Advancing Sustainable Household Energy Solutions (ASHES)

ASHES seeks to help shift the current household energy paradigm to increasingly efficient and sustainable solutions through collaboration between researchers, academics, and practitioners.

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ASHES Webinar Calendar

19 November 2020: World Health Organization’s Clean Energy Toolkit

14 January 2021: STAR 1 – Cookstove emissions, climate, and health impacts: an integrated lab, field, and modeling study

24 February 2021: STAR 2 – Experimental interventions to facilitate clean cookstove adoption, promote clean indoor air, and mitigate climate change

24 March 2021: STAR 3 – Linking cooking and trash burning to urban air quality in Ghana

27 April 2021: STAR 4 – What do we know (and need to know) about emission factors from biomass burning

20 May 2021: STAR 5

TBD June 2021: GRAPHS/CHAP

TBD July 2021: STAR 6

TBD – What would you like to hear about next? Let us know in the post webinar survey!

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ASHES Science to Achieve Results (STAR) Webinar Series Presents:

What do we know (and need to know) about emission factors from biomass burning?

There is no audio for this slide. The webinar will begin shortly.

Meet our Presenters:

Tami Bond is the Walter Scott, Jr. Presidential Chair in Energy, Environment and Health at Colorado State University.
Tami.Bond@colostate.edu

Cheryl Weyant is a postdoctoral scholar at the University of Michigan in the School for Environment and Sustainability.
chewey@umich.edu

Mariam Fawaz is a graduate student in Civil and Environmental Engineering at the University of Illinois Urbana-Champaign.
mfawaz2@Illinois.edu

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Household Air Pollution: A Global Concern

Exposure to household air pollution is a top-ten risk factor for morbidity and mortality and a leading contributor to the global burden of disease. Access to modern energy has been proposed as a basic human right, yet 3 billion people still rely on traditional energy sources to support household needs like cooking, heating, and lighting. Emissions from traditional energy sources create unhealthy levels of household air pollution and contribute to the earth's radiative energy balance; over the next century, unhealthy levels of air pollution are expected to inflict a major toll on human health.

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There is no audio for this slide. The webinar will begin shortly.

ASHES Webinar Etiquette

During the webinar you will have the opportunity to ask questions and interact with presenters. We encourage wide-ranging discussion and expect civil dialogue. We will answer as many questions, that are appropriate for the presenters, as we can in the given time. When applicable we may combine or rephrase them. Thanks for your cooperation.

There is no audio for this slide. The webinar will begin shortly.

Opening Remarks

Image shared by Michael Johnson

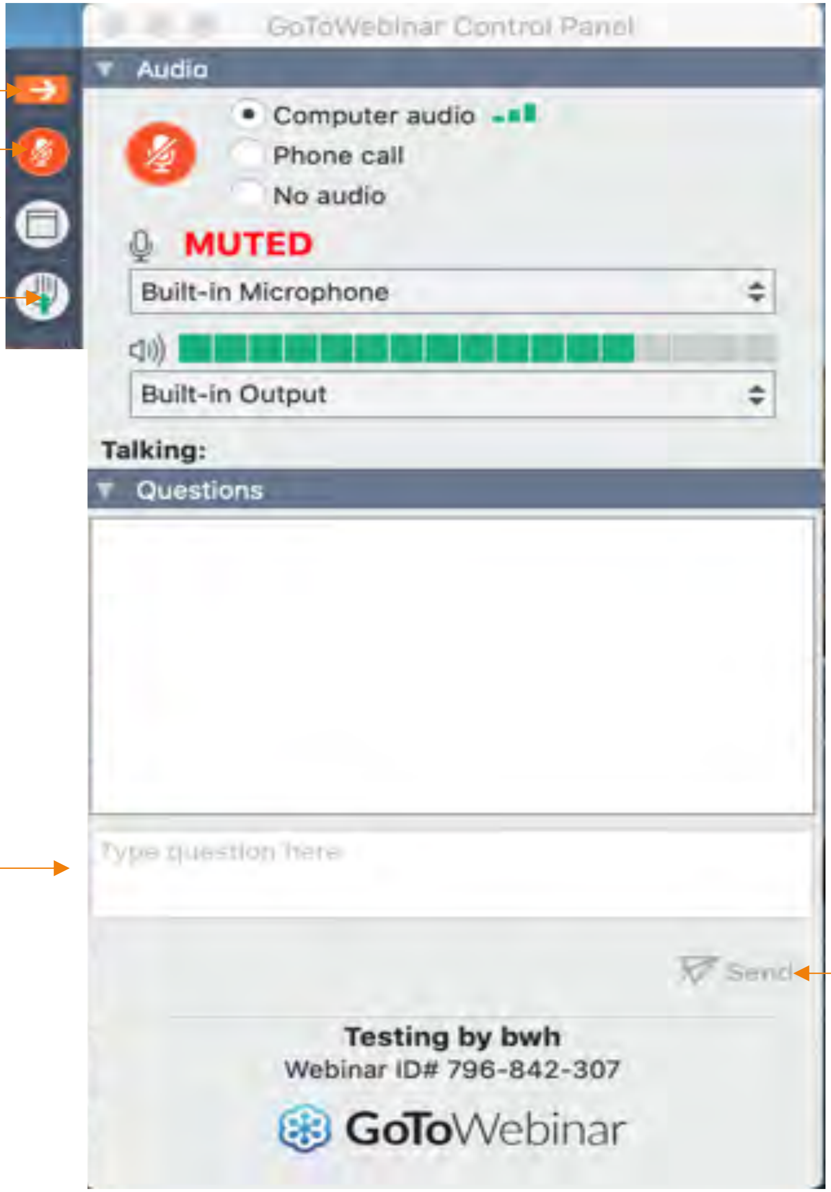
Webinar Control Panel

Minimize and maximize control panel

Listen only mode

Minimize and maximize screen

Not using this function



Type your questions here

Submit your questions by clicking ‘Send’

Science To Achieve Results (STAR) Extramural Research Grants

Measurements and Modeling for Quantifying Air Quality and Climatic Impacts of Residential Biomass or Coal Combustion for Cooking, Heating, and Lighting

- How would a feasible set of interventions for residential cooking, heating, or lighting in a developing part of the world impact air quality and climate?
- What is the realistic range and timeframe of foreseeable benefits to air quality and climate of various interventions in cooking, heating, or lighting practices in a developing part of the world, considering regional constraints (e.g., acceptability and availability of different technologies or fuels) and sustainability of alternate fuels or technologies?

RFA Published 2012, Projects Funded 2013/4 – 2018/9, Webinar 9/22/2020
Link to additional information, webinar recording, and publications list:
https://www.epa.gov/air-research/household-energy-and-clean-cookstove-research
Terry Keating, EPA Project Officer, keating.terry@epa.gov

Science To Achieve Results (STAR) Extramural Research Grants

6 teams

8 countries

13 field locations

>70 Publications

Technology
Fuel Availability
Costs
Preferences
→ Stove Use → Emissions

Emissions → Indoor Air & Personal Exposure → Health Impacts

Emissions → Ambient Air → Climate Impacts

Indoor Air & Personal Exposure ↔ Ambient Air

Ambient Air → Health Impacts

Science To Achieve Results (STAR) Extramural Research Grants

- Quantifying the Benefits of Improved Cookstoves:
  An Integrated Lab, Field, and Modeling Study
  John Volckens, Colorado State University

- Experimental Stove Interventions in Northern and Southern India
  Rob Bailis, Yale Univ/Stockholm Environment Institute

- Impacts of Cooking & Lighting Emissions in the African Sahel
  Michael Hannigan, Univ of Colorado, Boulder

- Health Impacts of Household Energy Intervention in Tibet
  Jill Baumgartner, Univ of Minnesota/McGill University

- Household Sources of Primary and Secondary PM in Northern India
  Kirk Smith, UC Berkeley; Ajay Pillarisetti, Emory University

- Mapping Feasible Residential Solutions for Cooking and Heating
  Tami Bond, Univ of Illinois/Colorado State University

Other participants

Field Measurement

University of Illinois: Nick Lam (now@Humboldt State), Paul Francisco, Zach Merrin, Emily Floess (now@ NC State), Ryan Thompson (now Mountain Air principal, Fangxing Liu, Sital Uprety

CRT/Nepal: Basudev Uphadyay, Shovana Maharjan, Ashma Vaidya, Ganesh Ram Shrestha

Beijing Univ of Chemical Technology: Chunyu Xue, Guangqing Liu, Bai Yun, Yafei Liu, Jasmine

Institute of Tibetan Plateau Research: Pengfei Chen, Chaoliu Li, Qianggong Zhang

McGill University: Jill Baumgartner, Ellison Carter (now@Colorado State)

Tlingit-Haida Regional Housing Authority : Craig Moore, Hank Copsey

Mapping and Modeling

University of Illinois: : Nick Lam, Lama Aoudi, Bora Ozaltun, Li Xu, Ekbordin Winijkul (now@ Asian Inst of Technology)

UC Irvine: Rufus Edwards; UC Riverside: Marko Princevac, Masoud Ghasemian

IIT Mumbai: Chandra Venkataraman

U of Leeds: Luke Conibear, Ed Butt, Dominic Spracklen

Other funding:
US NSF supported emission factor measurements 2004-2007, and supports Mariam's work now.
ClimateWorks supported emission measurements in Nepal 2010-2012.

What do we know (and need to know) about emission factors from biomass burning?

Tami Bond
Cheryl Weyant
Mariam Fawaz

ASHES
April 27, 2021

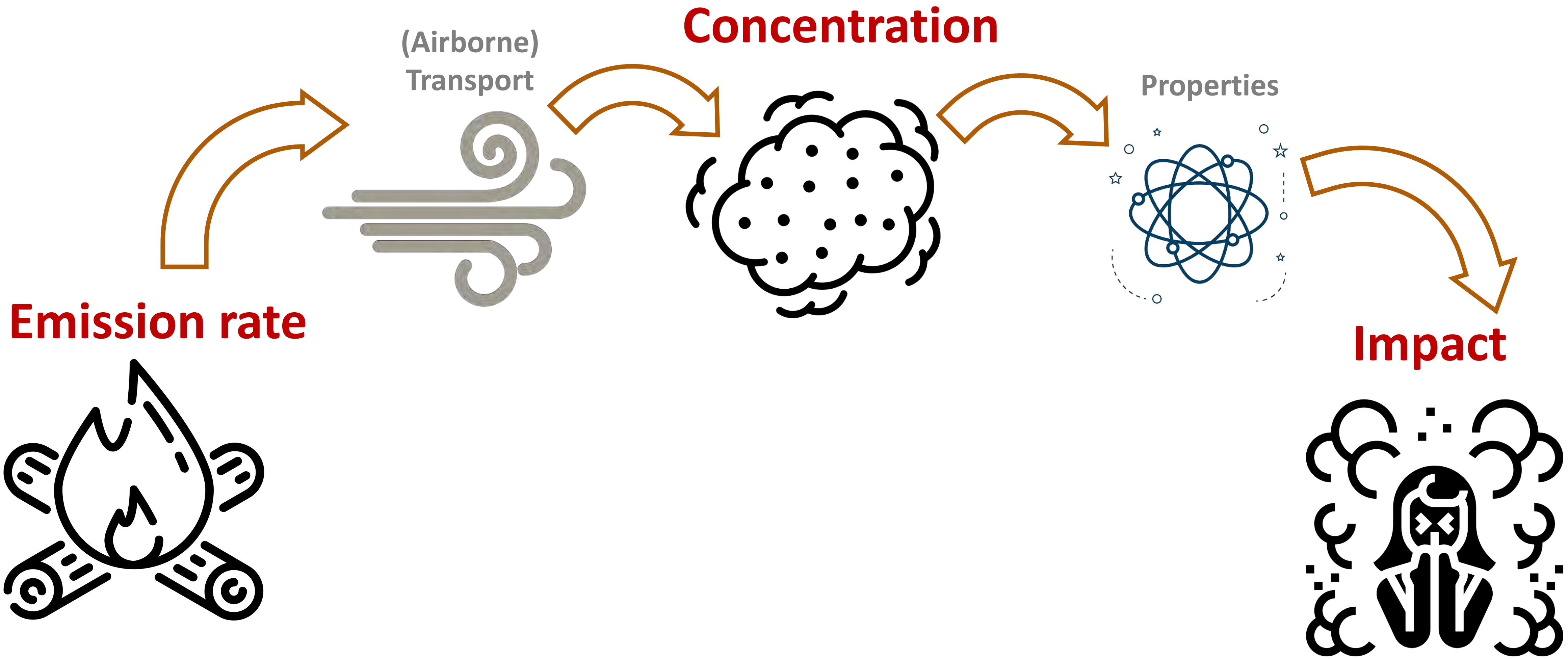
Biomass storage in Nepal.
Some stacks are fuel for fires; some are animal feed; some are both.

All B&W icons from The Noun Project, except as noted.

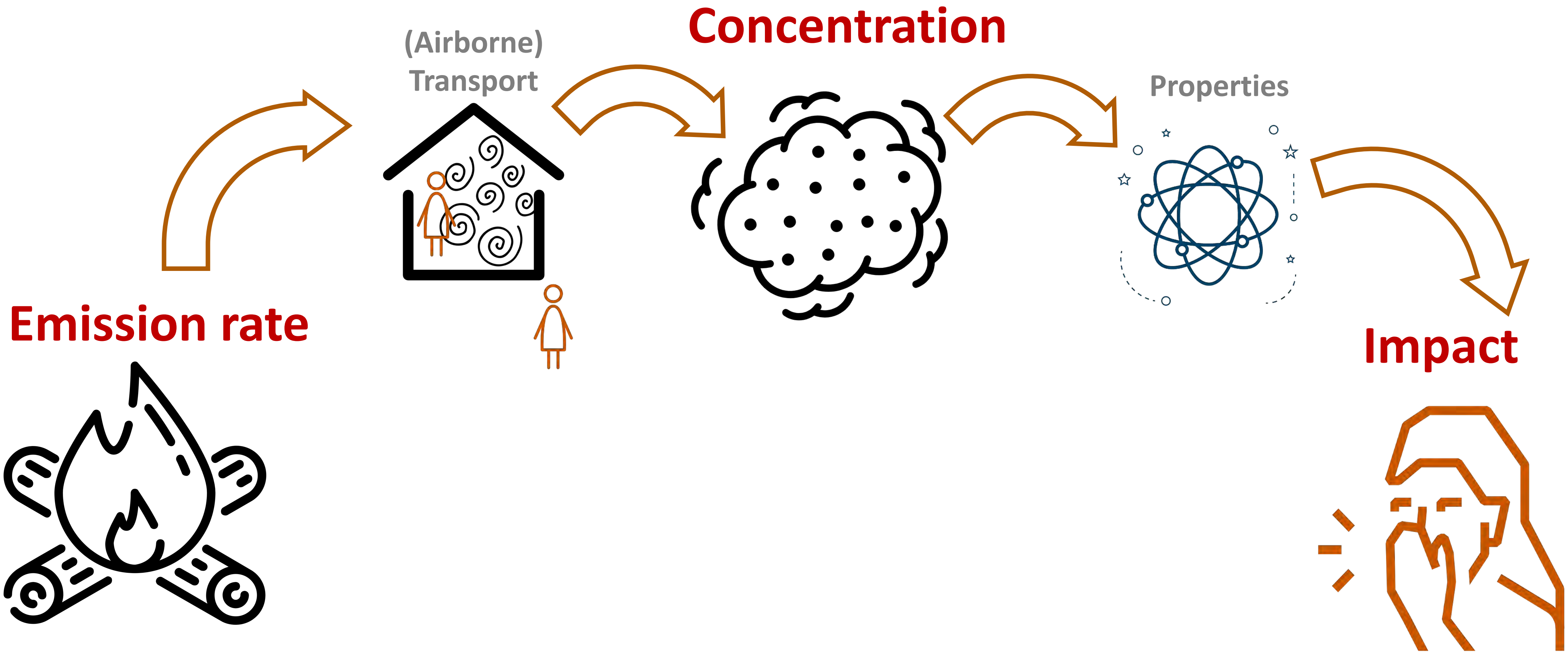
Course of Discussion

1. What matters for determining impact? (Tami)
2. EPA STAR project overview (Tami)
    - A few other activities
    - Emission factors: What we knew, what we were seeking
3. Field-measured emission factors (Cheryl)
4. Do we know emission rates yet? (Tami)
5. Pyrolysis principles to explain emissions (Mariam)
6. Summary (Tami)

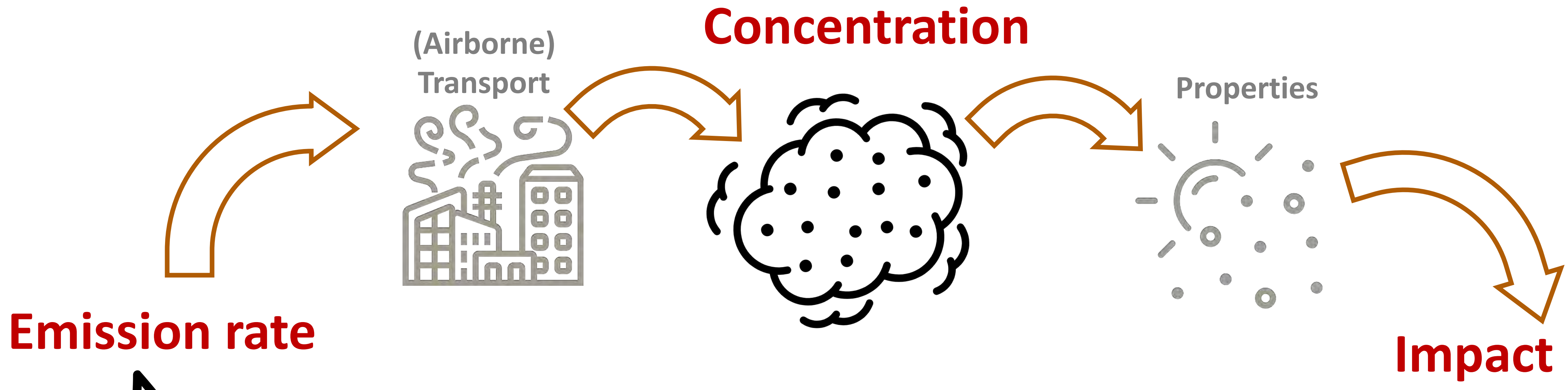
How are impacts estimated?

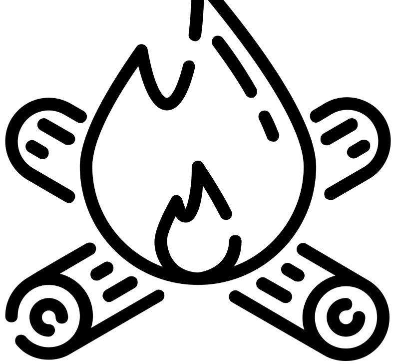


How are health effects estimated?



