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Methods and Uncertainty for Emissions Evaluation

September 5, 2022

IPCC TFI Expert Meeting on Use of Atmospheric Observation Data in Emission Inventories

Steven J Smith

Joint Global Change Research Institute

PNNL and University of Maryland

ssmith@pnnl.gov

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Emissions Uncertainty

All estimates, top down or bottom up, are based on some combination of data, measurements, and modeling.

1) There will be uncertainties in all methods.
2) Top-down and bottom-up methods can provide commentary information

Emissions evaluation/validation should be seen in the context of uncertainty.

- Are observations consistent with emissions from inventories within uncertainty bounds?
- What is the most effective way to *better understand* and reduce uncertainties?
- What uncertainties are most important to reduce?
    - *Are we more concerned with uncertainties in current emissions? Past trends? The effectiveness of current and future policy actions?*

We should allocate resources to the methods most likely to better quantify, and ultimately reduce, uncertainties where they matter the most.

GHG Evaluation Context

How we should think about evaluation & uncertainty depends on the policy goal

Much of our intuition overall comes from experience with air pollutant inventories, however the data needs and policy goals are very different for GHGs.

- Example: USA criteria air pollution goals -> incremental emissions reductions to stay within finite regulatory limits
  - *Highly regional: what emission species matter & source->concentration relationships*
- Stabilization of the climate system requires transformative change
  - *Many polices now framed in terms of net zero emissions*
  - *GHG emissions have global impacts (and overarching commitment is national)*

Data and evaluation needs are also different

GHG Uncertainty Example

The USA’s GHG inventory uncertainty estimate

- Largest absolute contributors to uncertainty are: LULUCF, oil CO2, N2O, and CH4
- Uncertainty estimates are often asymmetric
  - *Although USA net sources and sinks is fairly symmetric.*
- Uncertainty is not always driven by the largest sources
  - *Even though industrial oil use is < 15% of oil CO2 emissions, this contributes 1/3 of oil uncertainty (Table 3-17)*

2020 Estimates - USA				
		Uncertainty Range		
Gas	Emissions (MMT CO2 Eq.)	Lower (%)	Upper (%)	Std Deviation (MMT CO2 Eq.)
CO2	4,716	-2%	4%	76
Coal	836	-3%	9%	23*
Gas	1,611	-1%	5%	19*
Oil	1,896	-6%	6%	61*
Other	373	na	na	na
CH4	650	-8%	11%	33
N2O	426	-20%	29%	53
PFC, HFC, SF6, and NF3	189	-3%	13%	8
LULUCF Sector Net Total	-759	35%	-22%	110
Net Emissions (Sources and Sinks)	5,222	-5%	6%	148
* Estimated				

Bounds represent a 2.5% - 97.5% confidence interval

EPA (2022) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020. U.S. Environmental Protection Agency, EPA 430-R-22-003. Tables 1-6 and 3-17. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions- and-sinks-1990-2020.

Bottom-Up (Inventory) Methods

Emission inventories can:

- Provide fine-scale detail by sector and fuel
  - *Very valuable for understanding sources of emissions (and potential mitigation options)*
- Spatial detail often provided by use of proxy data
  - *Use of proxy data is sometimes integral to emission estimation process*
  - *Even if average emission factors, etc. are accurate, site-specific variables are difficult to account for, leading to larger uncertainties at smaller spatial scales*
  - *Spatial uncertainty should not be confused with uncertainty in national values!*

Extensive data and assumptions, often based on measurements, feed into inventories

- Often difficult to update or validate even key data and assumptions

Atmospheric observations can provide some measure of verification of emission results

Concentration Measurement Methods

A variety of measurement methodologies can be used:

- Stack measurements (CEMS)
  - *“Gold standard” for emissions, although uncertainties still present*
- Surface measurements (fixed, mobile, and temporary)
  - *Samples shipped and measured in a central laboratory (can include isotopes)*
  - *“Real time” on-site measuring equipment (accuracy – expense tradeoff)*

