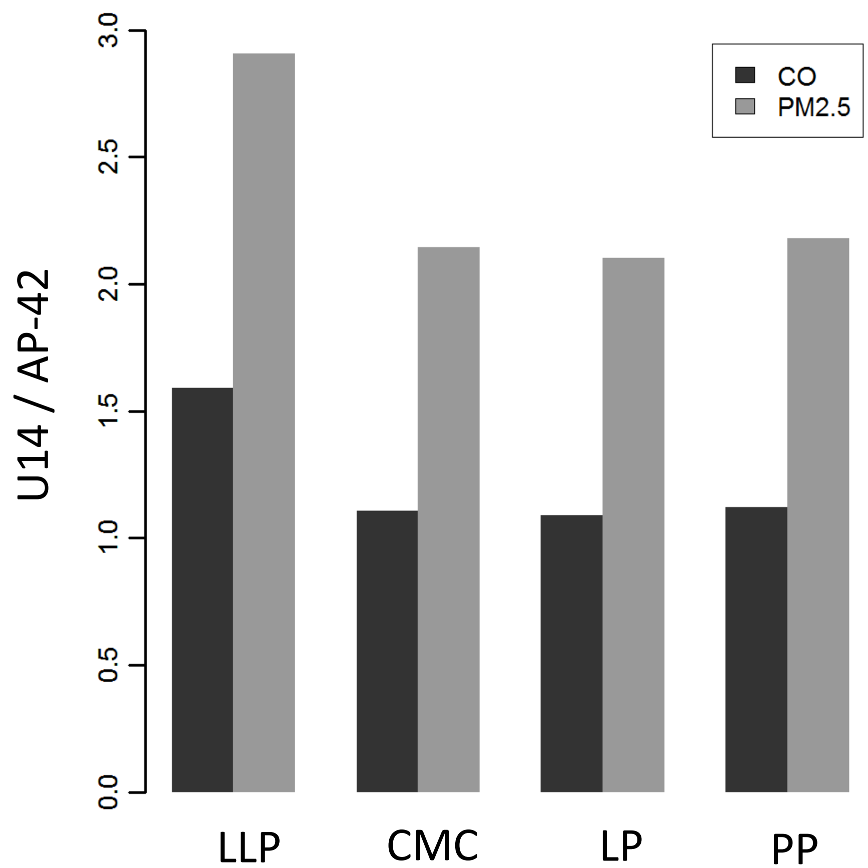
Urbanski (2014) (U14)

Apply 'un-lofted' EF to CONSUME residual smoldering fraction

Impact of Updated EF

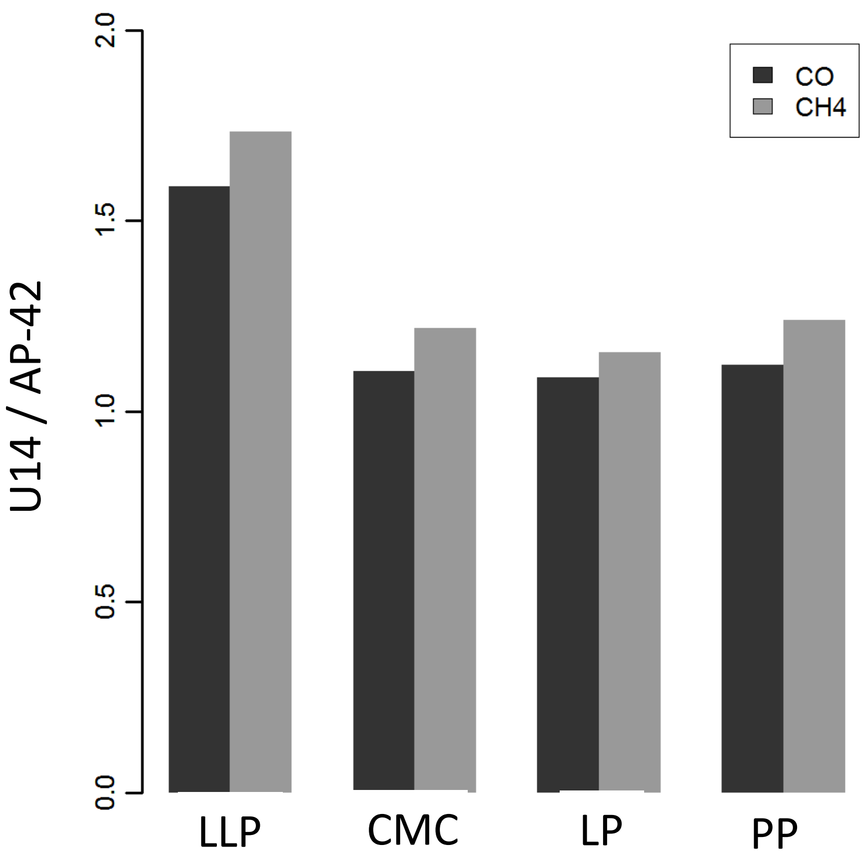
Emissions Rations for CO, CH_4, $PM_{2.5}$