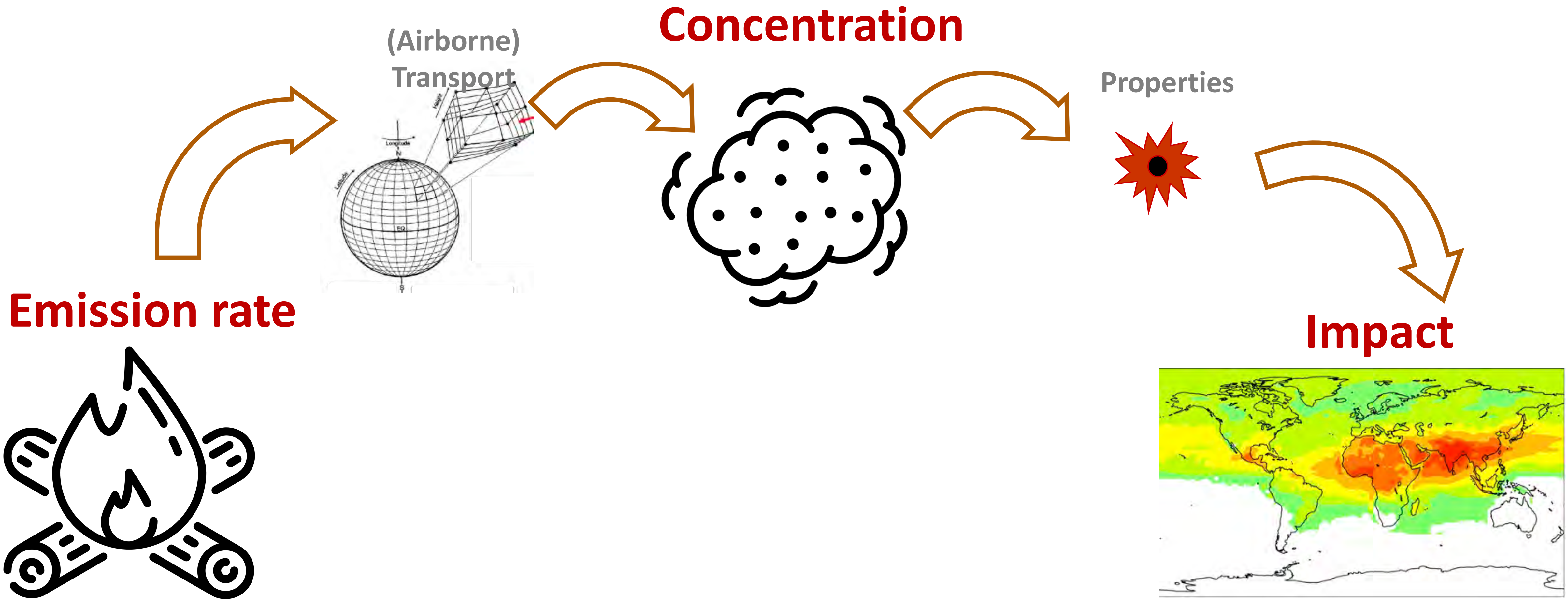
How is regional air quality impact estimated?





Donora smog in Pittsburgh, 1948
Image: NOAA OceanService Education

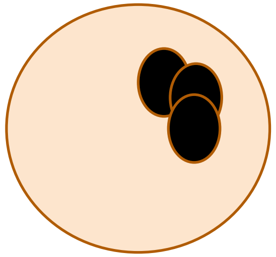
How is climate impact estimated?



Climate forcing by kerosene lamps
(Lam et al., ES&T, 2012)

Global grid image: D. Jacob

Chemical composition of particles is one of the important properties.



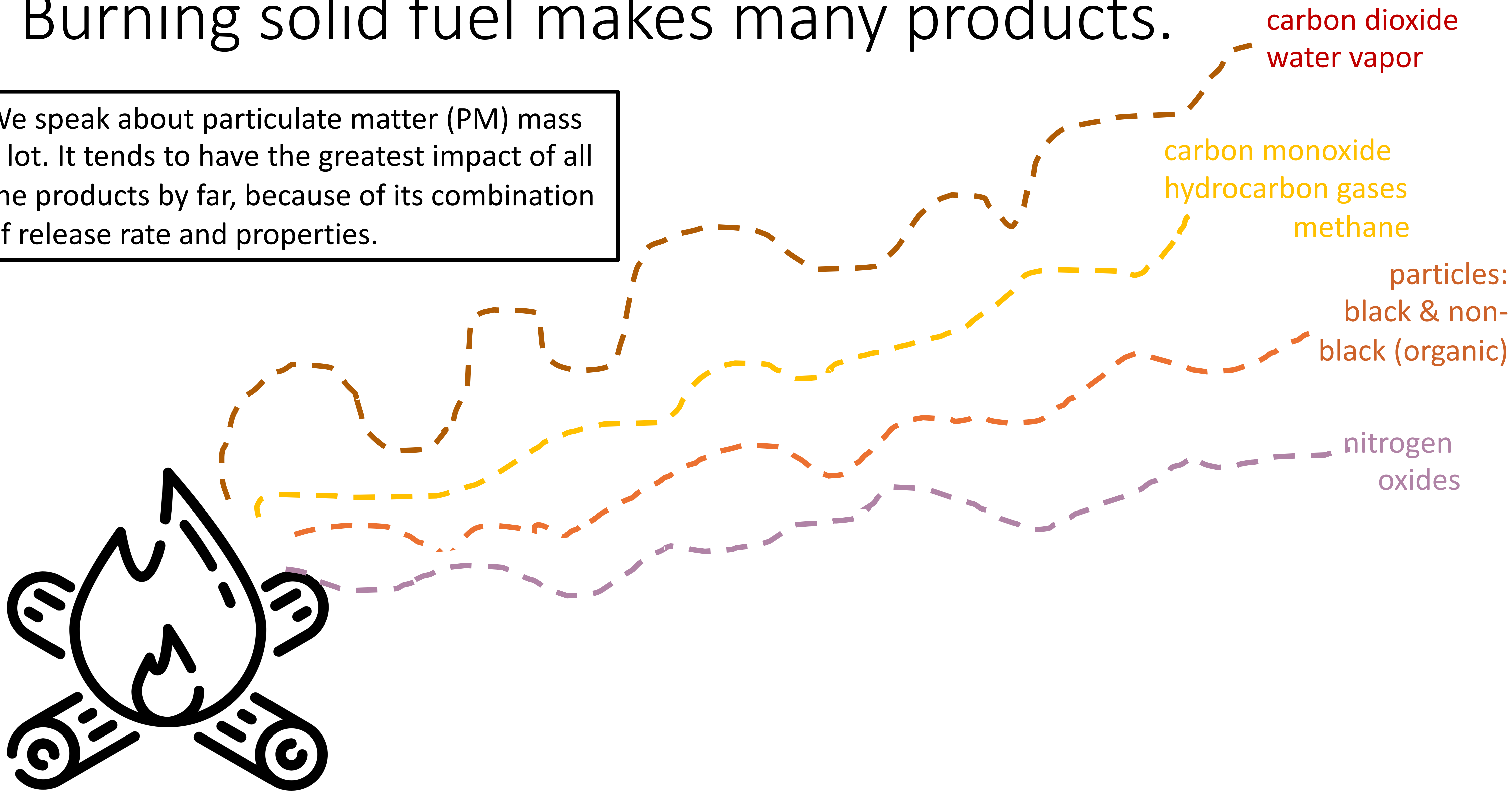
Particulate matter
from wood burning =
black or elemental carbon (a bit)
+ organic carbon (lots more)
+ a tiny bit of other stuff

1 gram *absorbs* as much sunlight as ~10 black umbrellas
Absorption makes the Earth hotter

1 gram *reflects* as much sunlight as ~3 white umbrellas
Reflection makes the Earth cooler
(but organic carbon from wood burning absorbs some light, and may be closer to neutral)

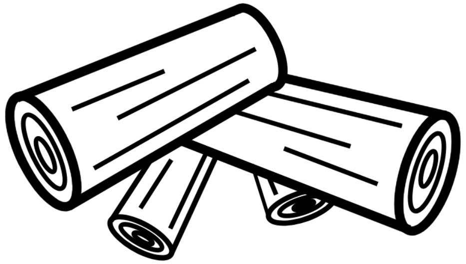
Burning solid fuel makes many products.

We speak about particulate matter (PM) mass a lot. It tends to have the greatest impact of all the products by far, because of its combination of release rate and properties.

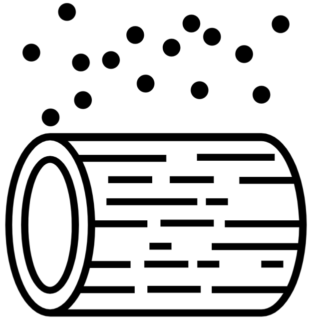


Emission rate is key; how is it estimated?

Emission rate (gram/second) = Fuel consumption (kilogram/second) × Emission factor (gram pollutant/kilogram fuel)



Few real reports –
Kitchen Performance Test
measures over 24 hours

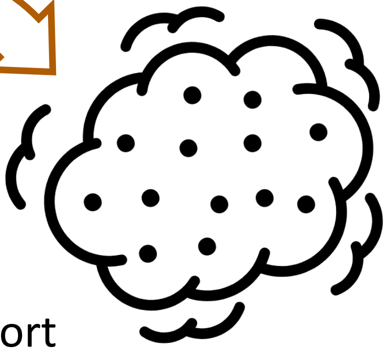


Measured in field with
carbon balance
method

Emission factor vs concentration

(Airborne)
Transport

Concentration



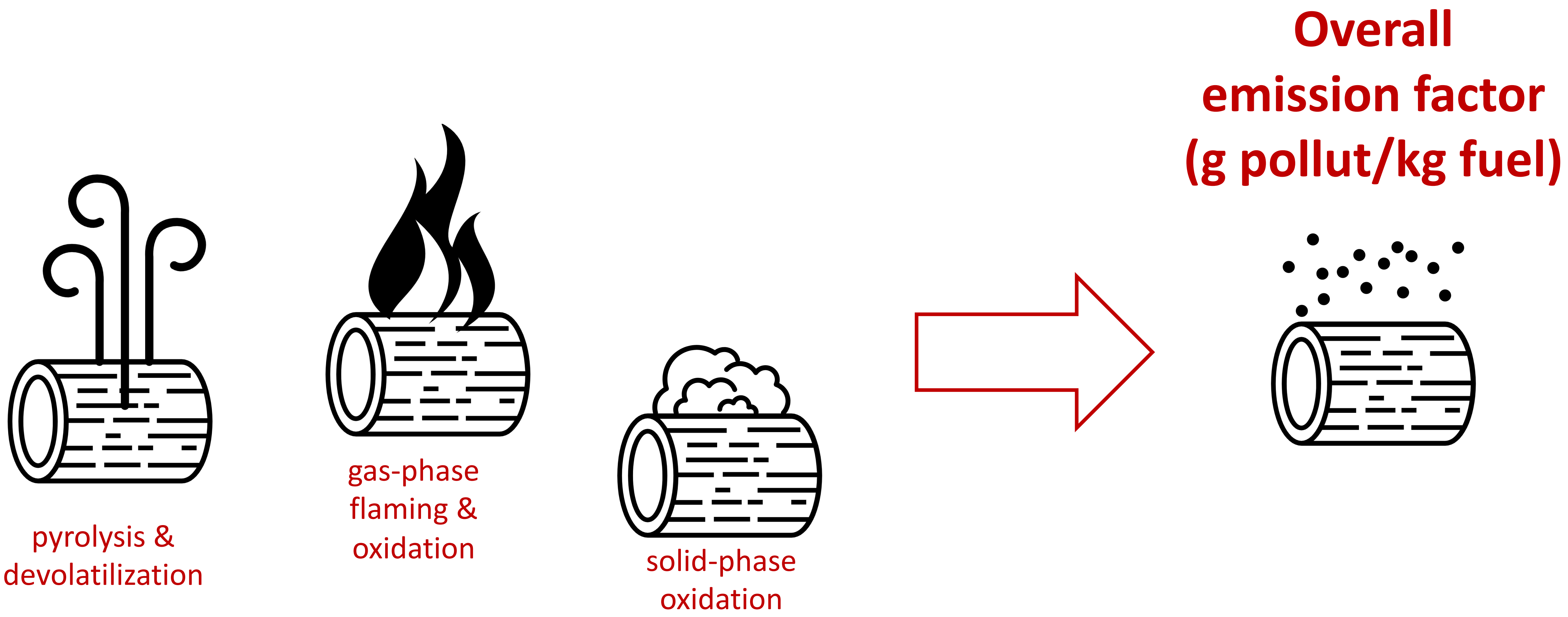
Concentration represents ONLY the location and time where it is measured.

Affected by transport including dilution

Emission rate

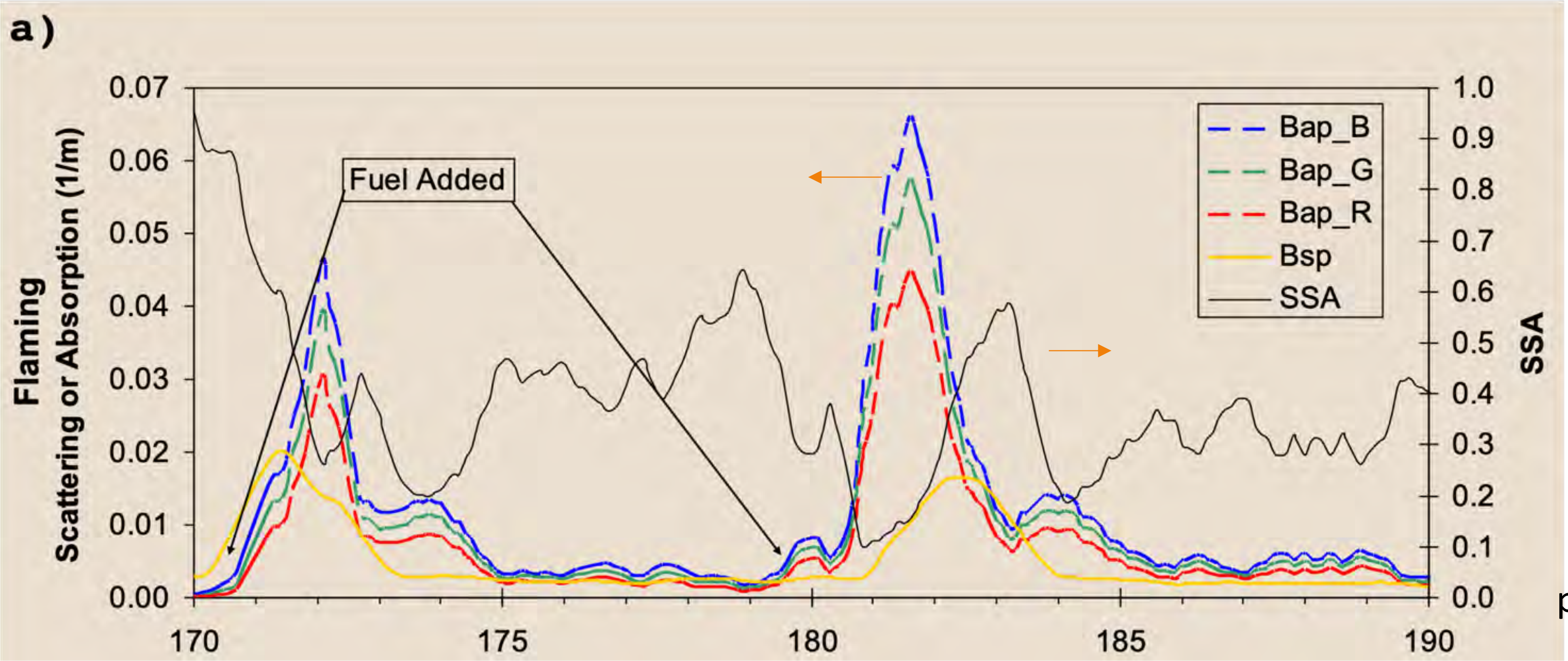
Need emission factors to get emission rates for models of impact.

“Combustion” includes many processes.



g/sec pollutant emitted ÷
g/sec wood burned

Emission rates & emission factors vary during the course of combustion (and cooking)



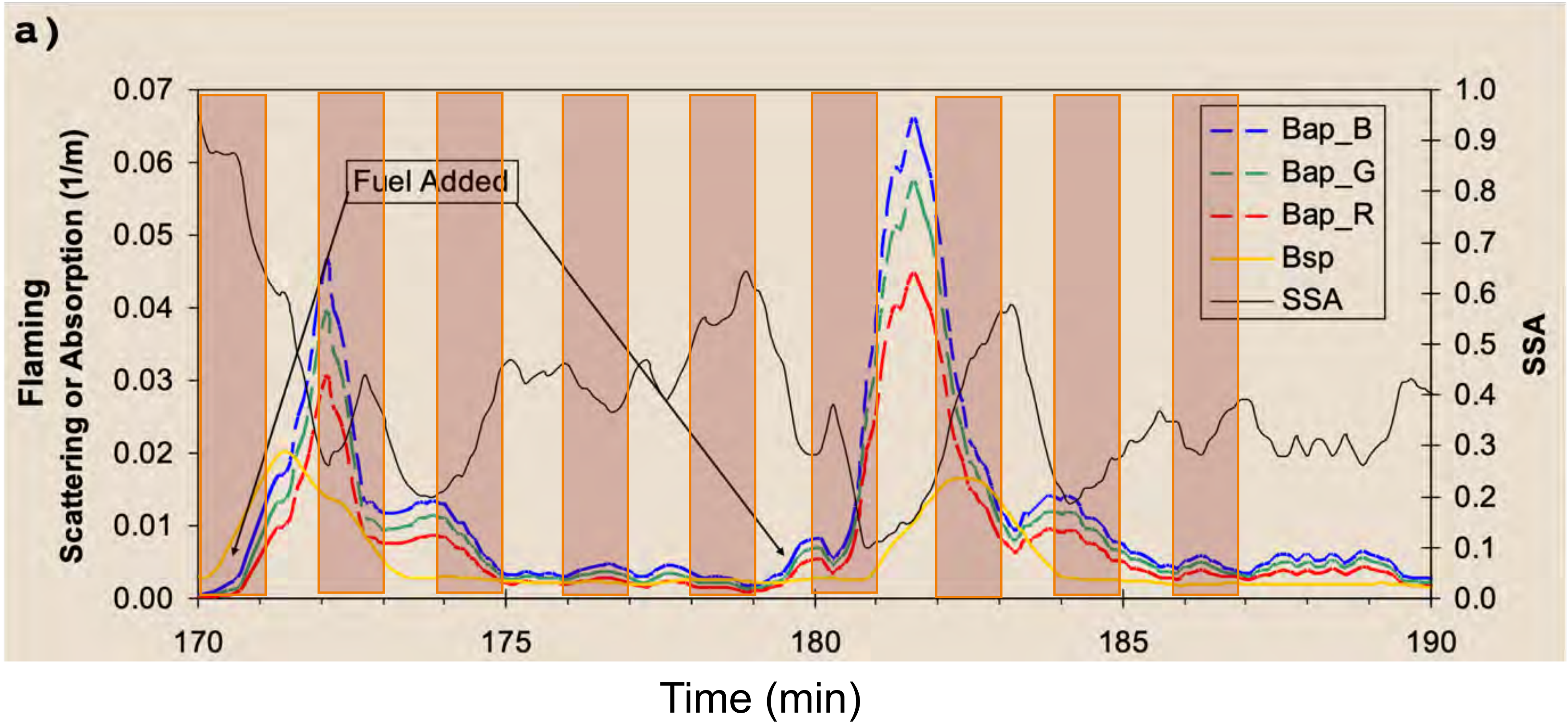
no absorption

perfectly absorbing

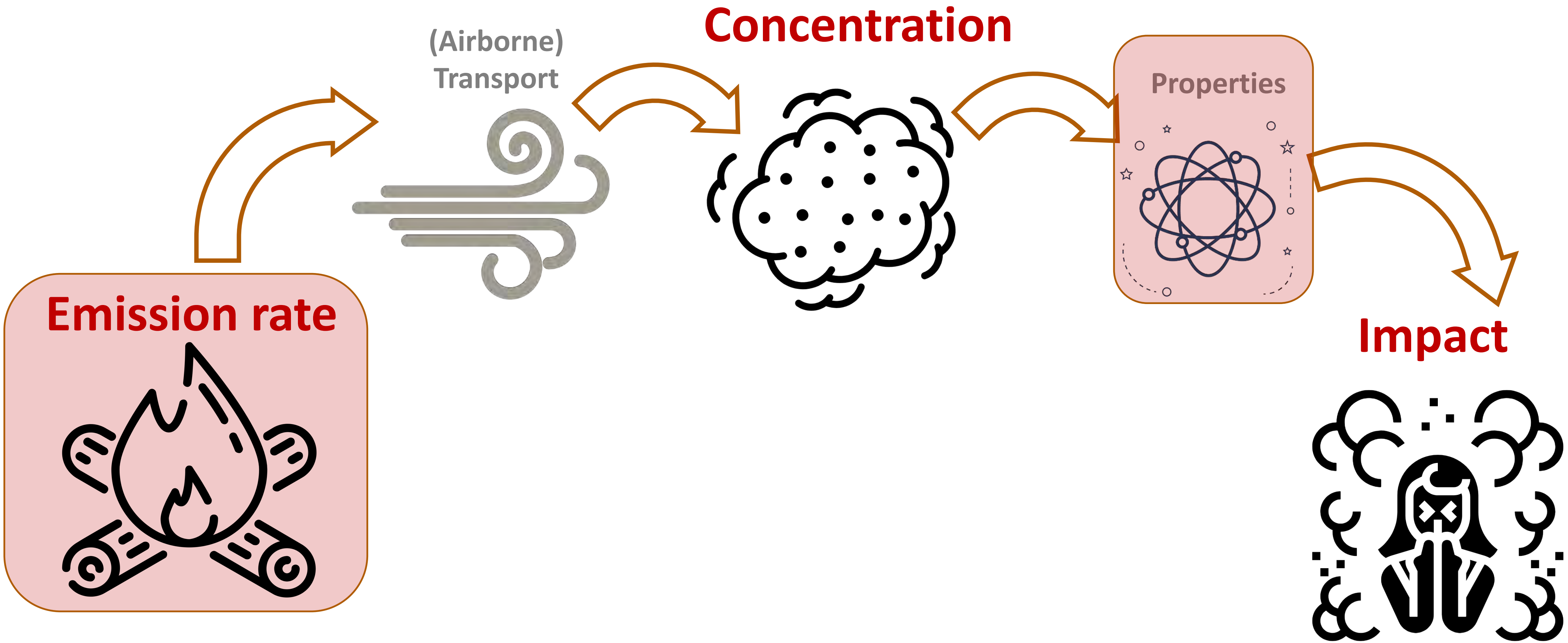
Bap and Bsp are absorption (black particles) & scattering (all particles), respectively.