  The set-up depends on the goal.
    - *Tower measurements reduce local influences to reflect regional signals*
    - *Surface measurements (“fence-line”, car/truck/ship, permanent station) can be used to estimate emissions from either a facility or region*
- Balloon sondes
  - *Commonly used for meteorological measurements, can be used for some GHGs using lightweight sensors (e.g. CO2, Palmer et. al 2018. https://doi.org/10.5194/acp-18-11753-2018)*

Concentration Measurement Methods (Cont)

- Aircraft measurements
  - *Generally not routine, but “one off” field campaigns with various purposes*
  - *Can, in-principle, measure where needed*
  - *Includes vertical distributions*
  - *Also sensors installed on routine civil air flights (also ships)*

- Satellite measurements
  - *Potentially large geographic and temporal coverage*
  - *See entire column not a specific atmospheric level*
  - *Geostationary vs other orbits (just see at a specific time)*
  - *Night vs day, cloudy vs clear-sky, winter vs summer*

None of these measure emissions
some method must be used to infer emissions from the observations.

Concentrations → Emissions

In general concentration measurements must be translated to emissions by adding information on flow velocity.

- For in-stack measurements flue gas flow velocities are measured.
- The most common data used for other types of measurements is three-dimensional estimates of wind speeds from metrological re-analysis data
- Flux towers also use local wind speed measurements at the tower (eddy co-variance method)
- Many methods make use of atmospheric transport models

Because GHGs are generally long-lived (~years or more) a modest number of stations can be used to estimate total net exchanges on large regional scales.

- However, depends on desired accuracy, magnitude of emissions, and goals of the observational program.
- *This is very different for air pollutants.* Because of their much shorter atmospheric lifetimes, a higher density of observations are needed to resolve emissions.

Concentrations → Emissions (cont)

Estimates based on observations can generally only provide total emissions, not anthropogenic emissions

- Isotope data can be used to provide information about emission sources
- In some locations natural emissions may be small enough to ignore or otherwise well characterized
- In some cases the observational focus is on “natural” emissions (*e.g.*, CO2), with fossil sources taken as “given” from bottom-up inventories. (uncertainty in fossil emissions much smaller than uncertainty in net ecosystem emissions)