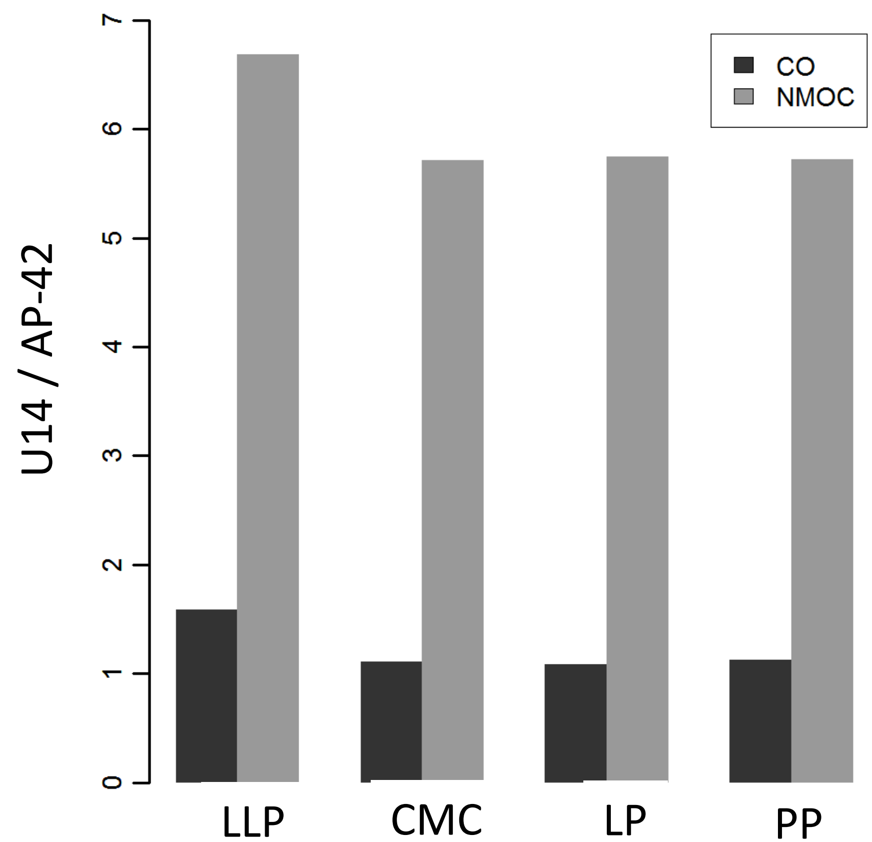




Impact of Updated EF

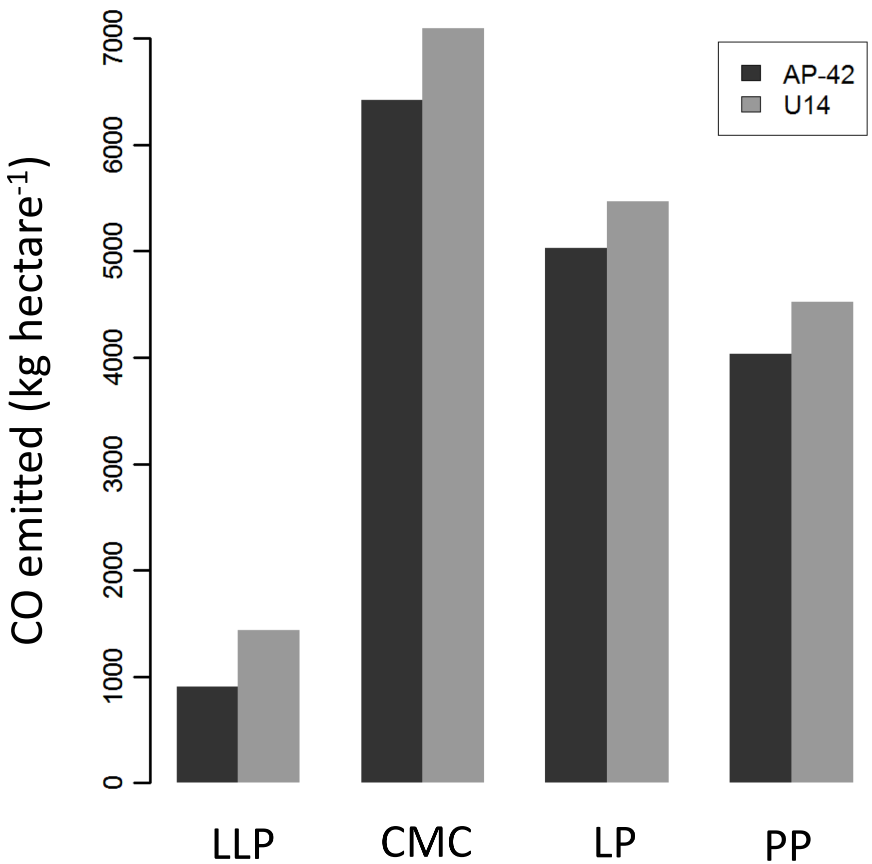
Emissions Rations for CO, CH_4, NMOC

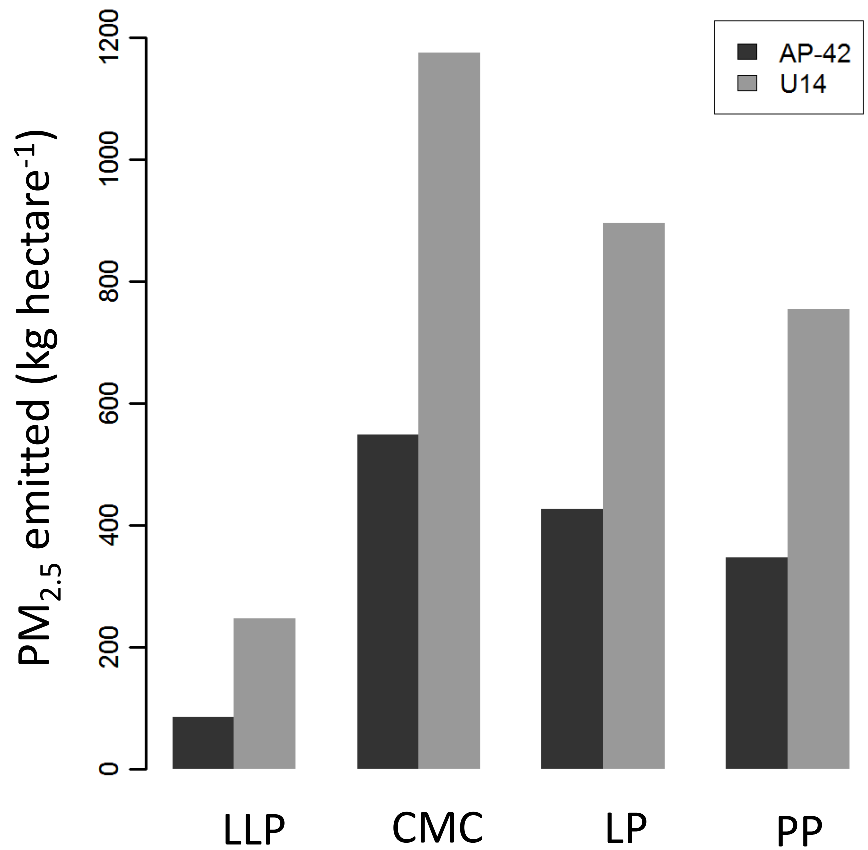




Impact of Updated EF

Emission Intensity for CO and $PM_{2.5}$





Emission Ratio: New/Old 2014