Roden et al., *Environmental Science and Technology 40, 6750,* 2006

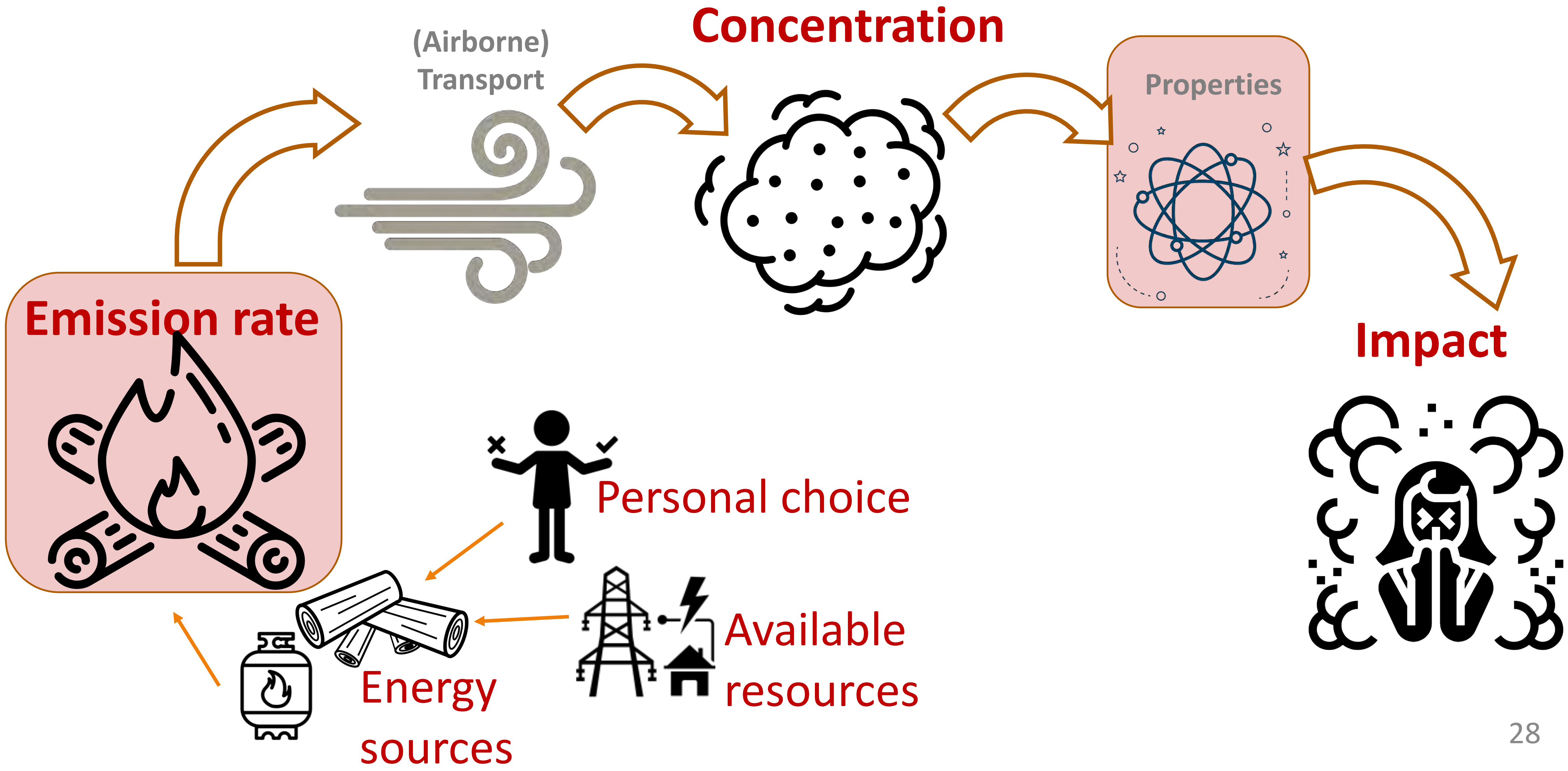
We treat each minute as a separate "event" to examine how frequently different modes appear.



Project goals: Improving a few of the pieces



Project goals: Improving a few of the pieces



Household energy and its transitions are part of a complex system.

Emission factor work was done under 3 grants

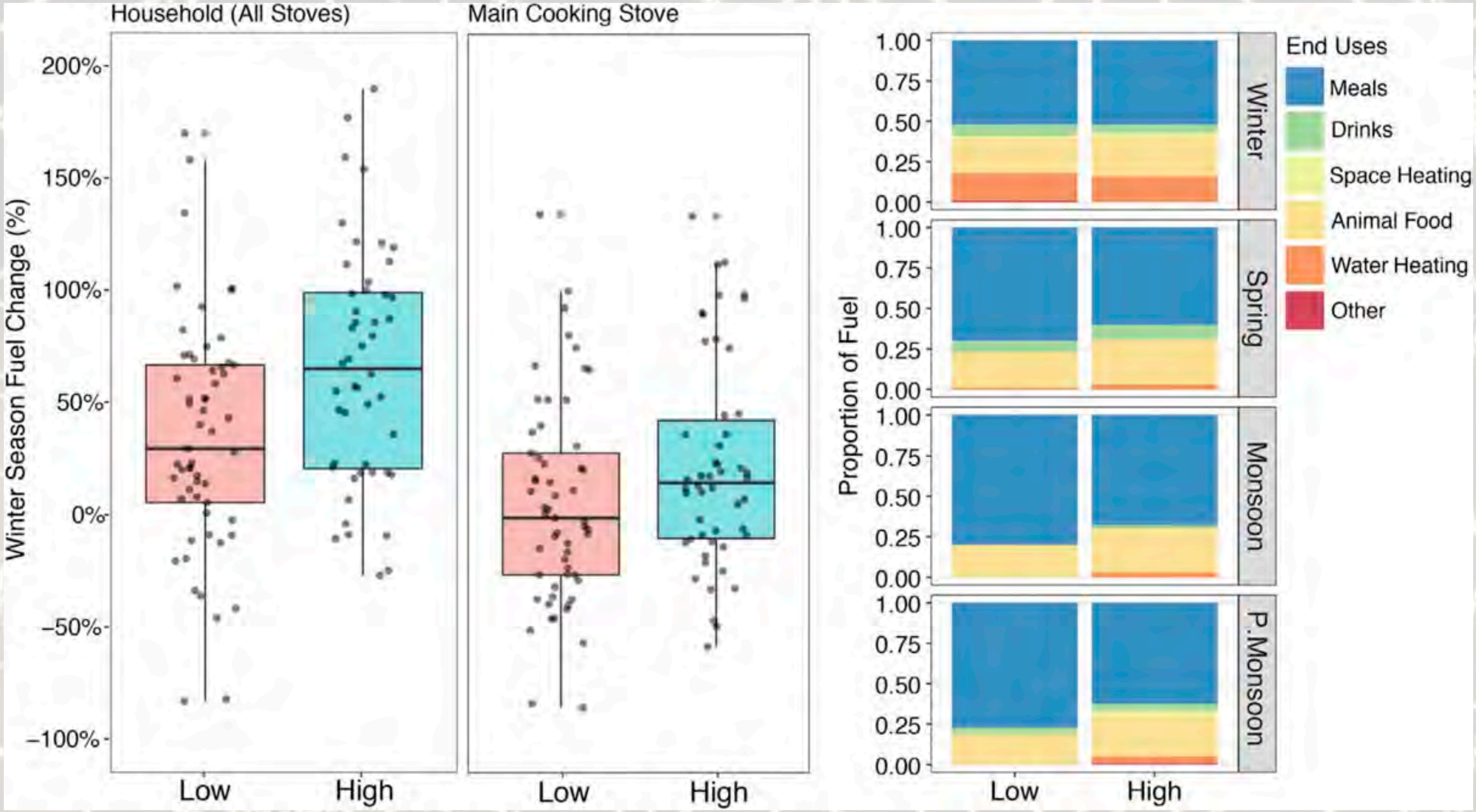
“Global Map of Feasible Stove Solutions”
Principal investigator T. Bond, then U of Illinois

“Small, Variable Emission Sources”
(under Black Carbon grants)
Principal investigator R. Edwards, UC Irvine

“Impact of Household Sources on Outdoor Pollution”
Principal investigator K. Smith, UC Berkeley

Household energy and its transitions are part of a complex system. Other work included…

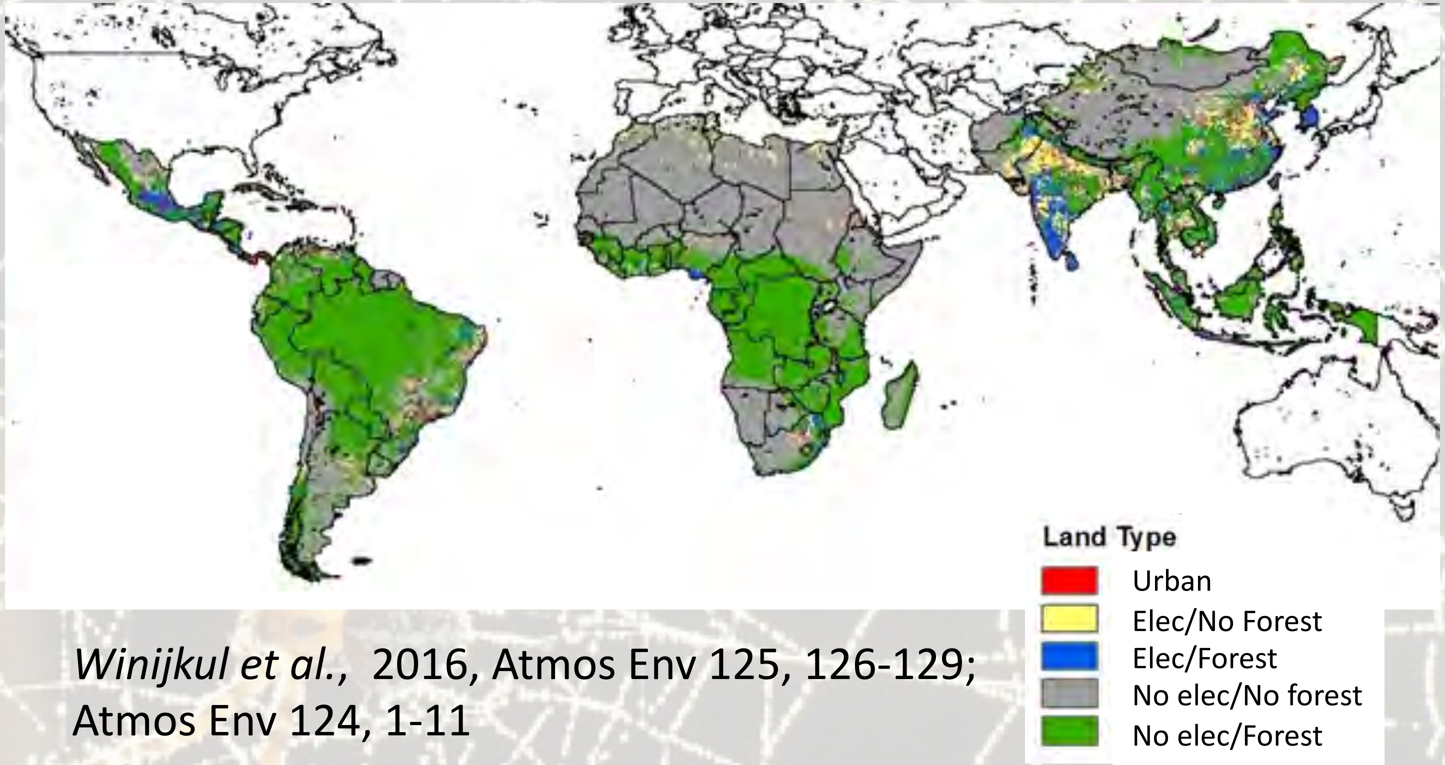
Observations of daily fuel consumption and emissions during 4 seasons in Far West of Nepal



Lam et al., 2017, Environmental Research Letters 12, 125011, 2017

Household energy and its transitions are part of a complex system. Other work included…

Quantifying spatial limitations that affect choice of energy sources



Winijkul et al., 2016, Atmos Env 125, 126-129; Atmos Env 124, 1-11

Household energy and its transitions are part of a complex system. Other work included…

Developing emission measurements and lab capabilities outside academia

(Cheryl Weyant
& Ryan Thompson)

RTKC at CRT/Nepal in Kathmandu

Now, back to emission factors!

Also not shown: Winter emission measurements in 2 provinces in China, and Alaska USA.

What are typical PM emission factors from other combustion devices?

Units are g pollutant per kg of fuel

10 g/kg = 1% of the fuel mass has turned into airborne particles

1 g/kg = 0.1% of the fuel mass has turned into airborne particles

Gasoline car	
Typical	<0.05
Superemitter	2-3
Diesel truck	
Early 1990s USA	1-2
Modern emission controls	<0.2
Superemitter	8-12
Coal power plant	
No emission controls	10-30
Modern emission controls	<0.1

Evolution of emission measurement

2004

2009

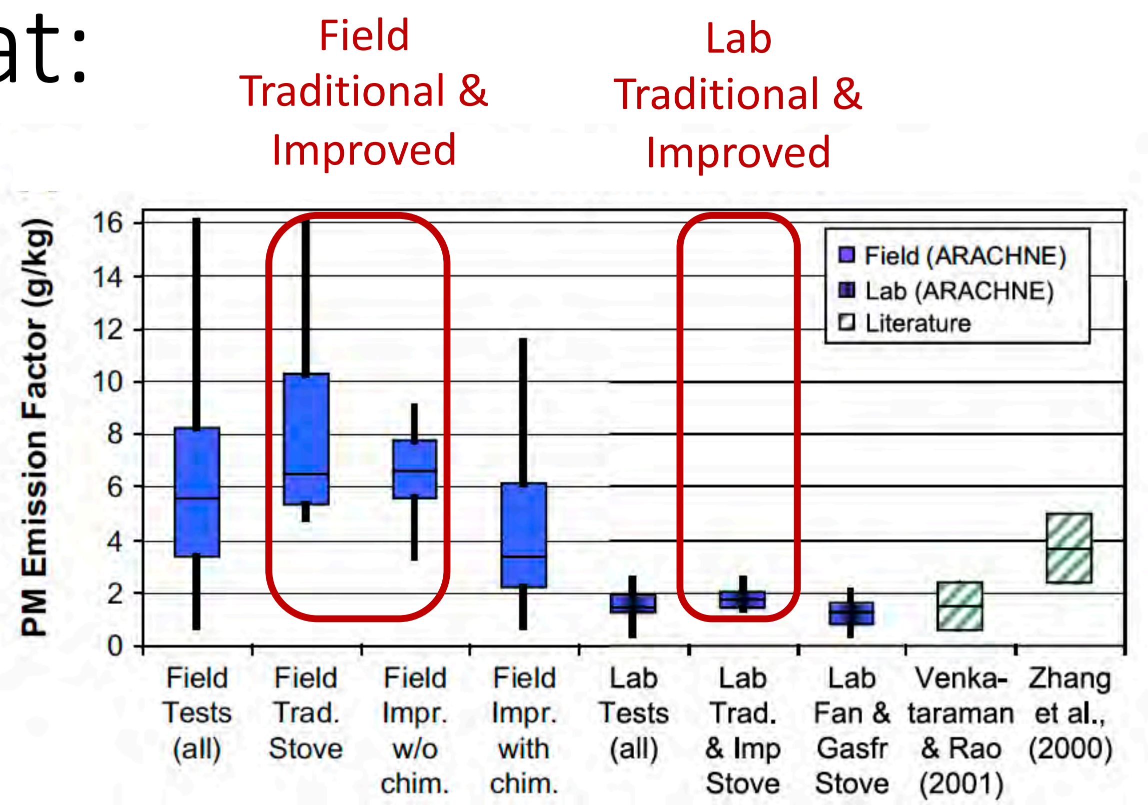
2010

2012

2013

We had already seen that:

- **Field performance is not like lab performance**, especially for particulate matter (PM)
  (& relationship isn't simple multiplication)
- Carbon monoxide (CO) & PM have **correlation** but not predictive ability
- **Space heating*** emission factors are not like cooking emission factors
- Better combustion makes **fewer but blacker particles** by burning out organic carbon

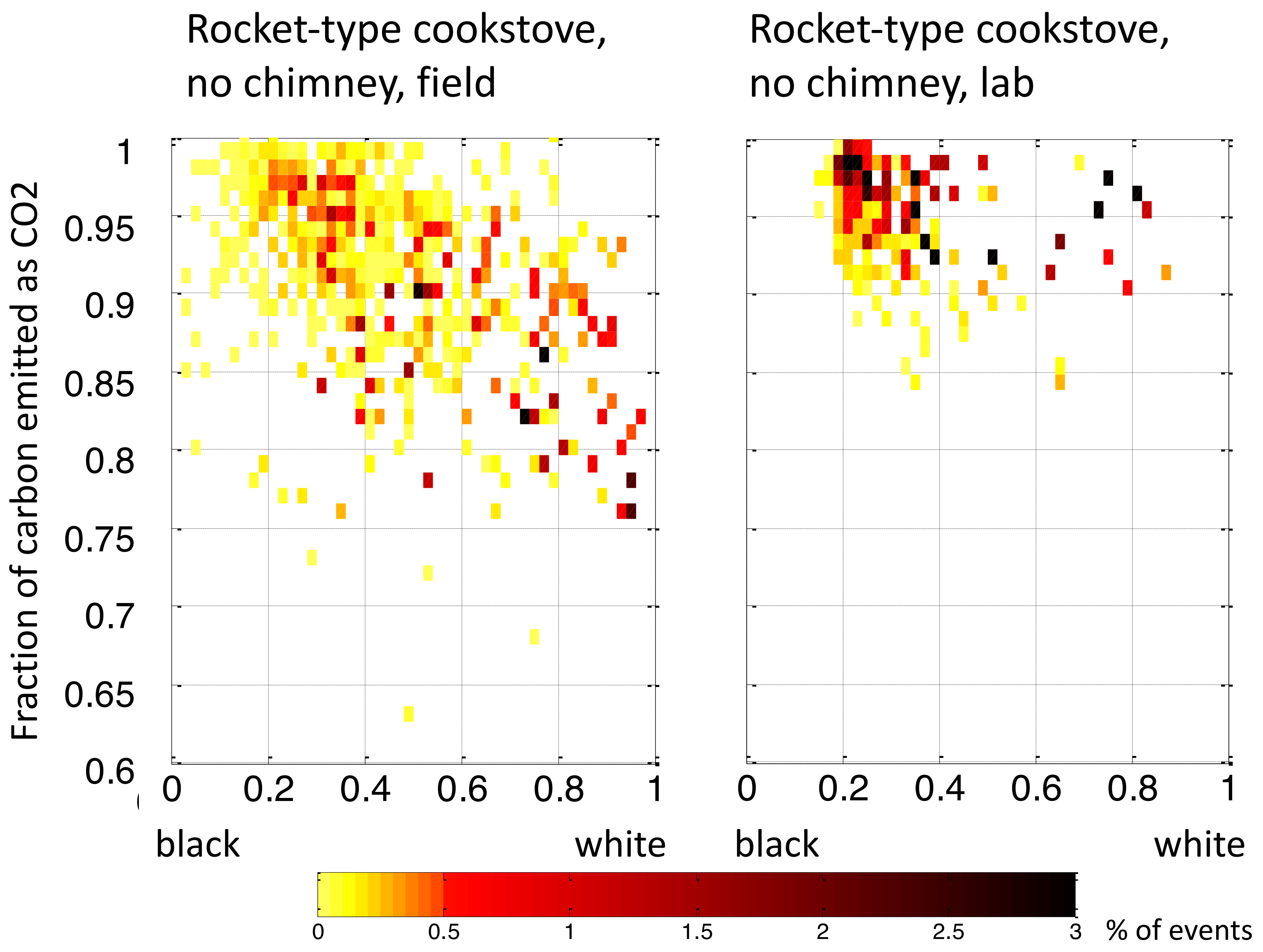


Roden et al., Atmos Env. 43, 1170-1181, 2009

* mainly from U.S/Europe measurements

Event analysis shows why lab & field differ.