UK GHG Concentration Measurements

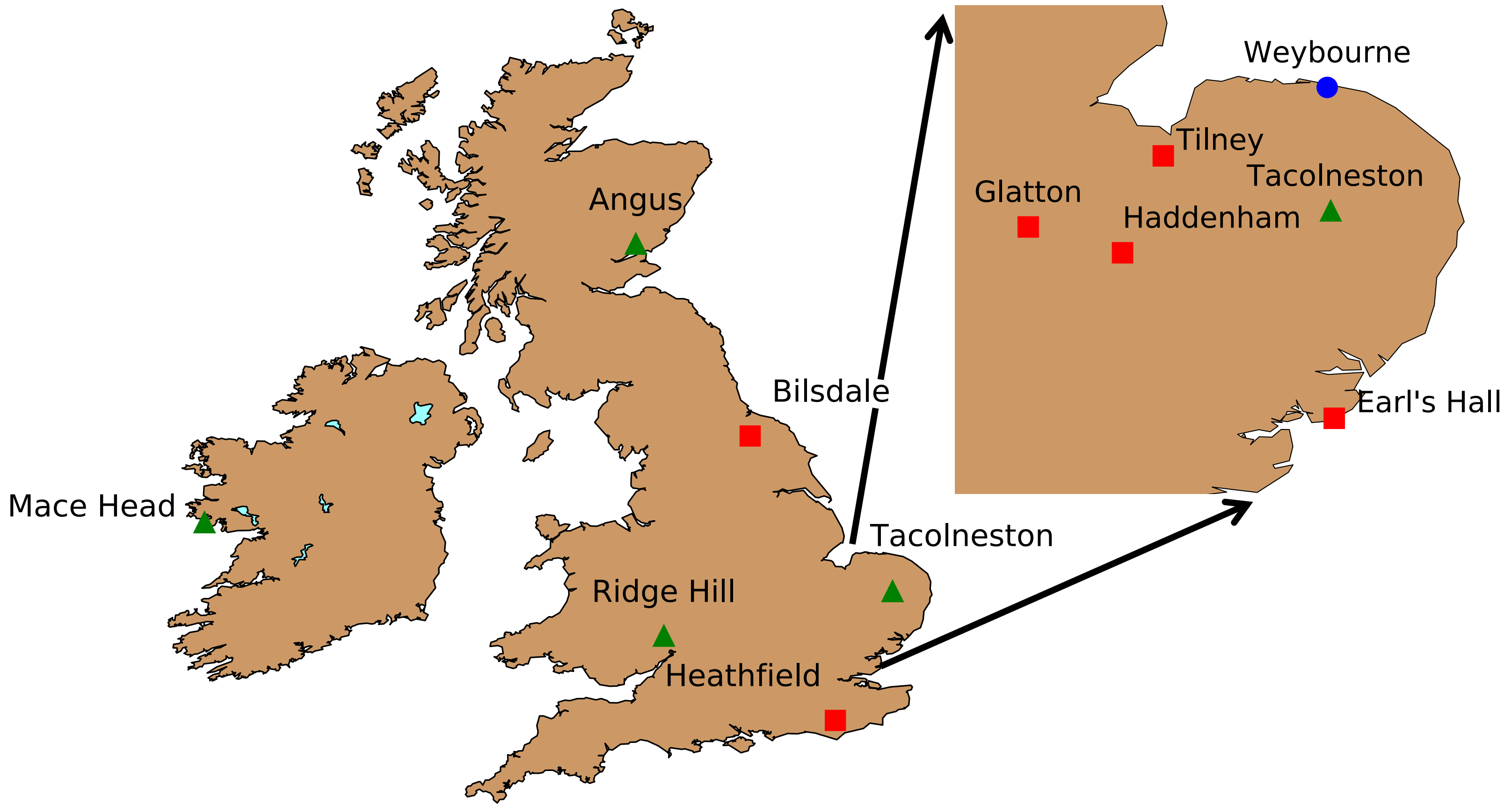


Figure 1. The UK DECC network funded by the UK government (sites denoted by green triangles, 2012–ongoing), the NERC GAUGE project (denoted by red squares, 2013–2015), and other (blue circle). Sites are described in Table 1 and Appendix A. The enlarged geographical region over East Anglia shows the church network. These sites are described in Table 4.

Much easier and less ambiguous to estimate emissions for an island!

Palmer et. al 2018. https://doi.org/10.5194/acp-18-11753-2018

Emission Estimates from Observations

Depending on the data and method used, emission estimates can be obtained for:

- A specific geographical area (Continental USA, UK, etc.)
- Specific point sources (estimates based on emission plumes or “fence-line” measurements)
- Spatially distributed emission estimates

Uncertainty will generally increase with a decrease in the size of the area considered