Analysis & slide from Susan O'Neill

	PM2.5	PM10	CO2	CO	CH4	NOX	NH3	SO2	NMOC
max	2.39	2.40	1.07	1.30	1.41	0.93	0.95	1.03	1.32
min	1.22	1.21	1.00	0.76	0.52	0.43	0.11	0.26	0.70
median	1.66	1.66	1.05	0.91	0.99	0.80	0.33	0.75	0.84
mean	1.71	1.71	1.04	0.95	0.98	0.79	0.35	0.72	0.88

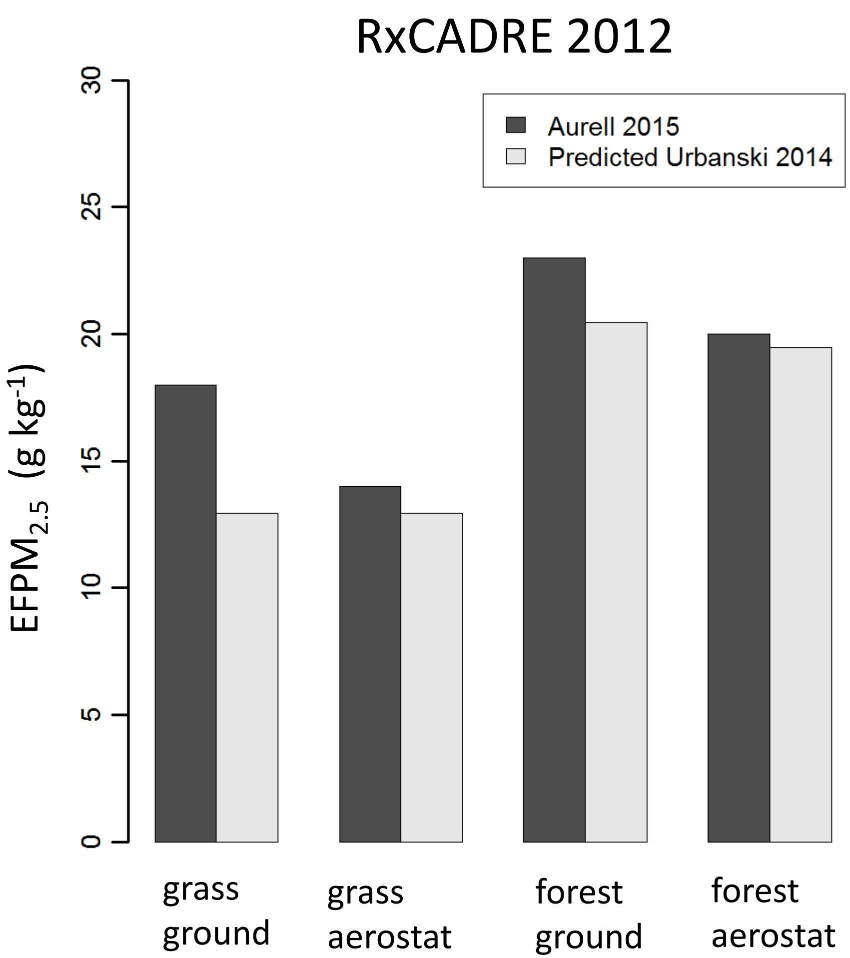
- For each day of 2014, emissions were calculated for all US fires using the new emission factors from Urbanski 2014. Emissions were summed for each day. The ratio was then taken between the new and the old emission estimates.