Lab has more time in high-efficiency mode that makes black particles



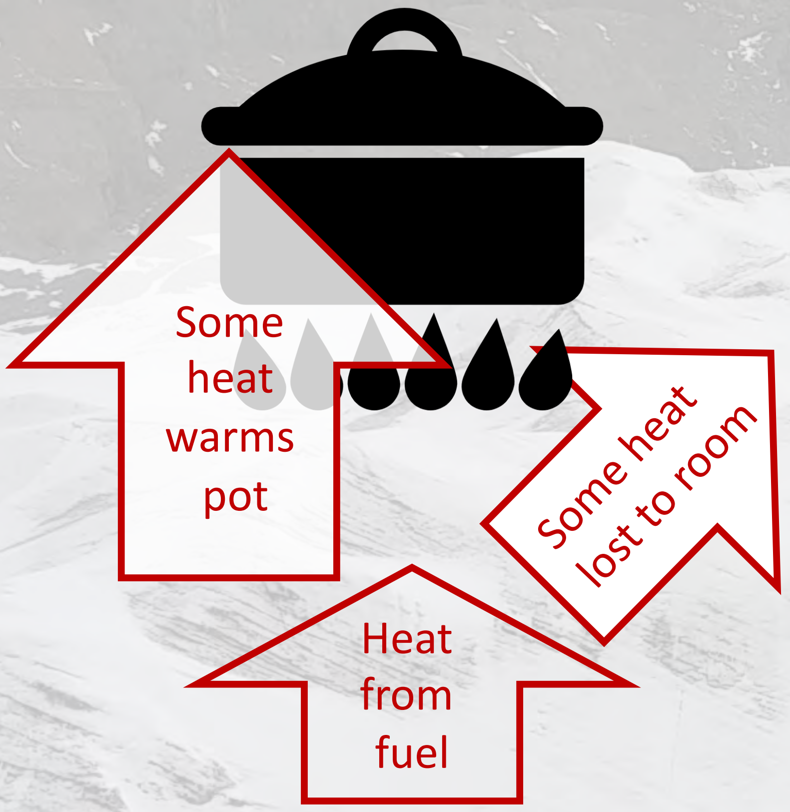
Chen et al., Env. Sci. Tech 46, 6110-6117, 2012

We didn't know whether:

- Emission factors would have **regional differences** (fuels, stoves, etc)
- **Space-heating & cooking** emission factors would differ in regions that had both uses
- Space heating **energy needs** would dominate household choice of device

Photo credit:
Accesscrawl, CC BY-SA 4.0, via Wikimedia Commons

We focused on cold regions because…



$$\text{Efficiency} = \frac{\text{Heat into pot}}{\text{Heat from fuel}}$$

1. People may not be motivated by efficiency if they have other uses for the heat.

We focused on cold regions because…

2. Homes are more likely closed in winter – may cause higher exposures.

We focused on cold regions because…

3. They are near ice and snow fields, where black carbon may have greater warming.

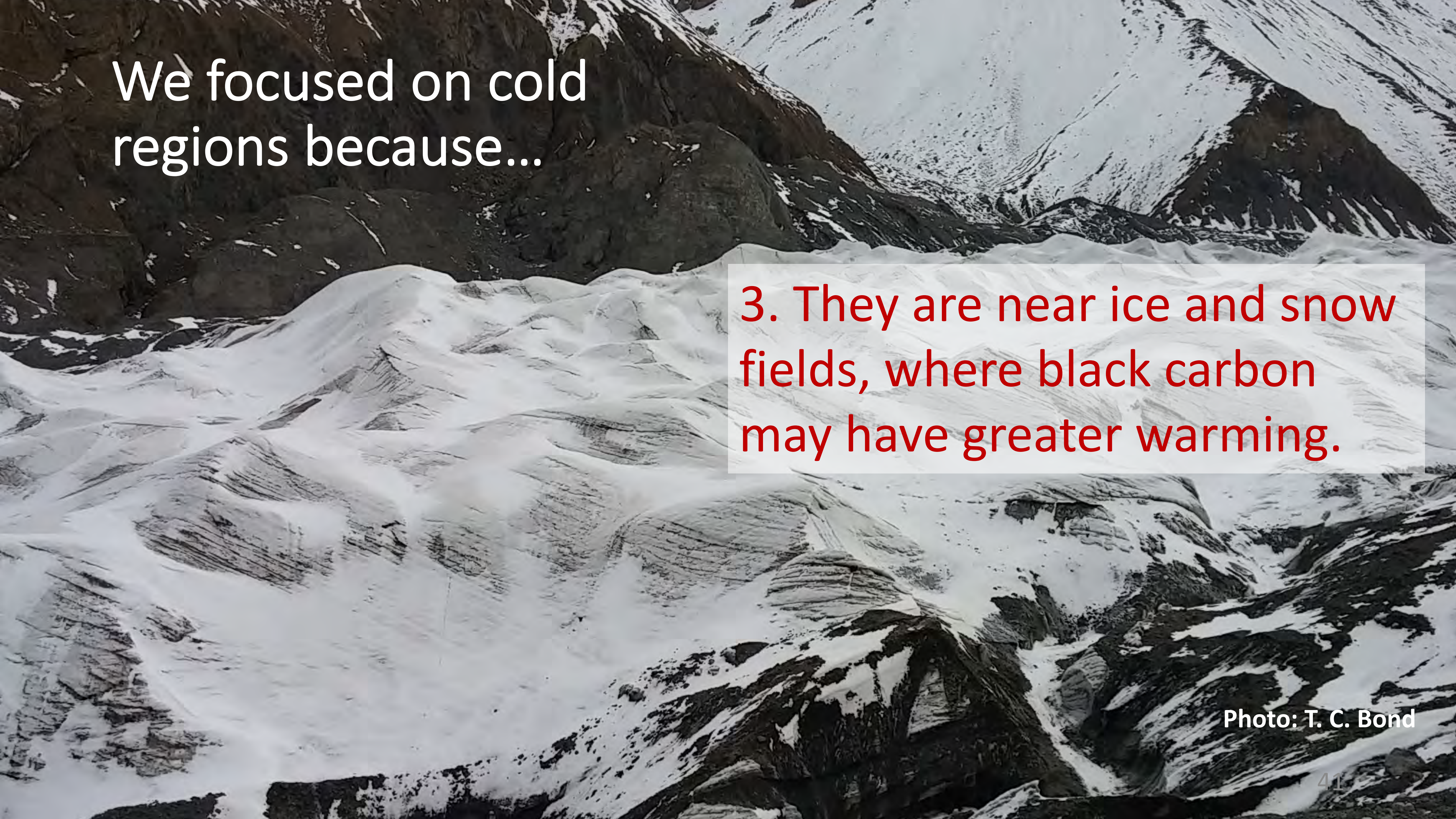
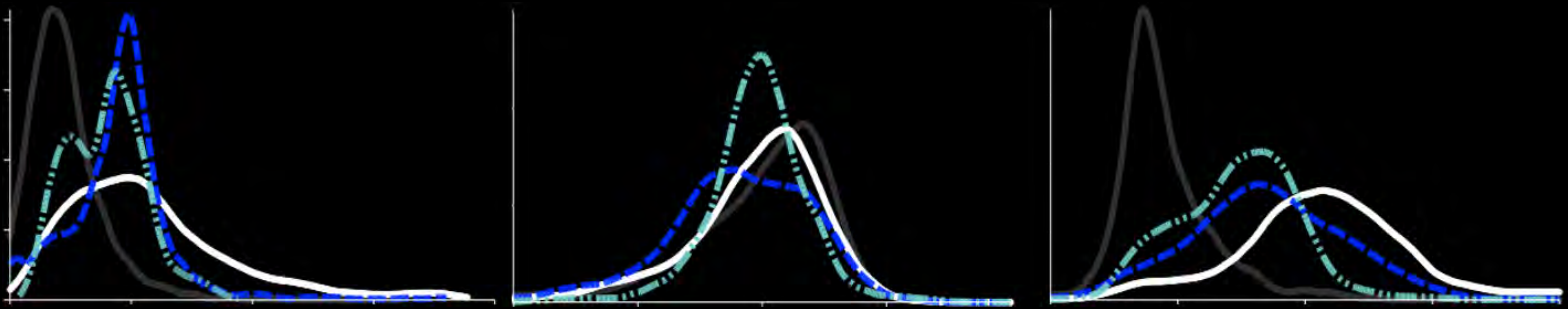


Photo: T. C. Bond

Cheryl Weyant: "Dr. Field Emission"

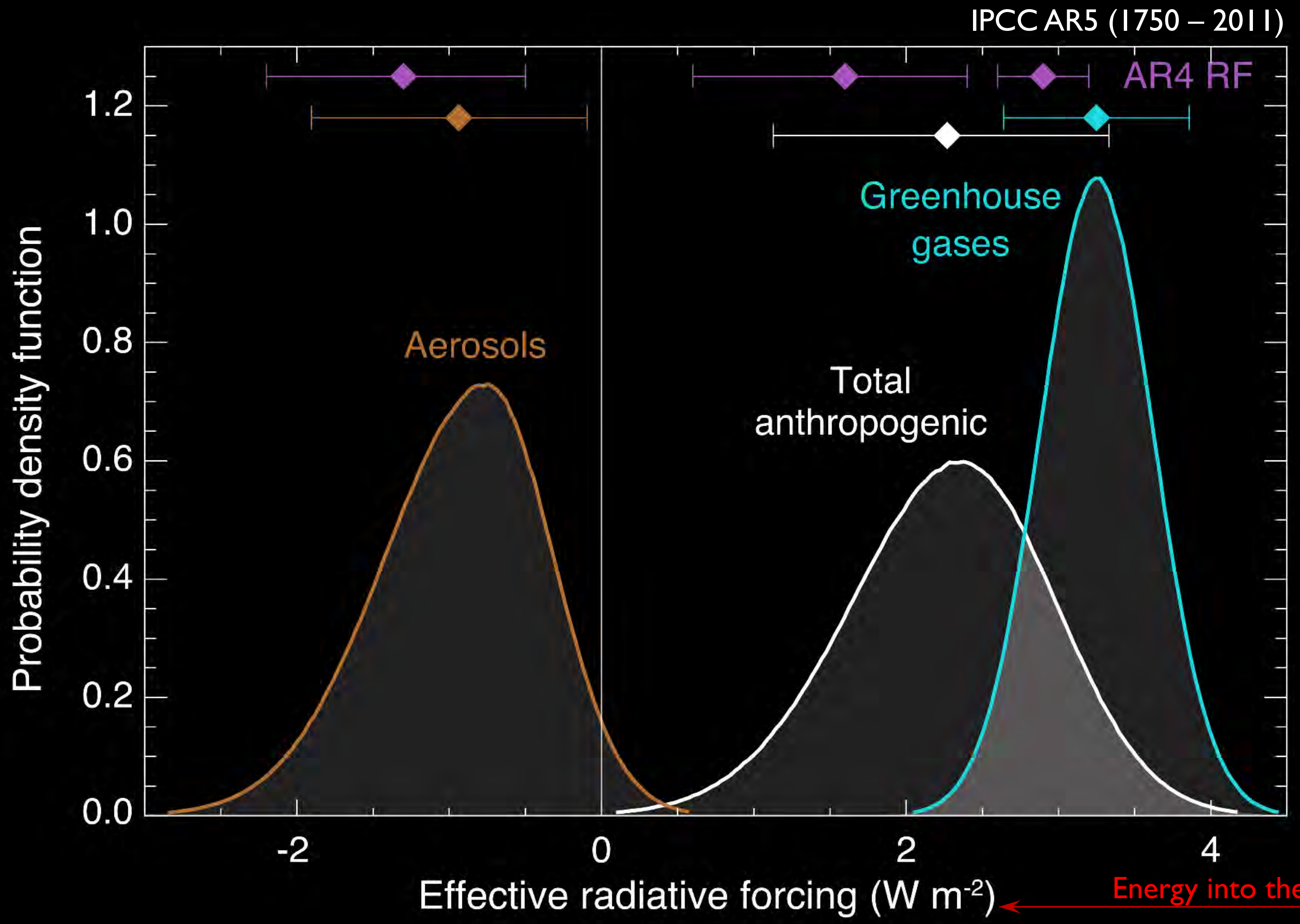
Fun fact: Cheryl has measured emissions from brick kilns, biogas stoves, gas flares, and kerosene lamps in addition to the dozens of stoves you'll see here.



FIELD MEASUREMENTS FROM TRADITIONAL BIOMASS STOVES

Cheryl Weyant
chewey@umich.edu
ASHES 4/27/2021

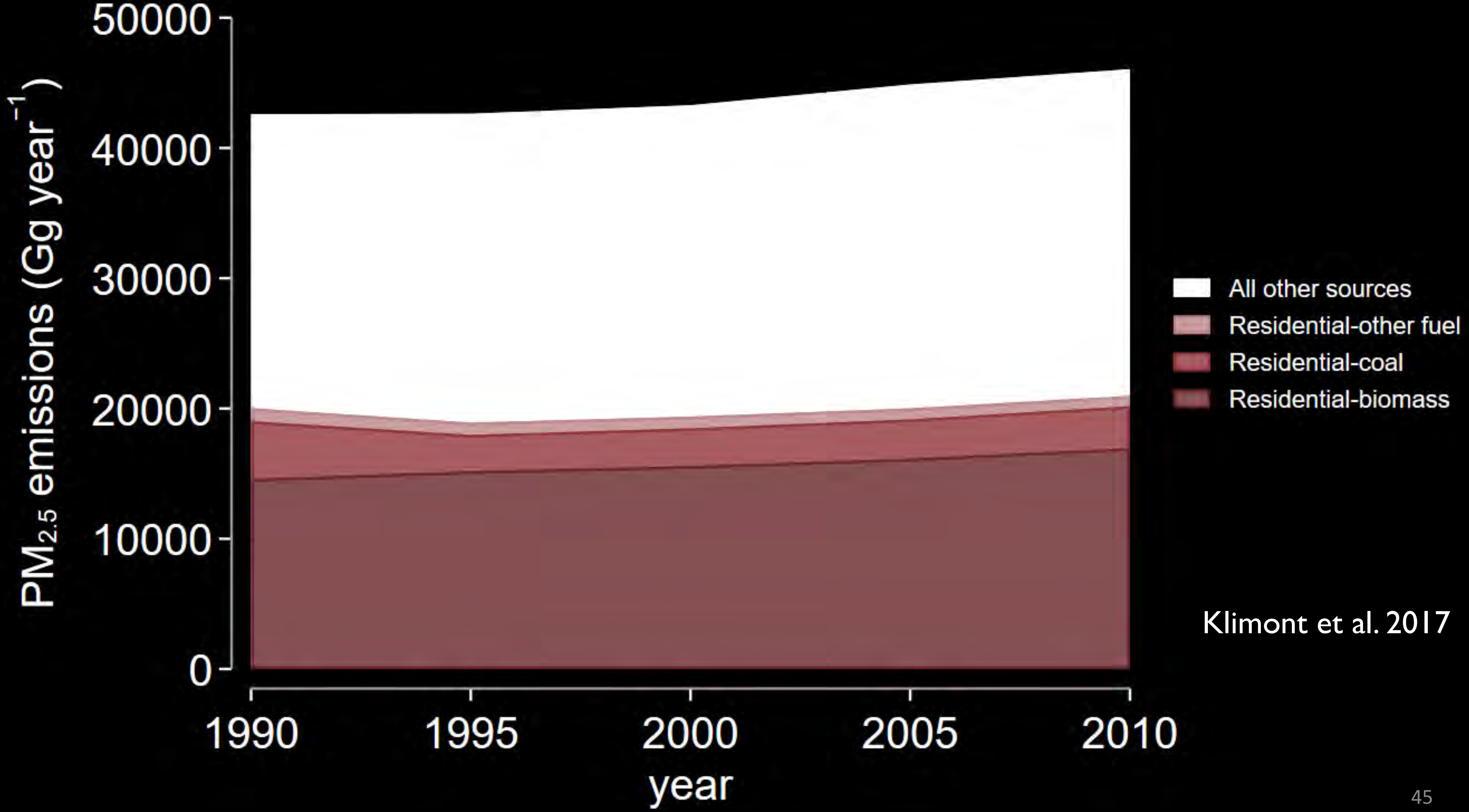
Aerosol cooling vs. greenhouse gas warming.