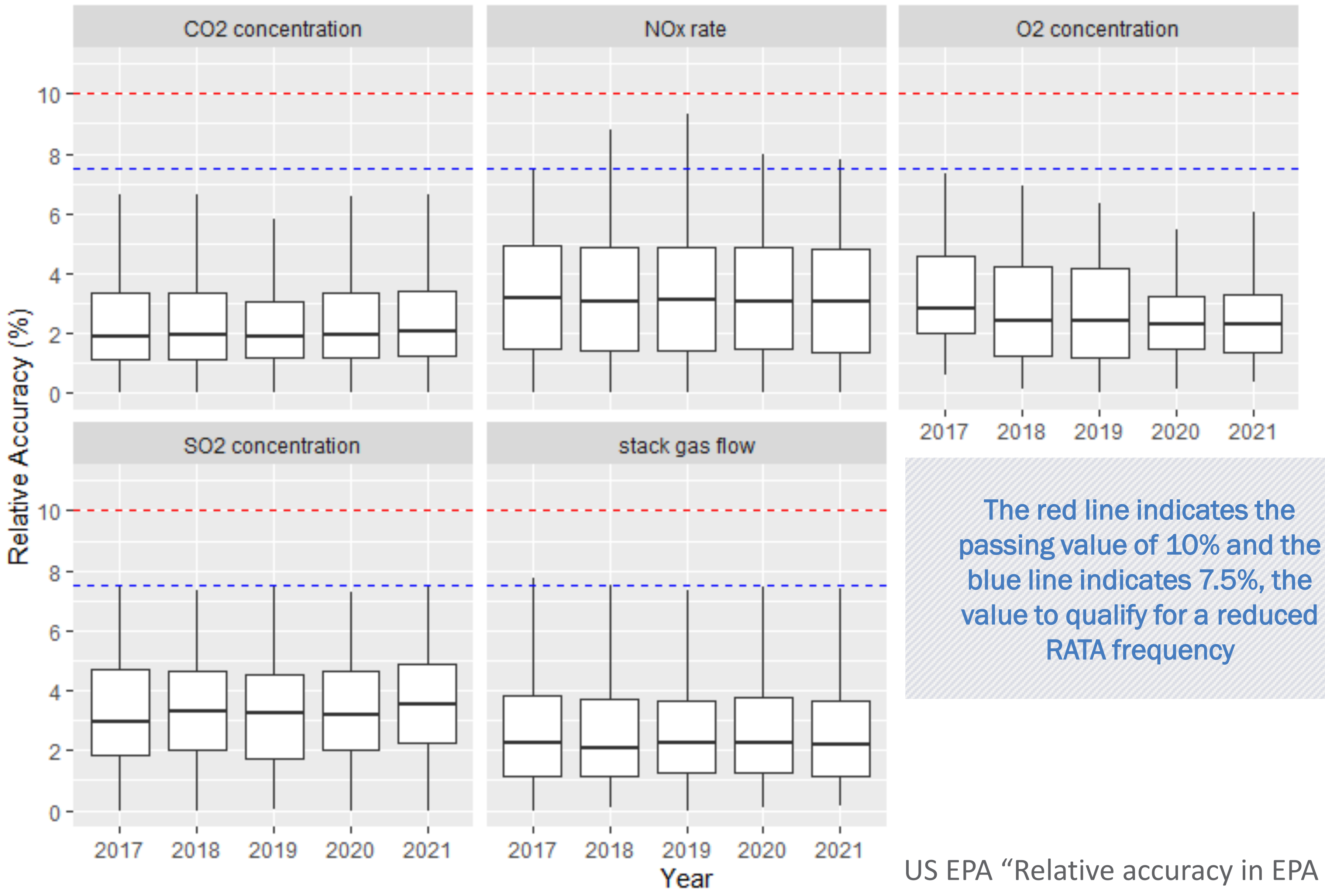
- More observations are required to obtain estimates for smaller geographic regions (*e.g.*, Lunt et al. 2021 – UK CH4 emissions well constrained, but not those for Scotland. https://doi.org/10.5194/acp-21-16257-2021)

- High uncertainty does not necessarily mean the data, however, Is not useful! (Detection of “large” CH4 point sources show where focused data gathering is warranted.)

Continuous Emission Monitoring Systems (CEMS)

Mandated in the US for large point sources, measuring CO_2, SO_2, NO_x.

Distribution of relative accuracy by year and parameter



The red line indicates the passing value of 10% and the blue line indicates 7.5%, the value to qualify for a reduced RATA frequency

Tested regularly against a reference method ("a relative accuracy test audit", or RATA).

However, the accuracy of the reference method, particularly flow rates, is difficult to quantify.