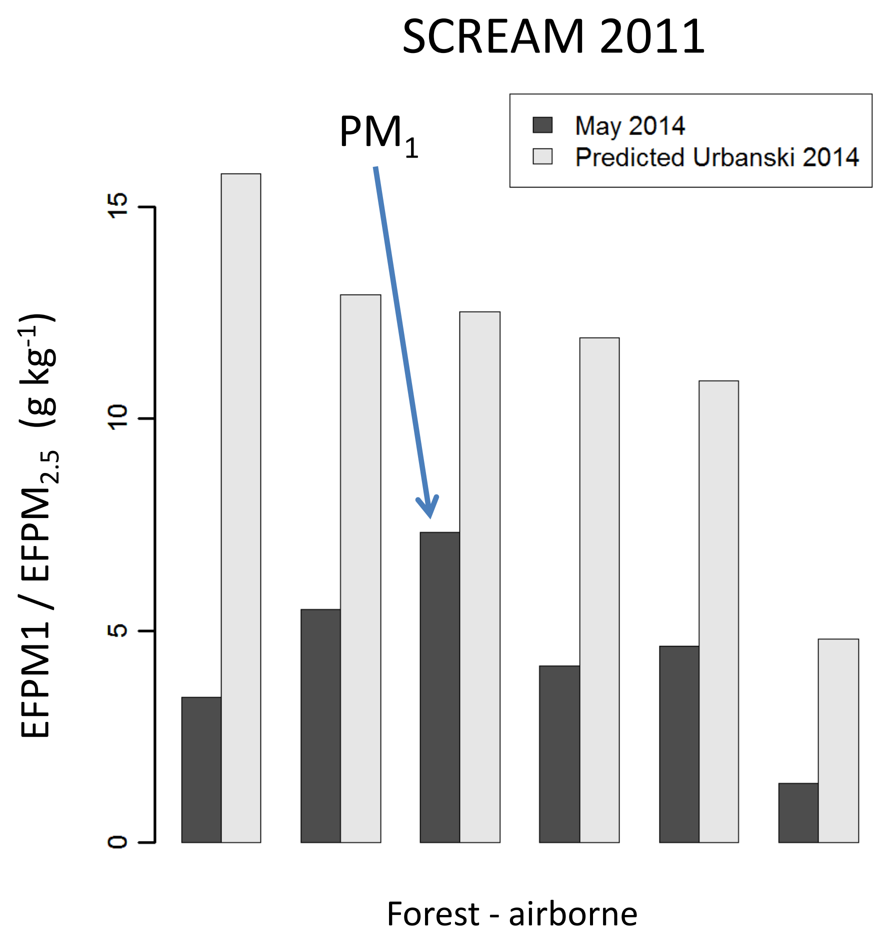
Do Updated EF & Implementation Uncertainties and Possible Errors

- MCE for wildfires – Based on small sample and may not be representative
- Extrapolation of EF based on MCE – How robust?
- Linear EF – MCE relationship not robust for independently smoldering fuel component (residual smoldering)
- Harmonizing emissions measurements and simulated fuel consumption

Extrapolated $EFPM_{2.5}$ - Do They Make Sense?

Recent field measurements vs. MCE based predictions
Southeastern broadcast prescribed burns