Energy into the atmosphere

Cooking and heating are major global sources of aerosols

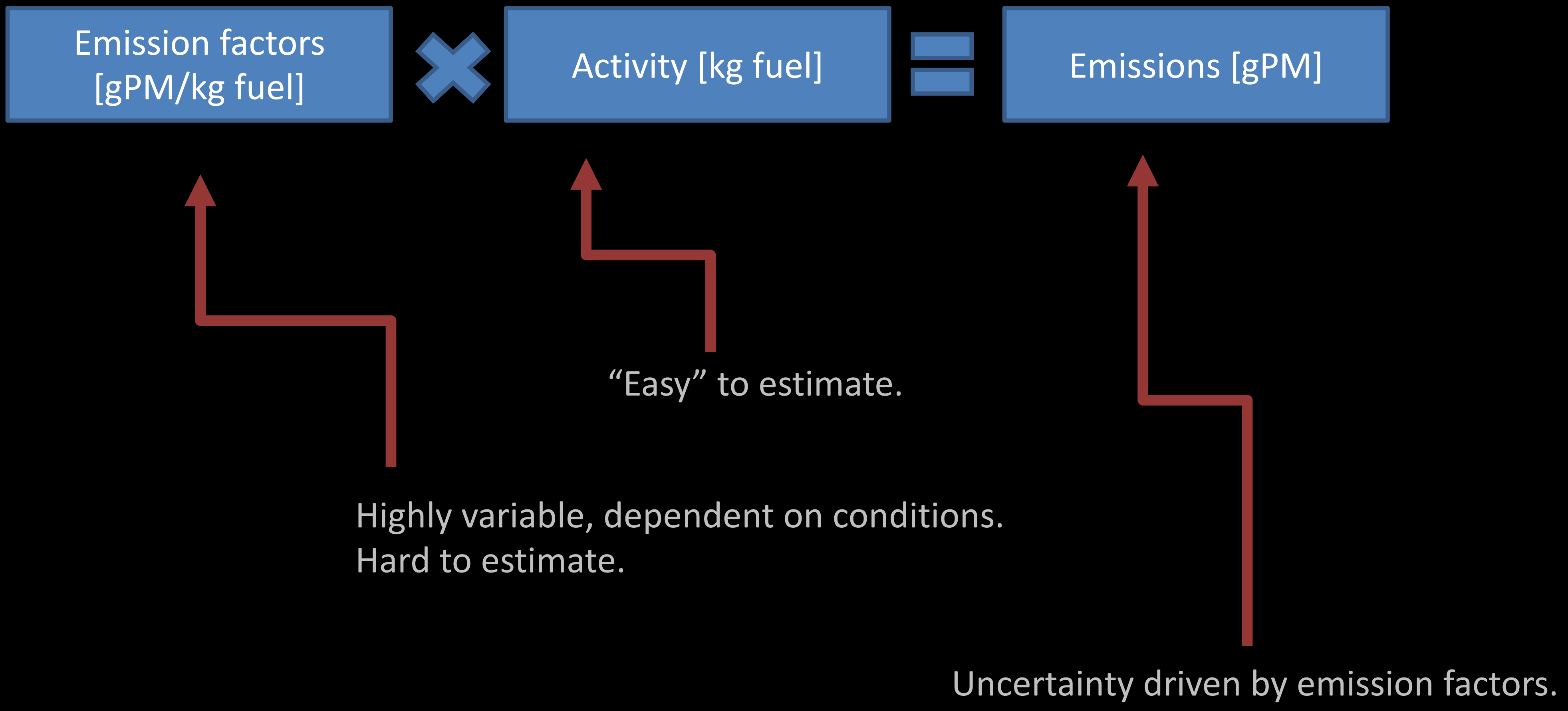
45% residential, 35% residential biomass



Klimont et al. 2017

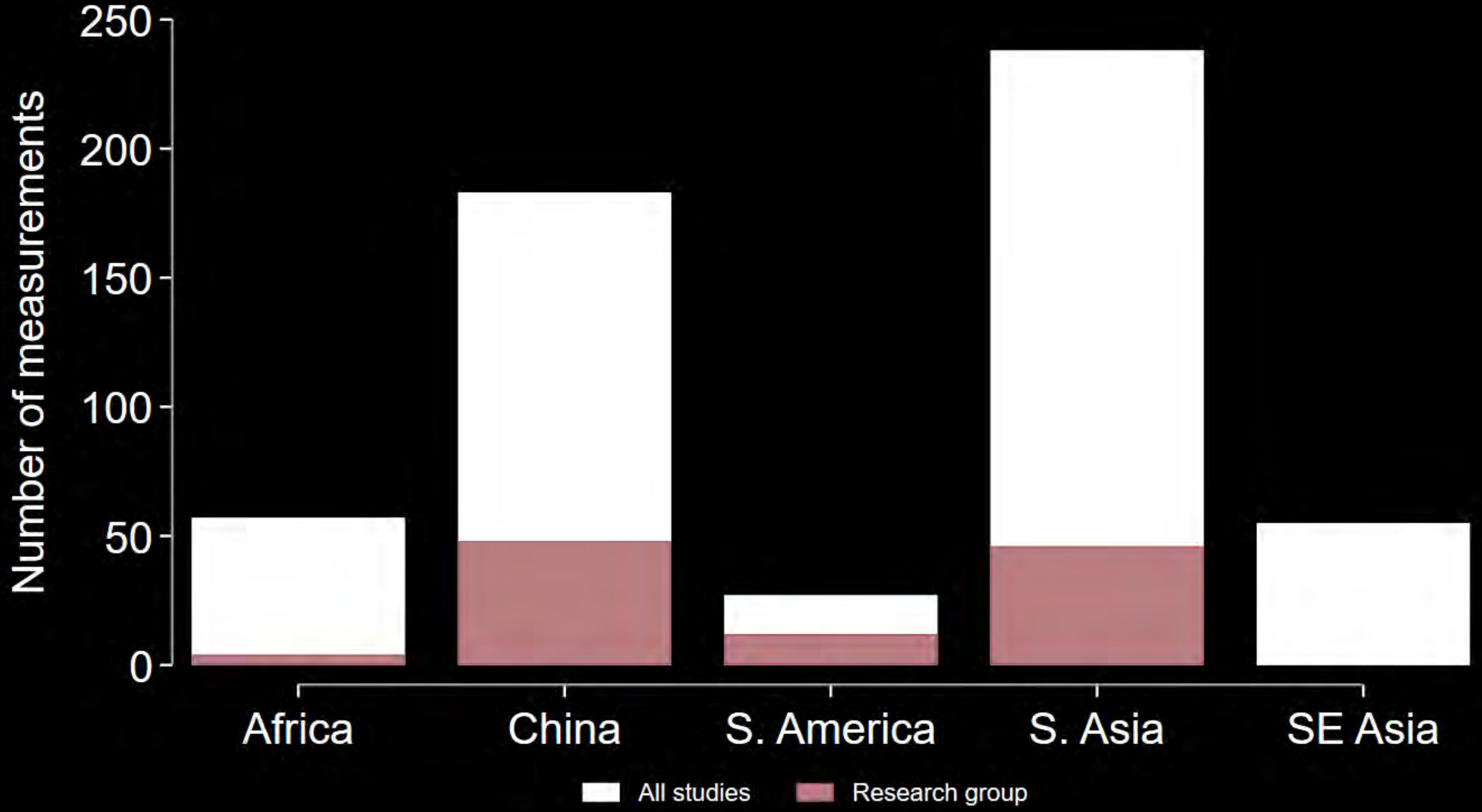
Estimate of global aerosol emissions from cookstoves.

Troublesome emission factors.



Field measurements: A challenging task.

~600 "traditional" stove measurement in the field.

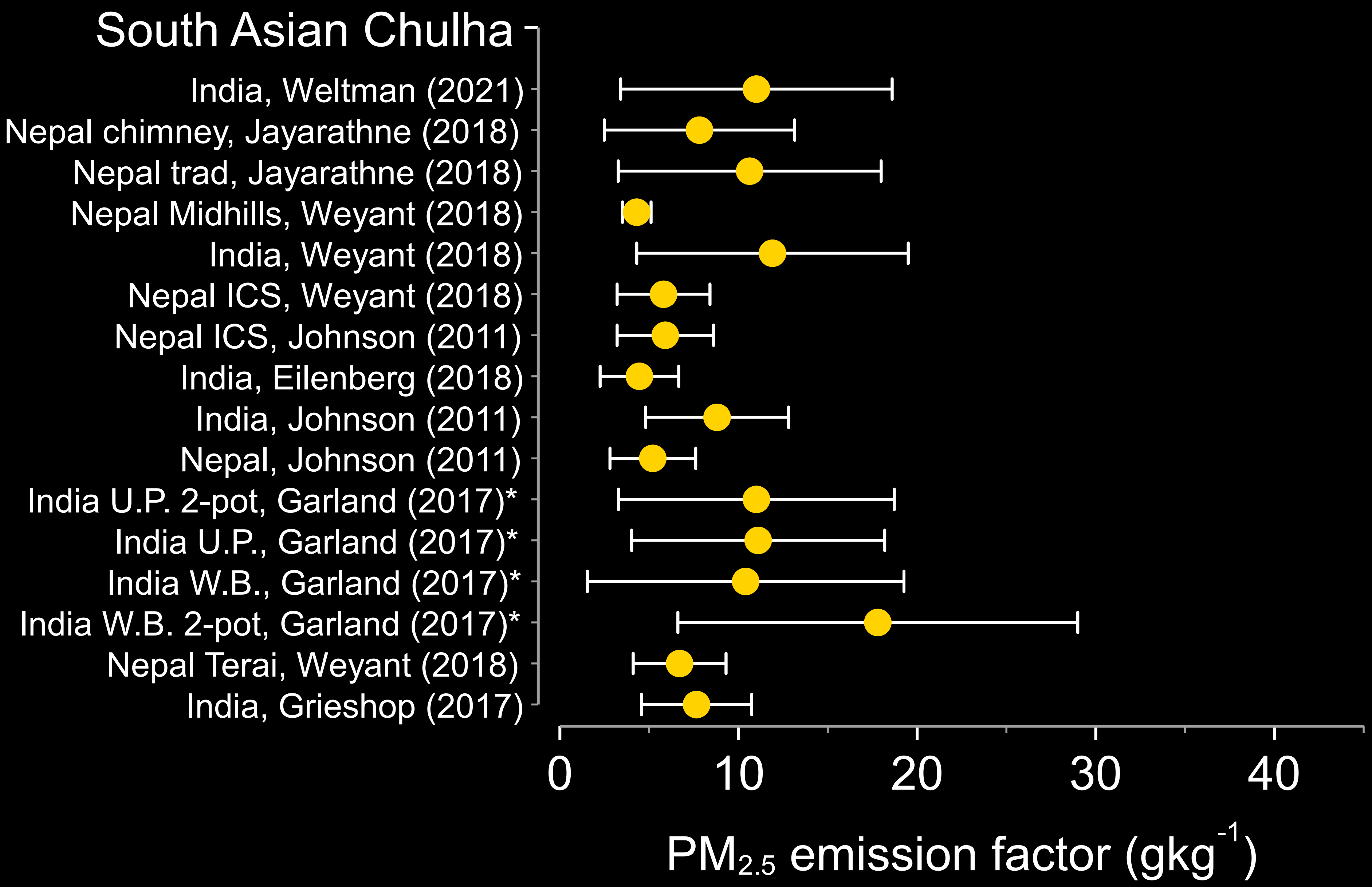


Field measurements are hard…

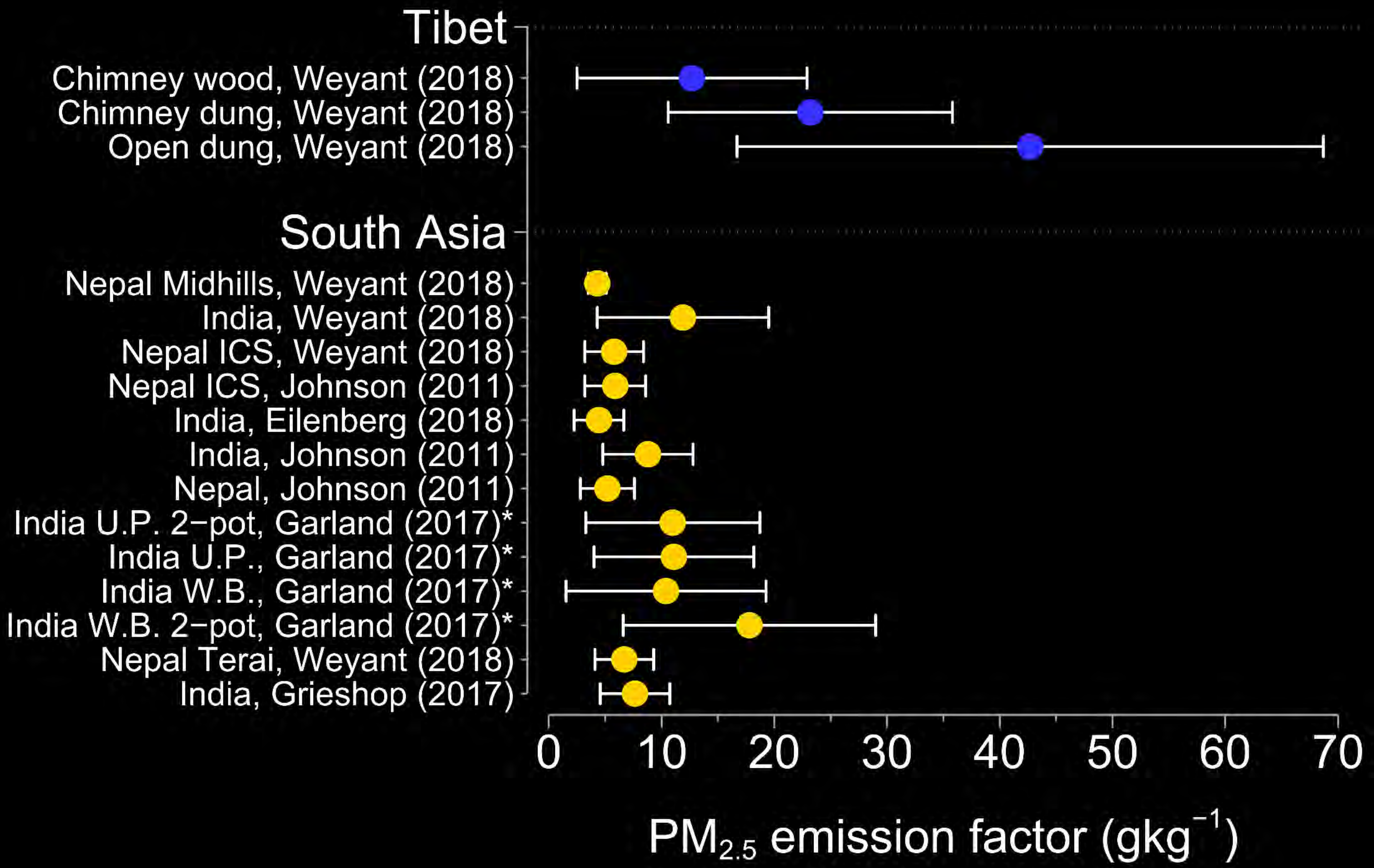
Are we there yet?

South Asian chulha.

Many studies: few surprises.



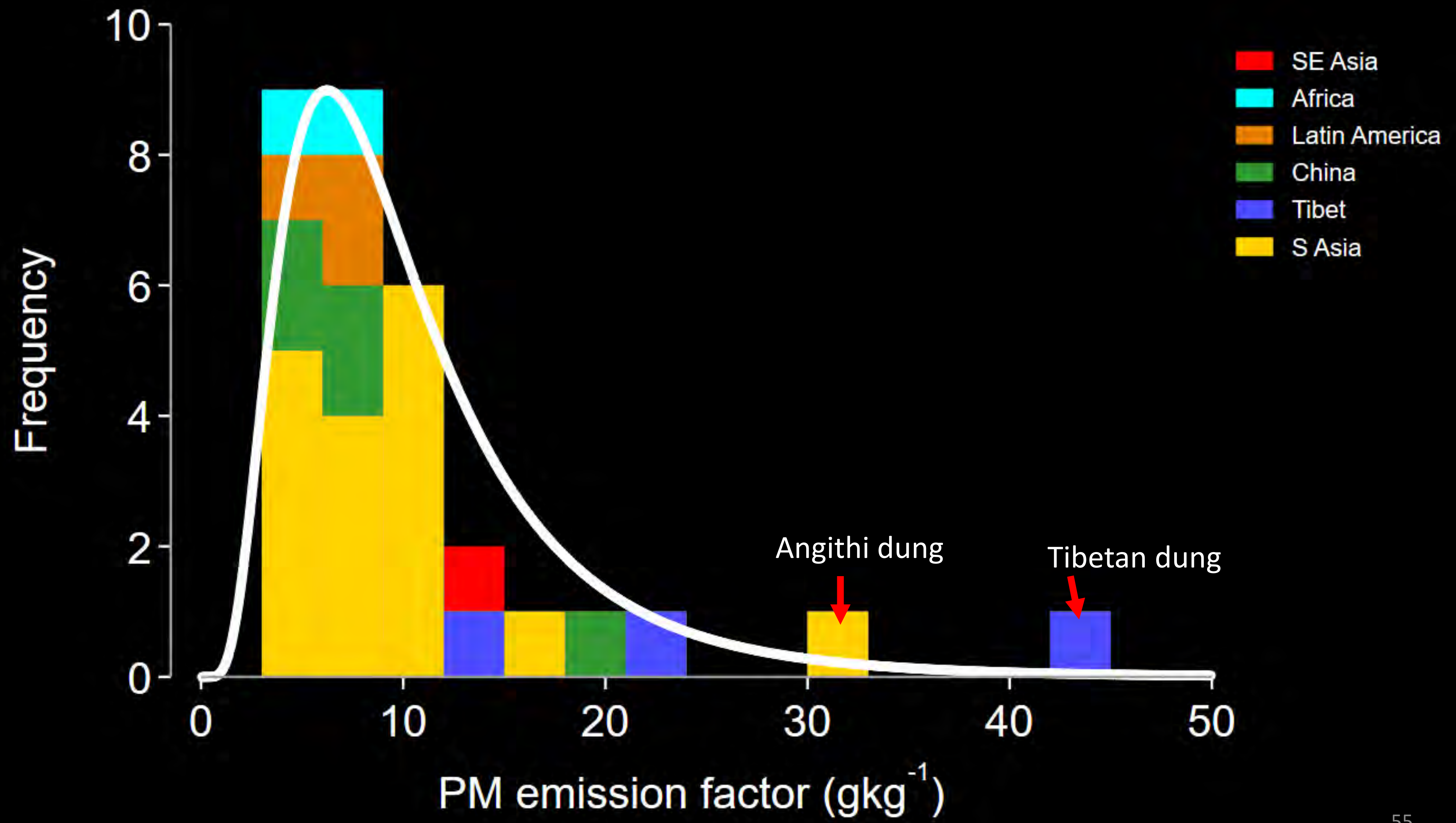
Some stoves are on the high end of $PM_{2.5}$ emissions



Tibetan open dung stove, flaming.

Tibetan open dung stove, smoldering.

Most stoves are like chulhas when burning biomass.



Why are some stoves "super emitters"?

- Examples of high emitters:
  - Tibetan dung stoves (42g/kg) Weyant (2019)
  - Indian Angithi (32g/kg). Weltman (2021)

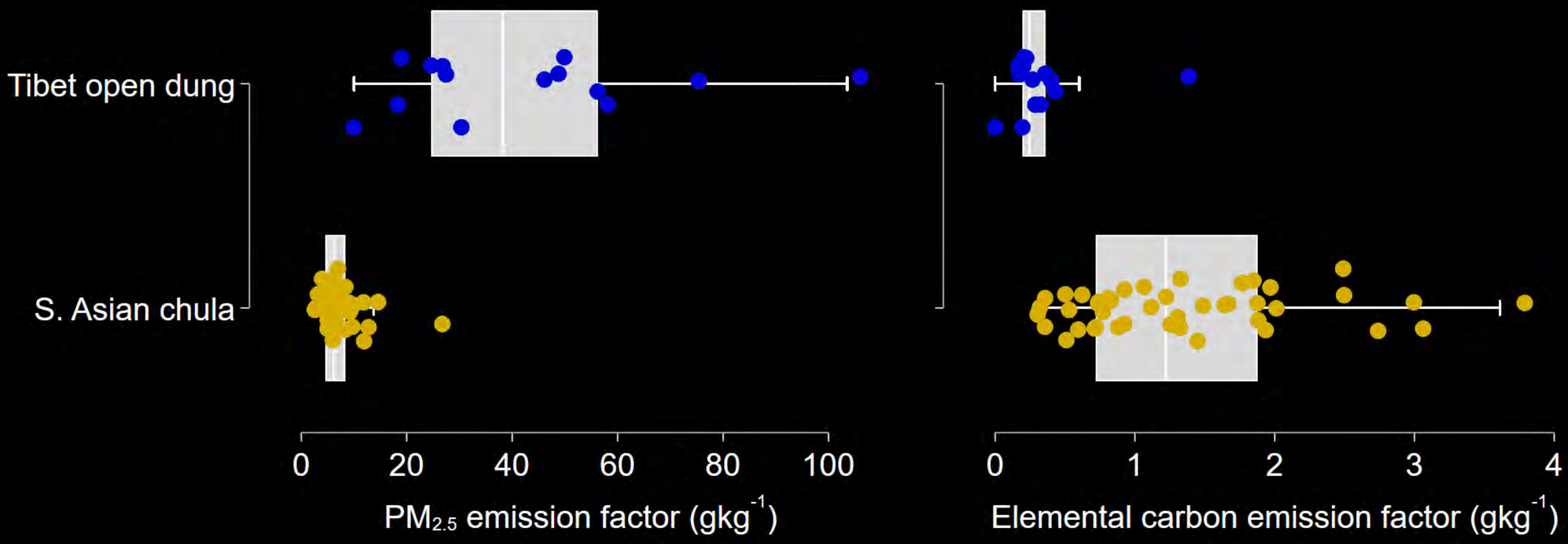
- Compared to the S. Asian chulha (8.7g/kg).