(See: Bryant et al. 2018, https://doi.org/10.6028/NIST.SP.1228)

US EPA "Relative accuracy in EPA CAMD's Power Sector Emissions Data", May 10, 2022.

An Example Regional Study

Observational constraints on methane emissions from Polish coal mines using a ground-based remote sensing network (Luther et al. 2022). https://doi.org/10.5194/acp-22-5859-2022

- … we report on CH4 emission estimates for coal mine ventilation facilities in the USCB *[Upper Silesian Coal Basin (USCB) in southern Poland]*.
- **pairwise upwind–downwind observations** … a network of **four portable, ground-based, sun-viewing Fourier transform spectrometers** … during the CoMet campaign in May–June 2018. … deployed in the four cardinal directions ...
- we inferred emissions .. using the Lagrangian particle dispersion model FLEXPART. … driven by wind fields calculated by WRF (Weather Research and Forecasting model) under assimilation of vertical wind profile measurements of three co-deployed wind lidars.
- our **instantaneous emission estimates** range between **80 and 133 kt** CH4 a^{-1} for the southeastern part of the USCB and between **414 and 790 kt** CH4 a^{-1} for various larger parts of the basin, suggesting higher emissions than expected from the annual emissions reported by the E-PRTR (European Pollutant Release and Transfer Register).
- **Uncertainties range between 23% and 36%,** dominated by the error contribution from uncertain wind fields.

Direct quotes from paper abstract.

Facility-level leak detection

Releases are often classified as either vented (intentional from normal process conditions) or fugitive (“leaks” - unintentional releases) emissions (Fox et al. 2019).

Technologies for detecting fugitive emissions range from close-range hand-held instruments (accurate but labor intensive) to a variety of screening technologies. Summarized by Fox et al.

Table 1. Comparison of CH4 leak detection technologies and methods (Fox et al. 2019)