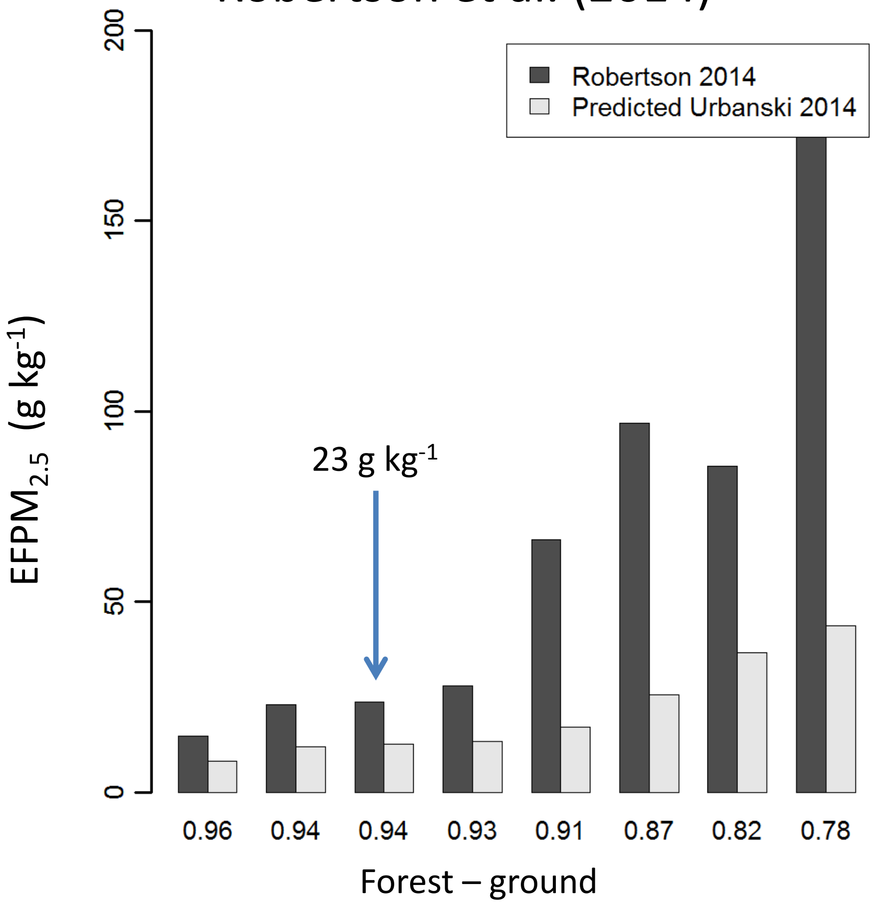




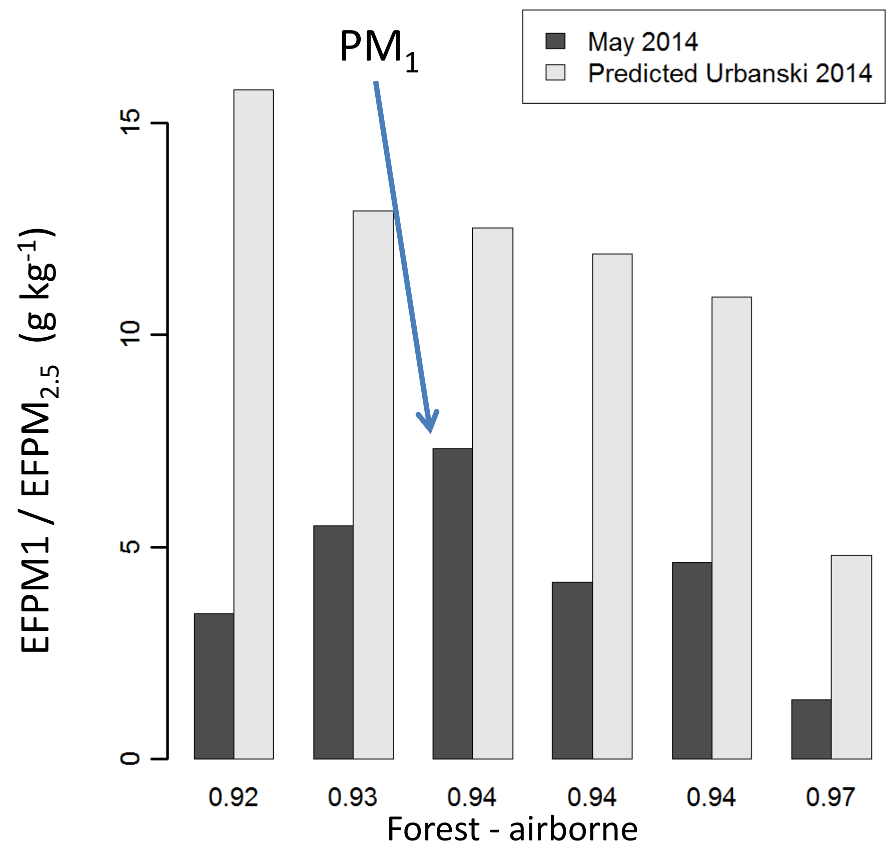
Extrapolated $EFPM_{2.5}$ - Do They Make Sense?

Recent field measurements vs. MCE based predictions
Southeastern broadcast prescribed burns

Robertson et al. (2014)



SCREAM 2011



How to Harmonizing Emission Measurements and Fuel Consumption Simulations?

Flaming

Smoldering

Residual Smoldering