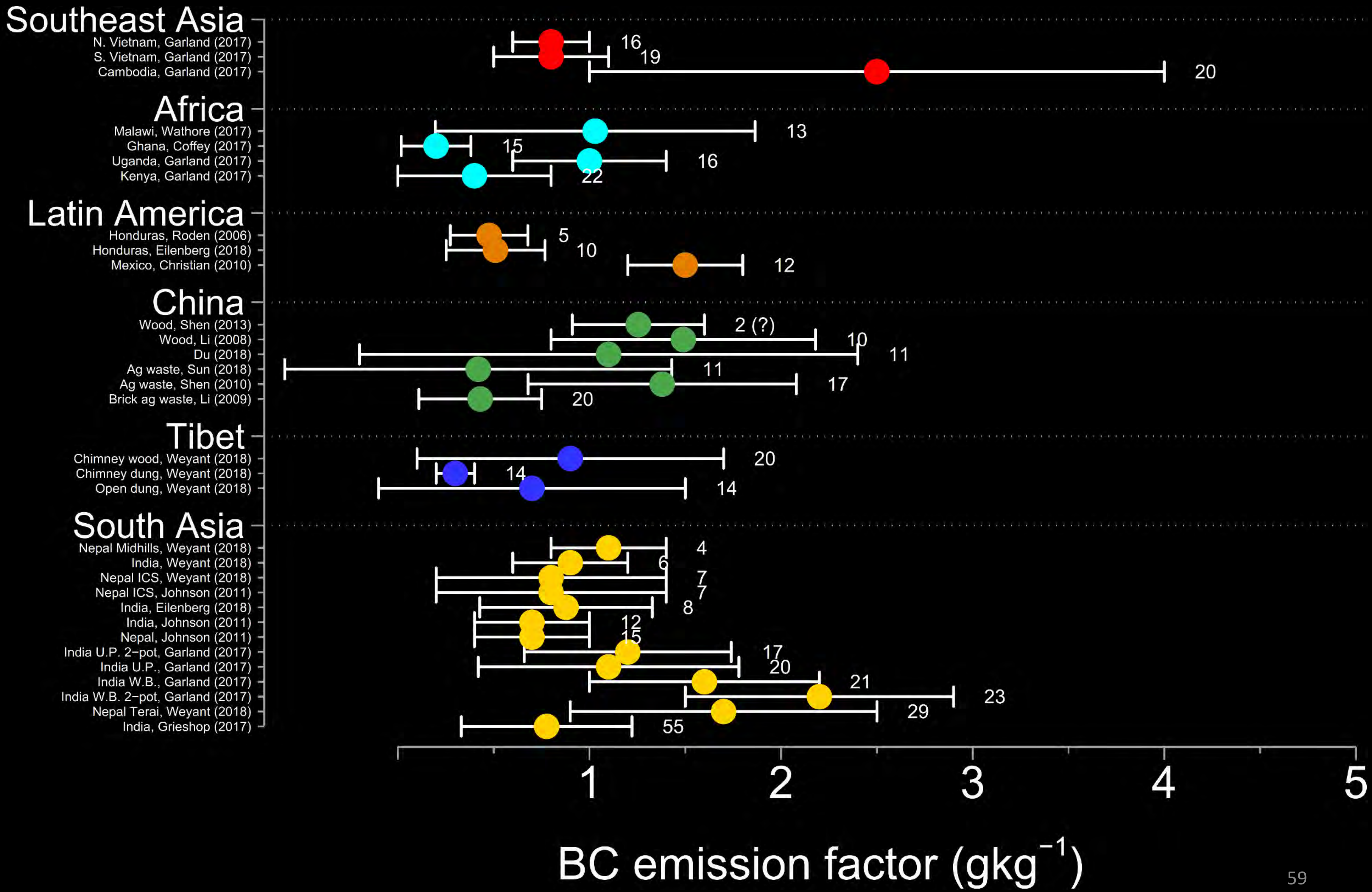
- Characteristics of high emitters:
  - Smoldering combustion.
  - Heating stoves.
  - Dung fuel.
  - Unattended burning.

- "Domestic open burning"

What about black carbon?

High $PM_{2.5}$ does not imply high black carbon.




Southeast Asia
N. Vietnam, Garland (2017)
S. Vietnam, Garland (2017)
Cambodia, Garland (2017)
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Africa
Malawi, Wathore (2017)
Ghana, Coffey (2017)
Uganda, Garland (2017)
Kenya, Garland (2017)
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Latin America
Honduras, Roden (2006)
Honduras, Eilenberg (2018)
Mexico, Christian (2010)
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12
China
Wood, Shen (2013)
Wood, Li (2008)
Du (2018)
Ag waste, Sun (2018)
Ag waste, Shen (2010)
Brick ag waste, Li (2009)
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Tibet
Chimney wood, Weyant (2018)
Chimney dung, Weyant (2018)
Open dung, Weyant (2018)
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South Asia
Nepal Midhills, Weyant (2018)
India, Weyant (2018)
Nepal ICS, Weyant (2018)
Nepal ICS, Johnson (2011)
India, Eilenberg (2018)
India, Johnson (2011)
Nepal, Johnson (2011)
India U.P. 2−pot, Garland (2017)
India U.P., Garland (2017)
India W.B., Garland (2017)
India W.B. 2−pot, Garland (2017)
Nepal Terai, Weyant (2018)
India, Grieshop (2017)
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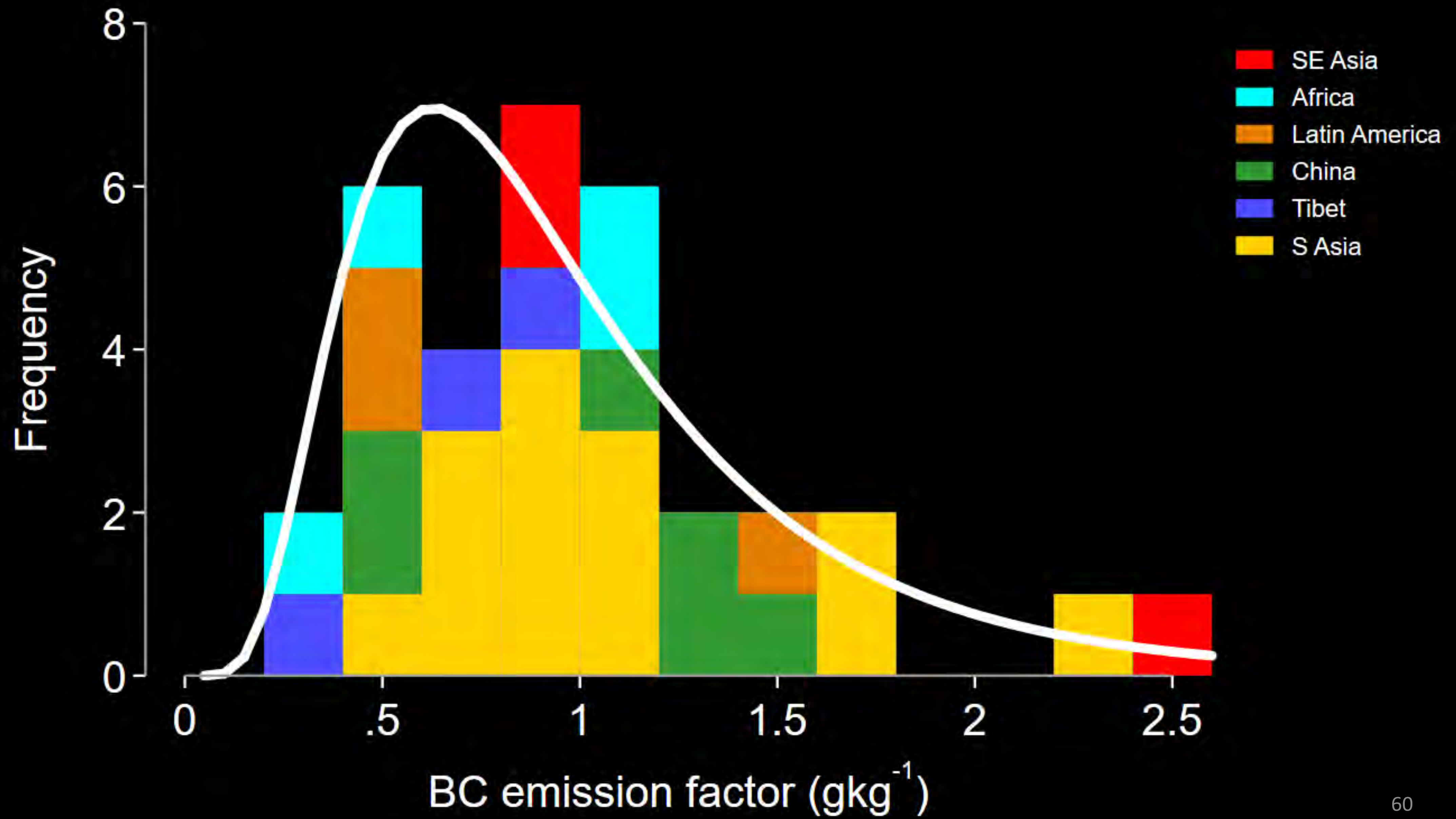
BC emission factor (gkg−1)

Nearly normal distribution of emission factors

No strong regional trends.



Few indications of significant outliers for BC.

Typically 1 ± 0.5 g/kg.

Black carbon EFs fall within this "expected range" even when the stove is a high $PM_{2.5}$ emitter

- Smoldering combustion does not produce BC.
- BC is produced in flaming combustion.

-Likely, a narrow range of combustion conditions are optimal for cooking.

Estimate of global aerosol emissions from cookstoves.

Troublesome emission factors → troublesome fuel consumption

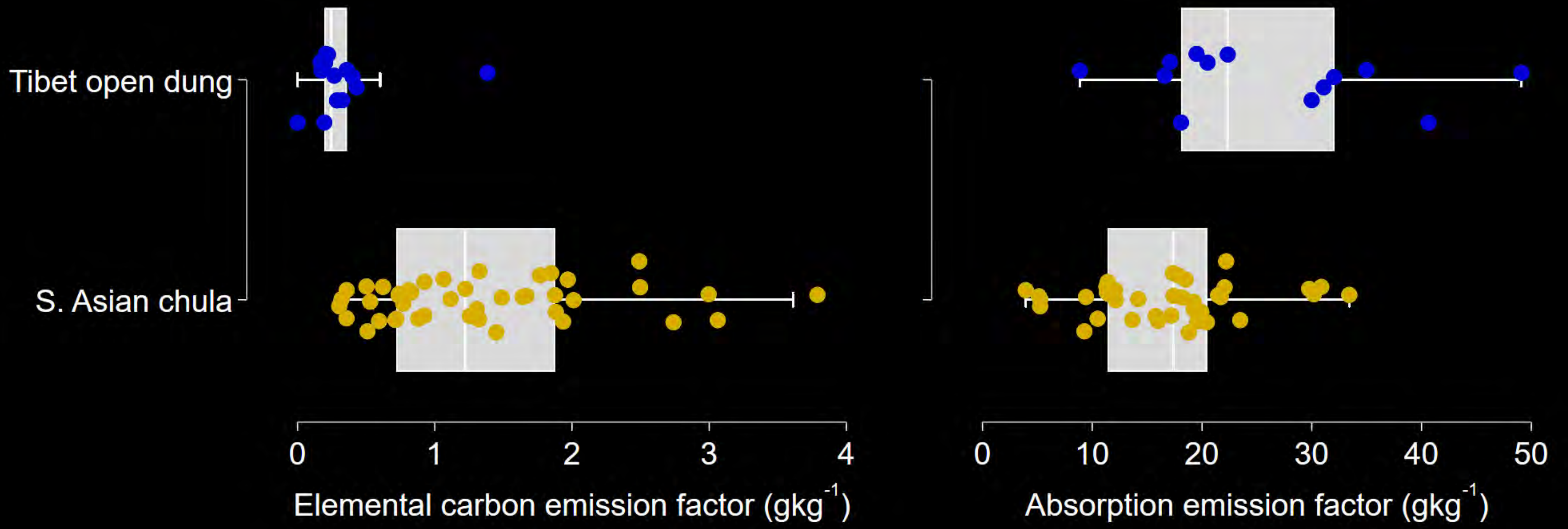
Emission factors [gPM/kg fuel] × Fuel consumed [kg fuel] = Emissions [gPM]

Little improvement in estimates or methods

Significantly reduced uncertainty

Uncertainty reduced, potential biasies due to fuel consumption

Smoldering combustion → significant OC absorption



Weyant (2019)

Cookstoves:
Controlled to regulate heat & flames

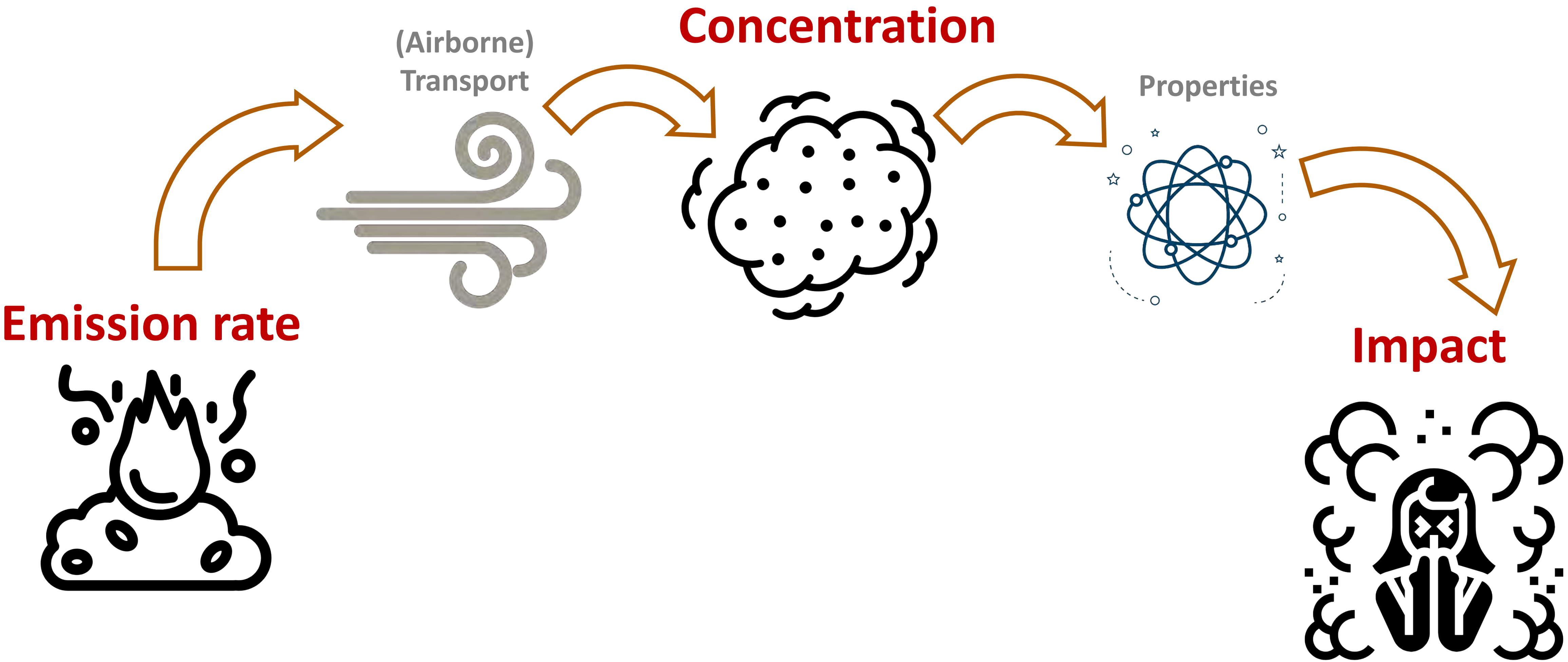
Domestic open burning:
Uncontrolled, smoldering.
High PM, low BC, absorbing OC.

Jayarathne (2018)
Johnson (2011)
Eilenberg (2018)
Garland (2017)
Greiship(2017)
Weltman (2021)
Shen (2013)
Li (2009)
Du (2018)
Sun (2018)
Shen (2010)
Christian (2010)
Roden (2006)
Wathore (2017)
Coffey (2017)
Weyant (2019)

Thank you

What more do we need to know about emission factors & characteristics?

…Well, why are you asking?


Emission rate
(Airborne)
Transport
Concentration
Properties
Impact

Question:

Do stoves produce warming via particle emission?

Purpose:
Estimate climate benefit of improving or replacing stoves.

Requirements:

- Black-to-organic carbon ratio

A: When stoves operate non-ideally *(which is most of the time),* they make more cooling via organic carbon than warming via black carbon.

- Especially when you count clouds.
- However, they DO have large impacts on radiative balance, anyway.
- Black carbon warming may dominate if the surface is snowy.
- Looking forward: Focus on health of region's atmosphere rather than average warming

Question:

Can we predict how much PM is emitted in a village or region?

<u>Purpose:</u>
Model regional air quality (current & possible)

<u>Requirements:</u>

- Average emission factor
- Total consumption of different fuels

A: Average emission factor of "normal" stoves *(including slight improvements like mud stoves)* is probably known as well as it ever will be.

Cooking vs heating emission factor is within natural variability.

Looking forward: Understanding emissions within one's own region is worthwhile.

Question:

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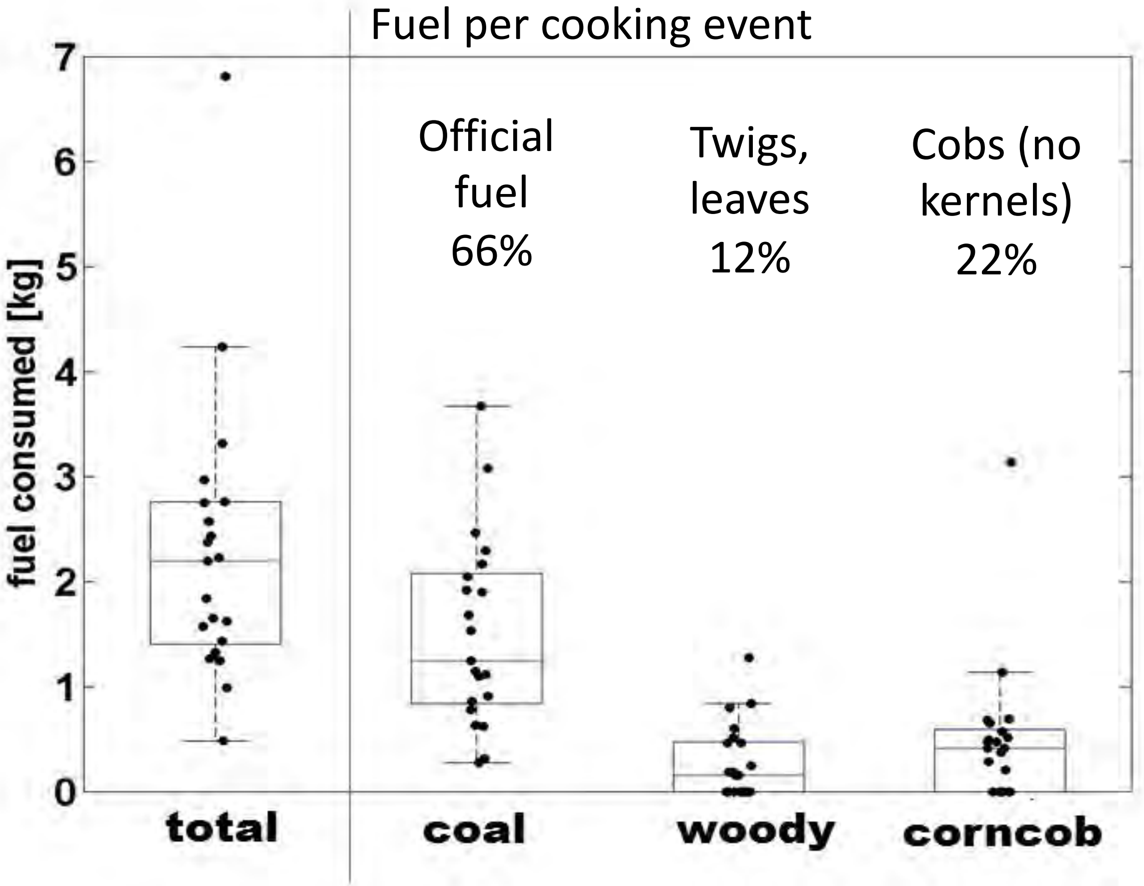


Thompson et al., 2019, ES&T 53, 3323-3330

Question:

Can we predict how much PM is emitted in a village or region?

<u>Purpose:</u>
Model regional air quality (current & possible)

A: Fuel quantities *(connected to household practices and needs)* are still quite uncertain.

<u>Requirements:</u>

- Average emission factor
- Total consumption of different fuels

Quantity will never be precisely known, and maybe it's not necessary

Looking forward: Take lessons from failures of simple model (e.g. fuel mixtures not single fuels)
They indicate needs that aren't being met with simple solutions.

Question:

Can we predict emission from a single stove if we know enough about its design?

Purpose:

Identify changes in a single home

Requirements:

- Average emission factor
- Total consumption of different fuels

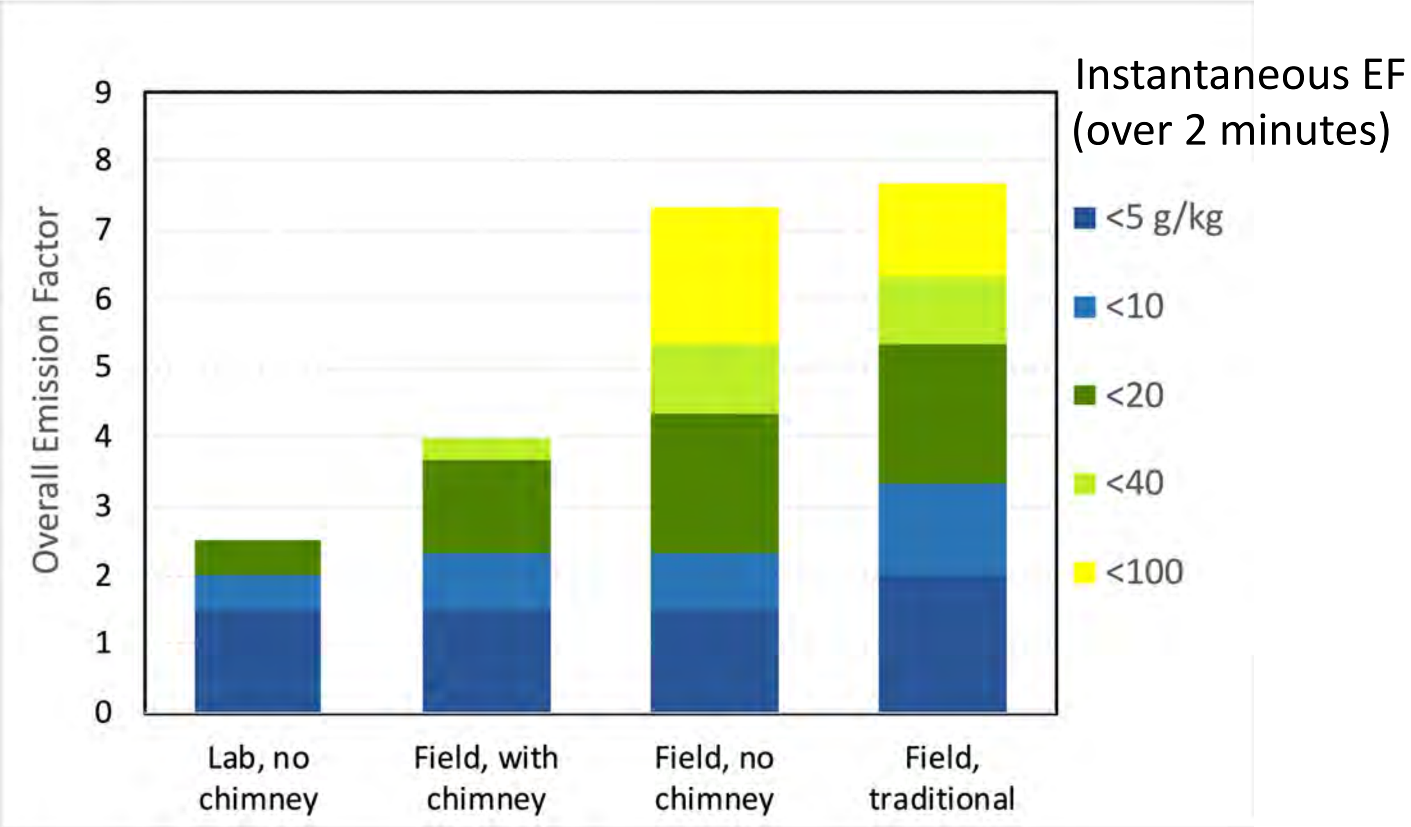
A: If it burns solid fuel, overall emission factor varies within a factor of 2-3.
Fuel quantity also uncertain x2.
These uncertainties are likely to remain.

Looking forward: “Baseline” performance has high variability. Field measurements should confirm robustness of improvements.

Question:

What about short periods of high emission? Can't those be improved?

A: Why, yes! High-emitting periods are quite important.



Data from Chen et al., Env. Sci. Tech 46, 6110-6117, 2012; real-time PM emission inferred from scattering

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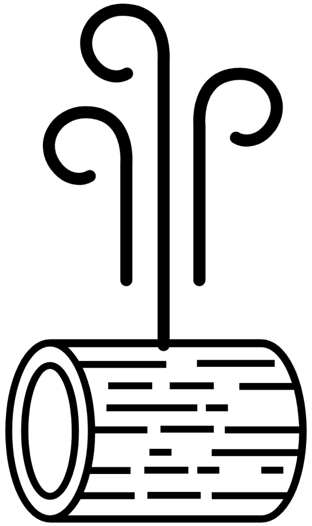


pyrolysis & devolatilization

These high-emitting periods tend to occur right after fuel addition.

Data from Chen et al., Env. Sci. Tech 46, 6110-6117, 2012; real-time PM emission inferred from scattering

Mariam Fawaz:
“(almost)-Dr. Cookstove Pyrolysis”

Fun fact: Mariam is an amazing photographer and applies her skill to documenting wood transformation, among other things. Image sequence from Fawaz et al 2020.

Emission of organic aerosols from wood combustion: Bridging the gap between atmospheric science and pyrolysis

Mariam Fawaz

ASHES workshop

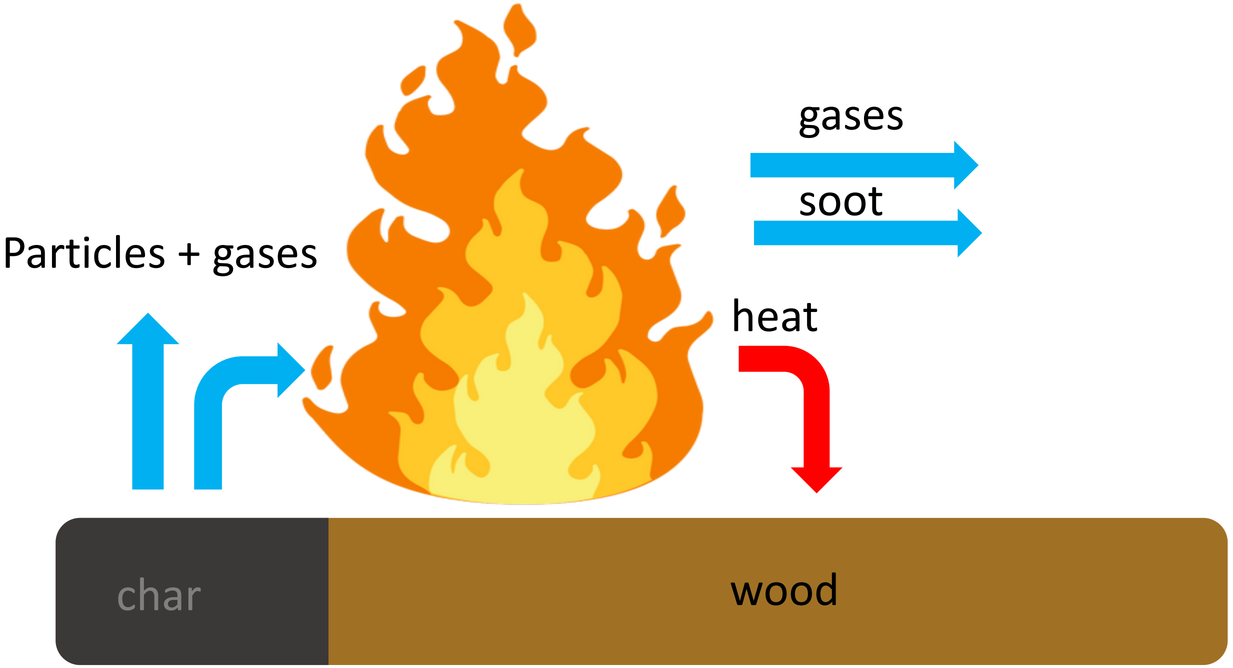
April 27, 2021

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

To understand emission, simplify the process

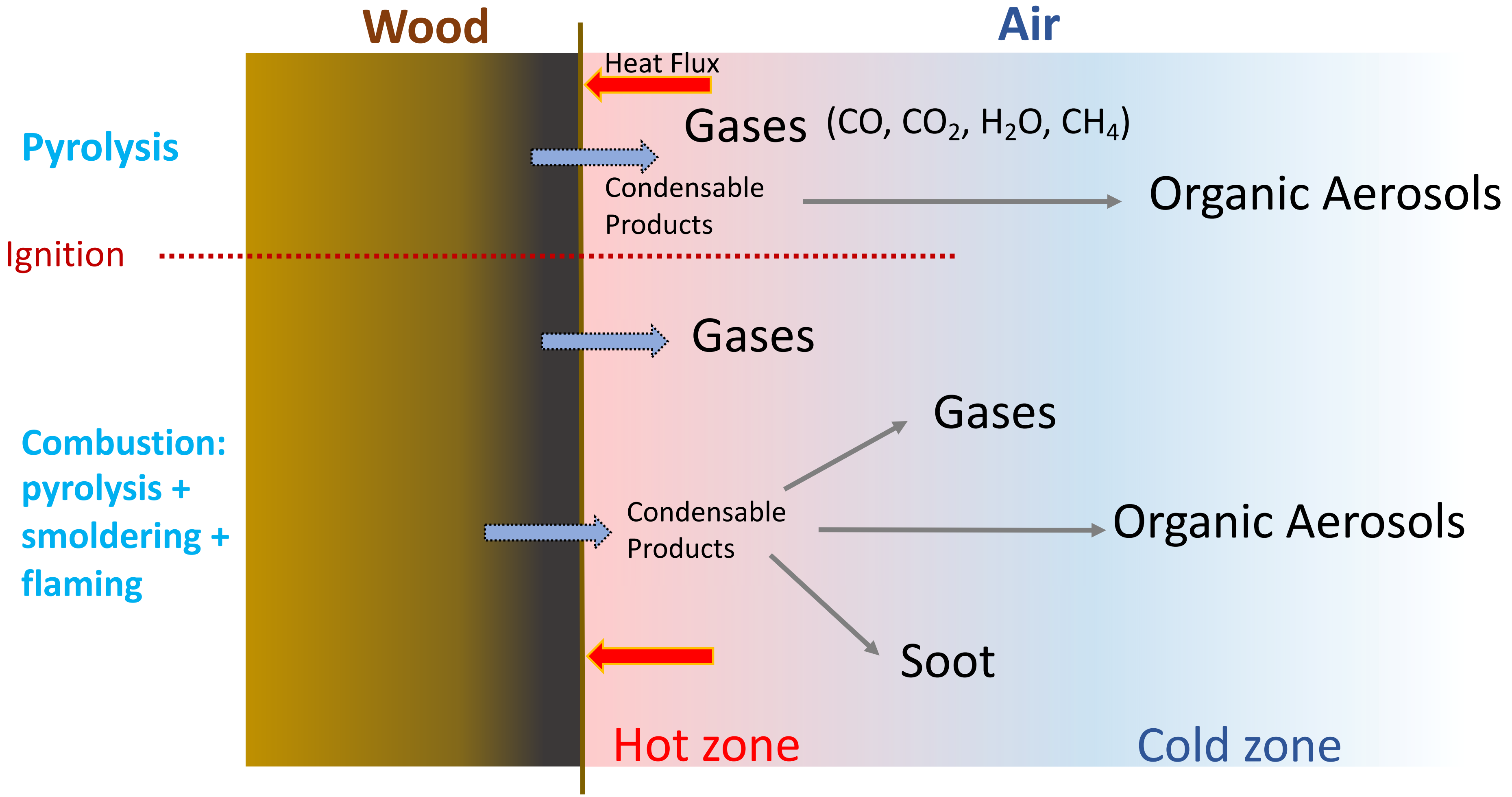
Emissions from wood burning for residential energy use

Remove Interferences

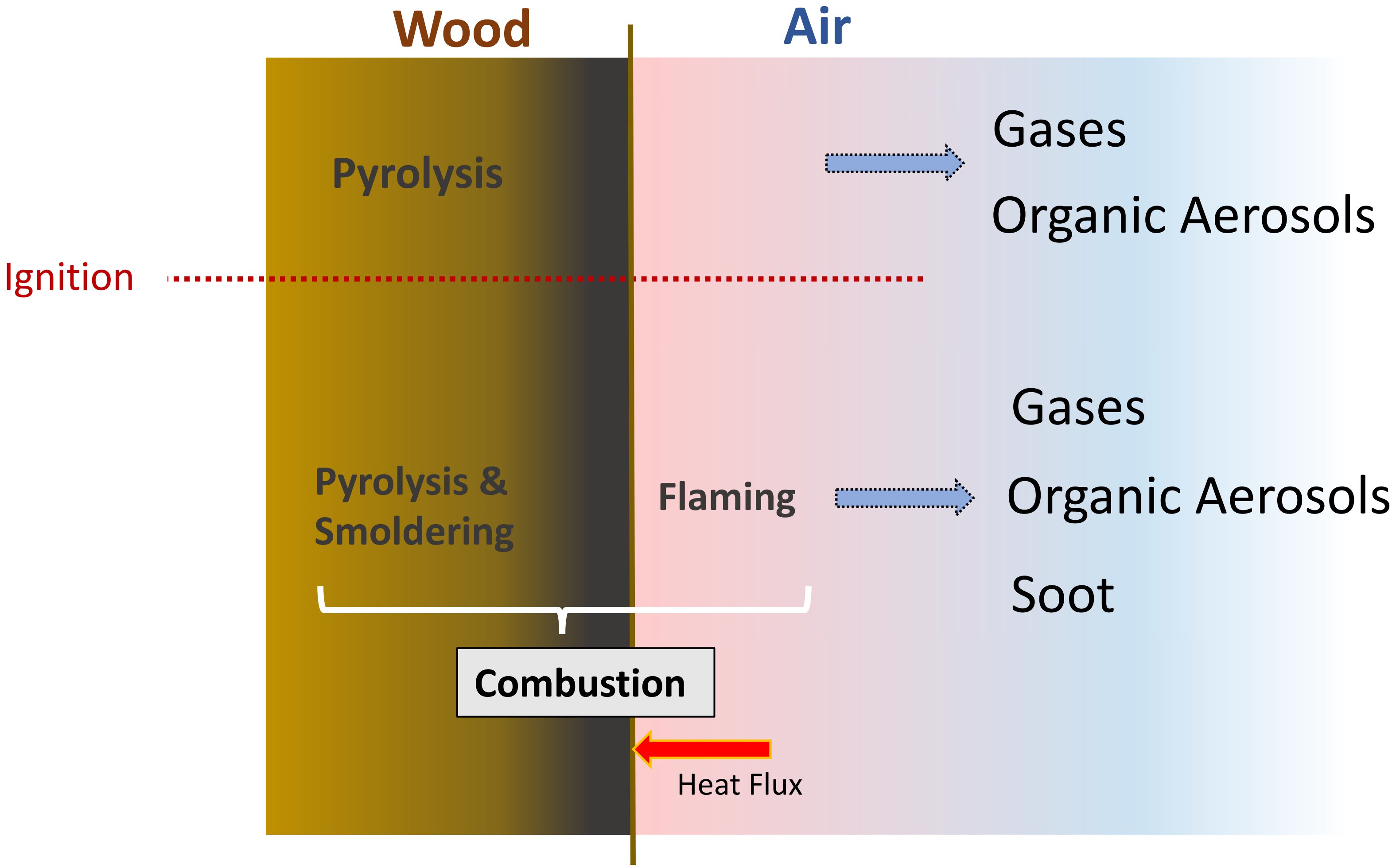


Base process for what happens during combustion, a combination of pyrolysis, flaming, and smoldering

What happens during combustion?



Role of Pyrolysis in combustion



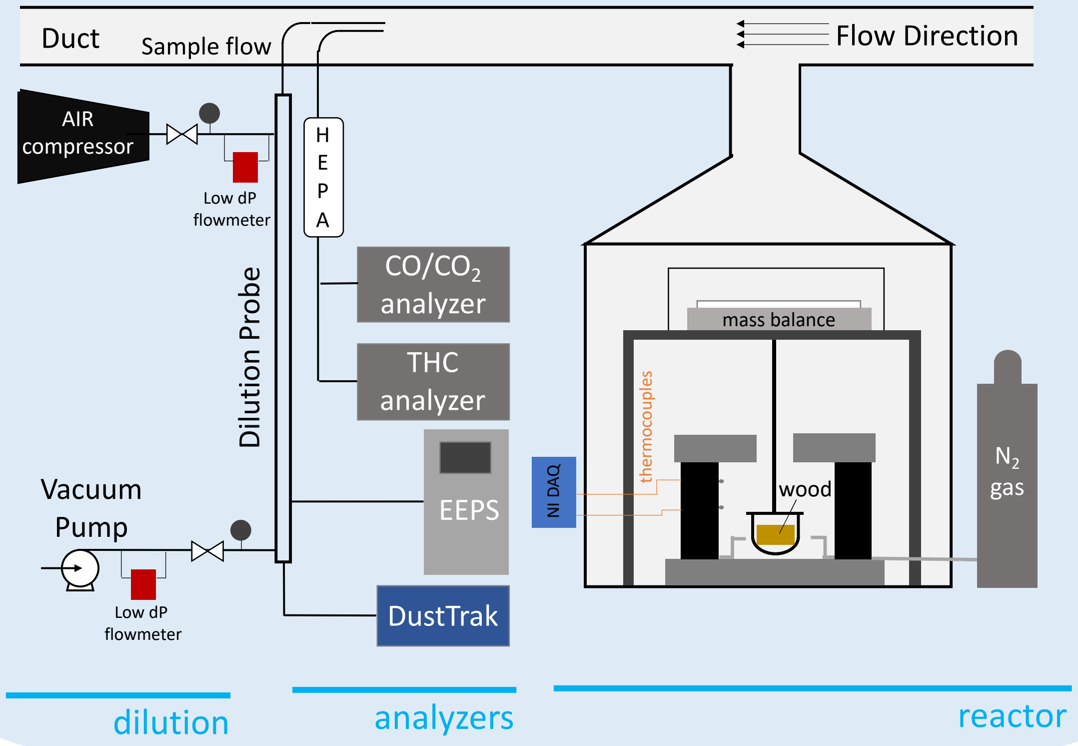
- Pyrolysis is the core solid phase process responsible for product formation, some of which become organic aerosols
- To understand wood combustion emissions study pyrolysis

Objective

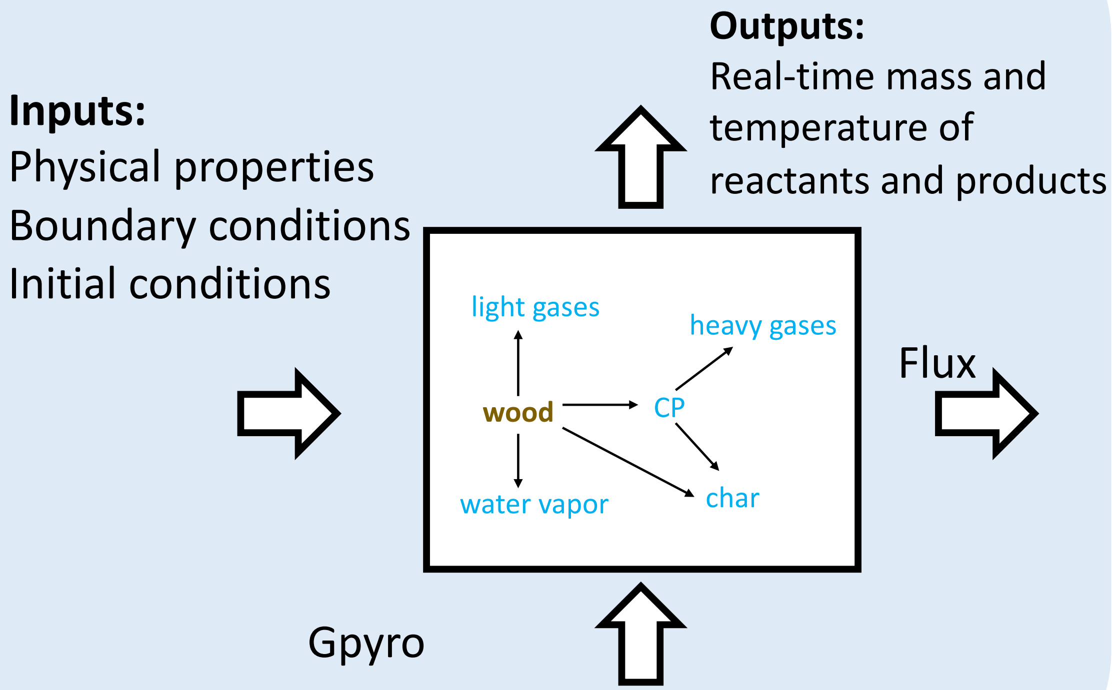
Explain the release rate of particles and gases in the absence of flame by including pyrolysis principles

Study design: Experiments coupled with modeling

Experiment



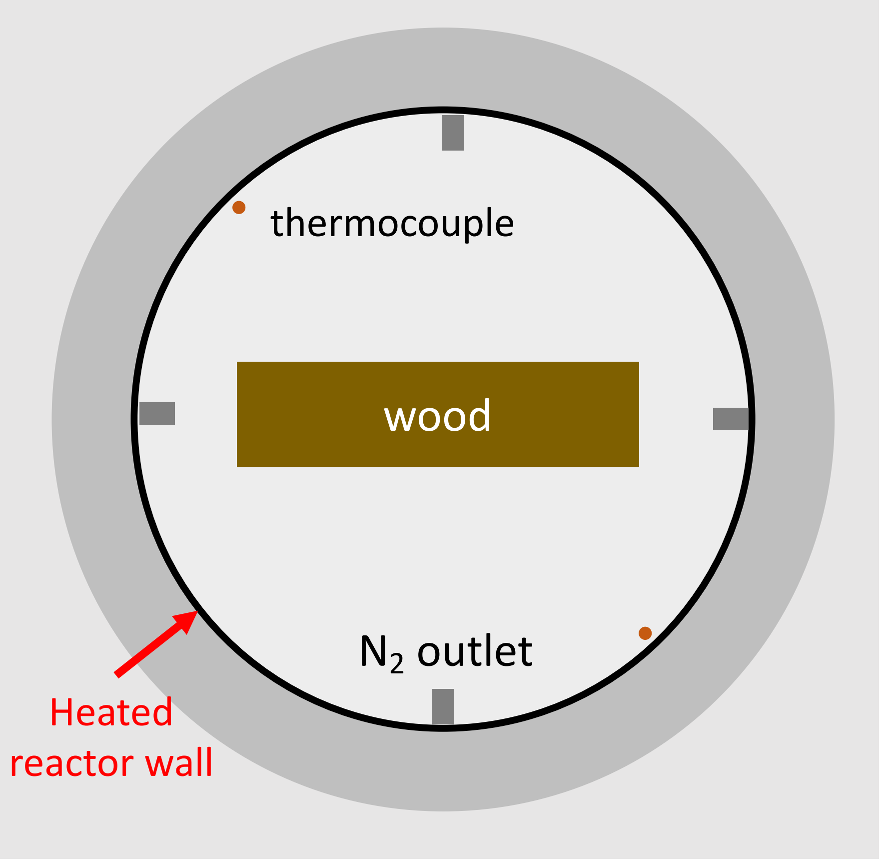
Model



Pyrolysis Setup Principles

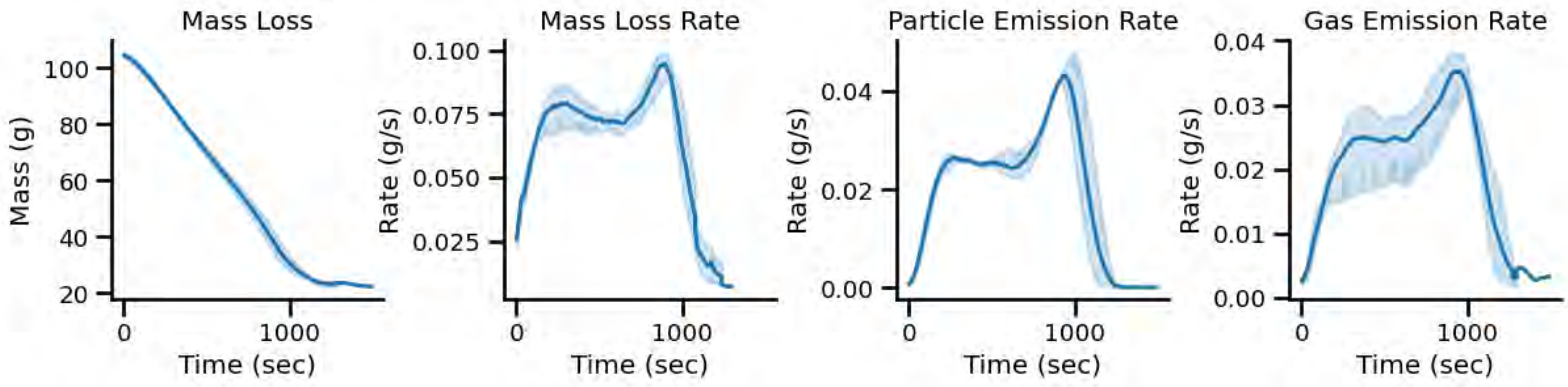
- Nitrogen gas reactor environment
- Reactor temperature control:
  - Isothermal heating (setpoint: 400, 500, 600°C)
  - Ramp heating (1-20°C/min)
- One wood sample is placed in the reactor, size: 14x3.8x2.9 cm
- Wood is heated from the sides, top and bottom sides are unheated

Reactor top view



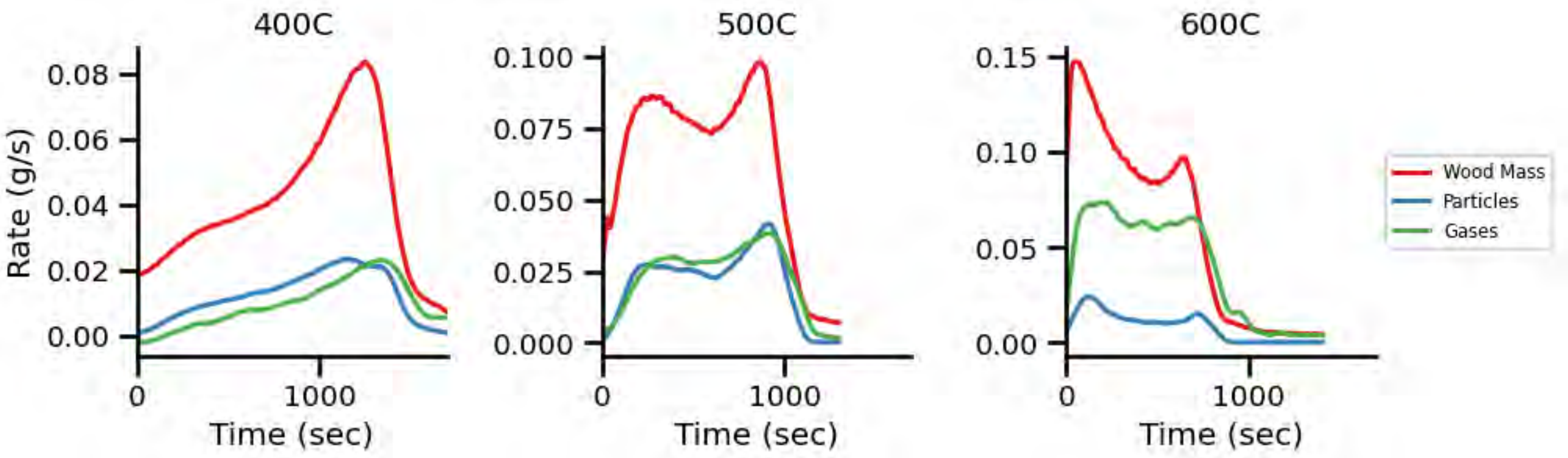
Measurements of emission rates and mass of the wood are repeatable

An experiment of birch wood at 500ºC pyrolysis temperature, repeated five times



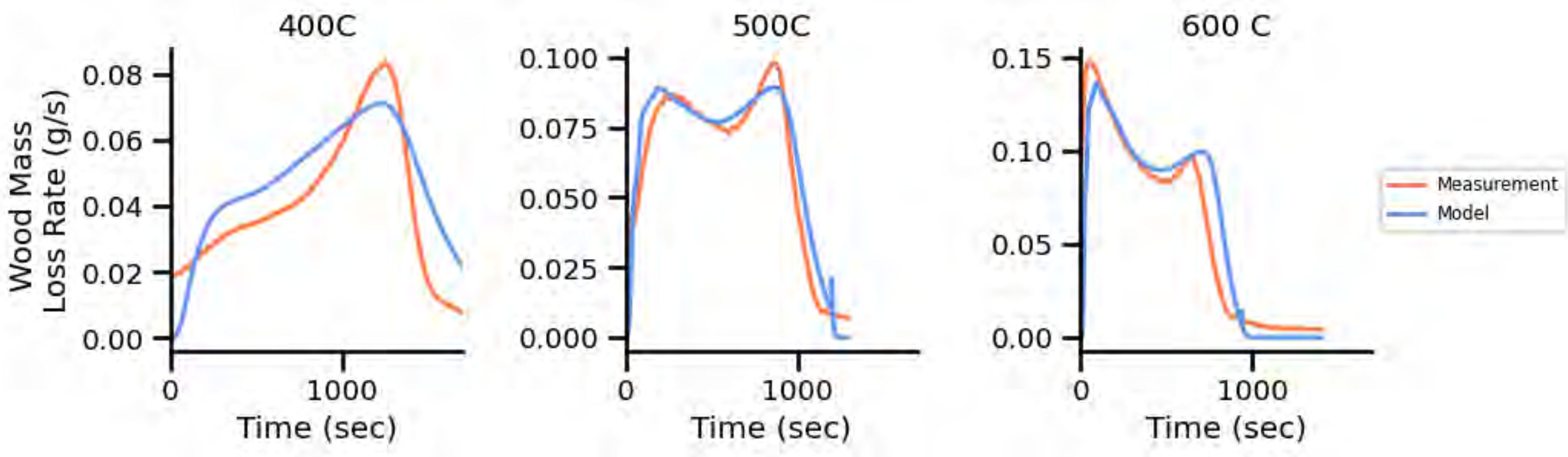
Emission rates of particles and gases are temperature dependent

- Particle and gases emission rates follow the mass loss rate of the wood
- The higher the heating rate in the wood, the higher the pyrolysis rate
- Thermal gradient between surface and center causes the difference between rates throughout the experiment

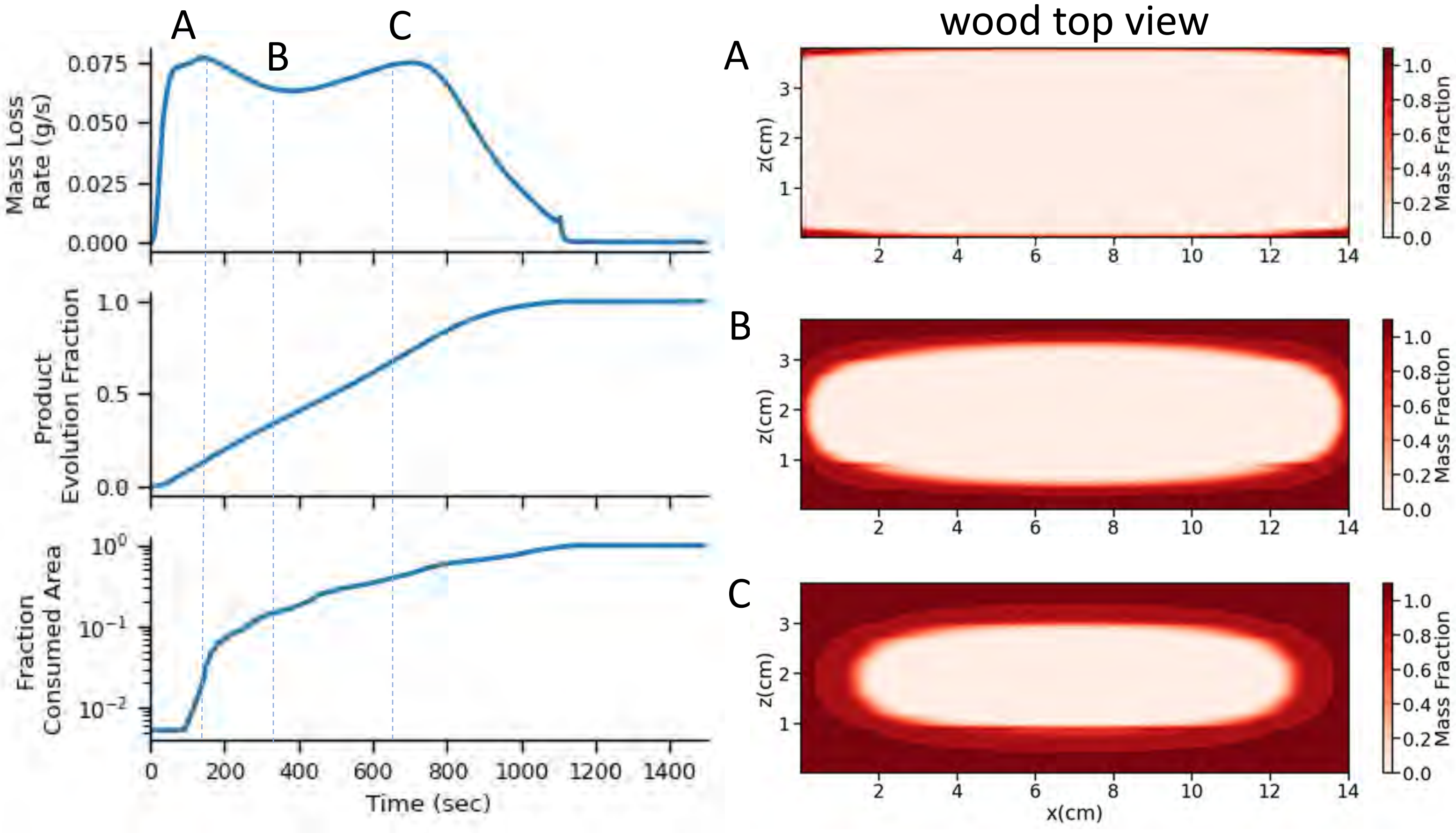


Wood mass loss rate can be predicted

At all pyrolysis temperature, there is a magnitude and shape agreement between model and measurement of mass loss rate



Pyrolysis relationship with real emission



- The first peak is responsible for ~10% (10g/kg) of product emission
- First peak emission consumes 2% of the wood mass
- Initial pyrolysis peak is likely responsible for emissions observed in field measurements

Conclusion

- Release of particles and gases is a repeatable and deterministic process
- During pyrolysis particle and gas emissions are controlled by heat and mass transfer
- An expansion of the system to include more combustion processes improves the understanding of emission from biomass burning

Summary:
What do we need to know about emission factors & rates & characteristics?

What’s better known

1. Emission factors for most in-field “normal” stoves are variable but converging – probably good enough

    Now one of the best-characterized sources in the world

    However, confirm field emission rates of “much-better” stoves

2. High PM emission is organic, not black

3. Release rates of combustible material are predictable

Needing exploration:

1. Causes of super-emitting stoves

   Best candidates for replacement for health reasons, not for (average) climate

2. Exploiting principles of release rate (pyrolysis)

   Reduce transients = reduce PM emissions

3. Fuel quantities unconstrained

   At least 50%; perhaps x2 - produces permanent uncertainty

4. Household energy service demand and connection to transition

   Household is a system; stove can't be replaced in isolation

Thank you for listening!

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Better known:

1. Emission factors for "normal" stoves
2. High PM emission is organic, not black
3. Release rates of combustible material

Needing investigation:

1. Causes of super-emitting stoves
2. Exploit pyrolysis principles
3. Fuel quantities & types
4. Energy services – Household is a system

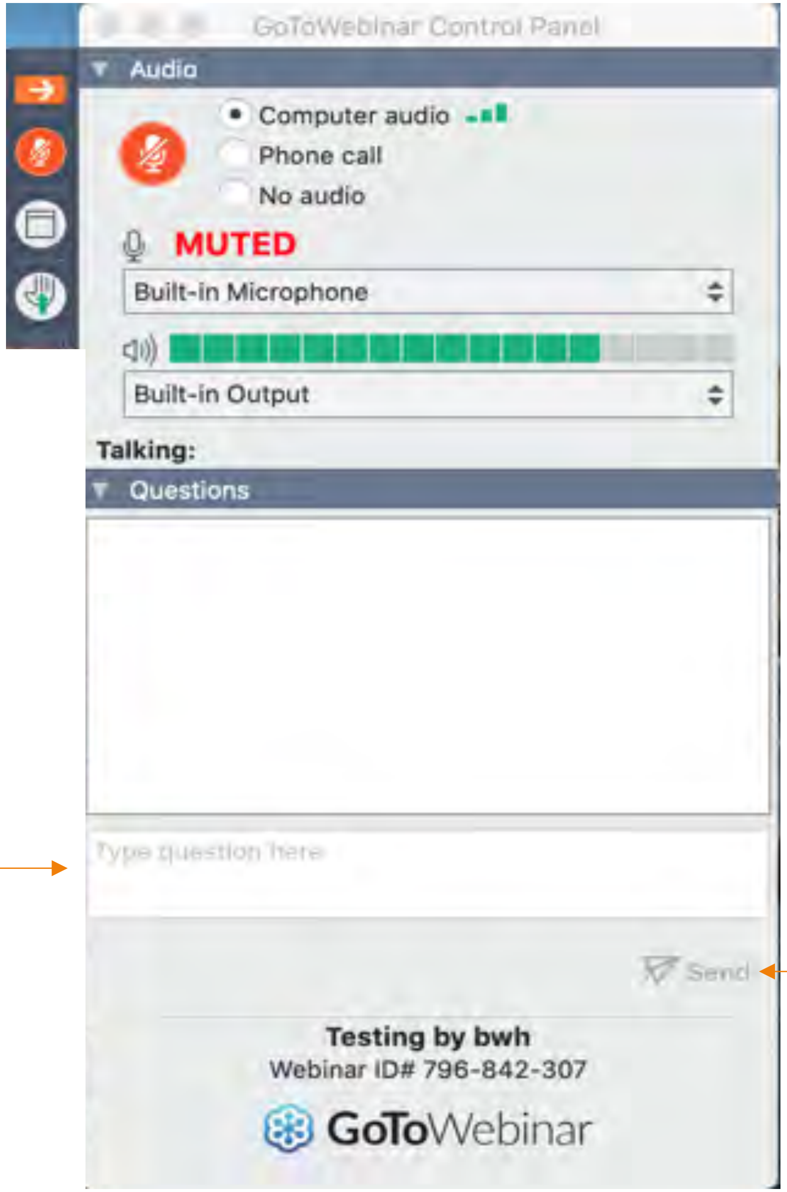
Question & Answer

Listen only mode

Not using this function

Type your questions here

Submit your questions by clicking 'Send'



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