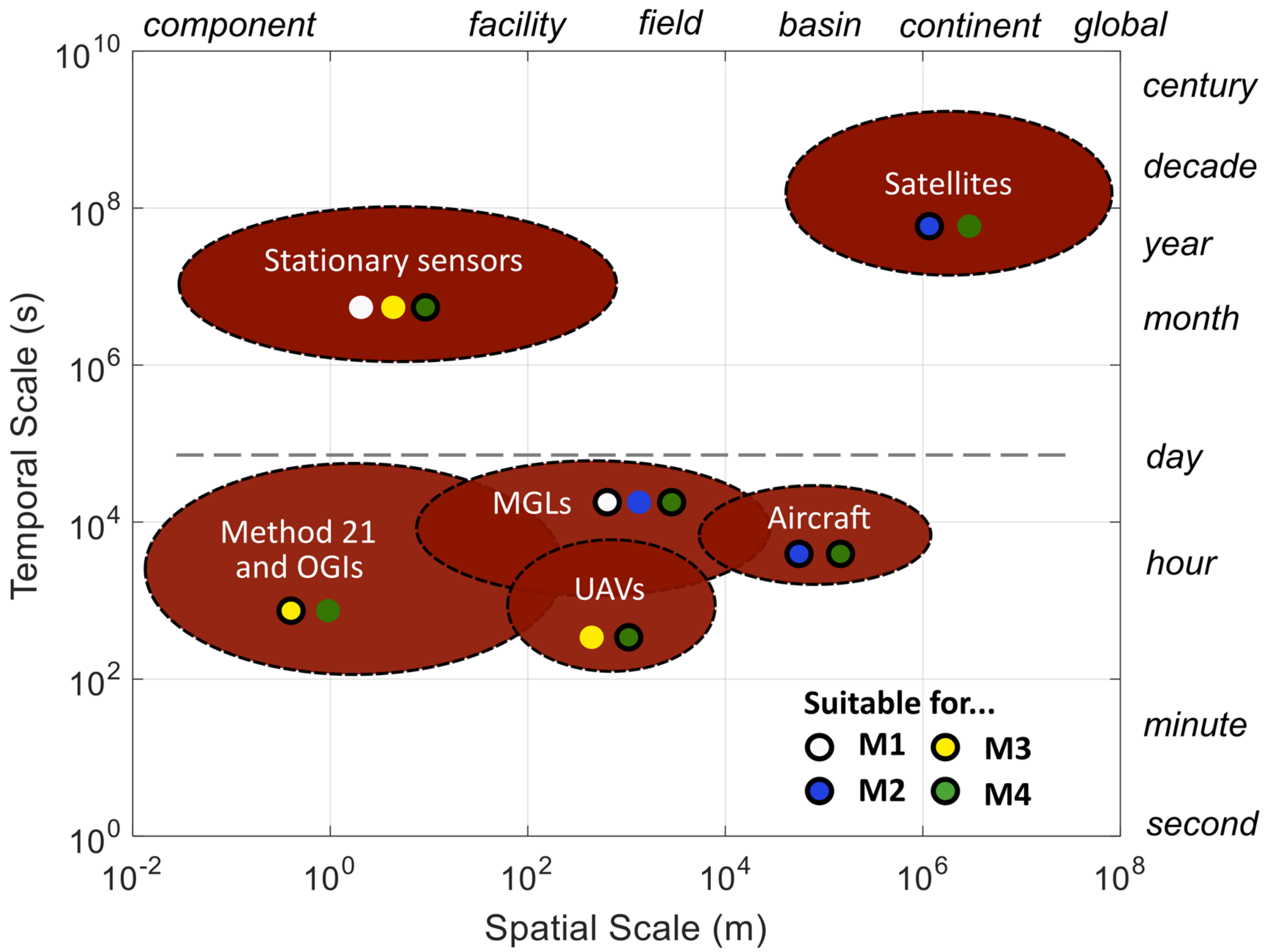
	Method 21	OGIs	Fixed sensors	MGLs—stationary	MGLs—tracer	MGLs—mobile	UAVs	Aircraft—facility-scale	Satellites—facility-scale
Limit of detection (g/h)	<1	20	96	9–36	$700–1.2\times10^4$	6–2124	39.6	$2000–4.6\times10^4$	$2.5\times10^5–68\times10^6$
Flux estimation uncertainty (%)	NA	3–15	31	25–60	20–50	50–350	25–55	1–24	Not Avail

MGL = Mobile Ground Lab; OGI = Optical Gas Imaging; UAV = Unmanned Aerial Vehicle

Method 21 - regulatory method introduced by EPA in 1983 (OGIs are now preferred)

A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas (Fox et. al 2019).
https://doi.org/10.1088/1748-9326/ab20f1

Facility-level leak detection (cont.)



- M1: Develop and refine emissions factors to improve inventories,
- M2: Estimate top-down emissions from a region with multiple sources,
- M3: Conventional, close-range LDAR using hand-held instruments, and
- M4: Rapid screening for anomalous emissions.

These motivations stem from two fundamental goals:

- Goal 1: Understand emissions (M1 and M2), and
- Goal 2: Mitigate emissions (M3 and M4).

Figure 2. Technology classes categorized based on the spatial and temporal extent of coverage. Colored dots represent suitability for measurement motivations 1–4. Dots without black borders either show promise or may be useful in a limited capacity.

A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas (Fox et. al 2019). https://doi.org/10.1088/1748-9326/ab20f1

GHG Evaluation Vignettes

- Bottom-up fossil CO2 combustion emissions are already quite accurate nationally, where high quality energy statistics and data on fuel characteristics are available
  - *A modest investment in bottom-up emission data might substantially reduce current uncertainties*
- Petroleum combustion emissions are the most uncertain fossil component (in the US)
  - *If the policy goal is to electrify the vehicle fleet then how much do we need to improve these estimates?*
- CH4 fugitive emissions depend strongly on technology, practices, and source characteristics (e.g. basin)
  - *Remote sensing techniques can already detect many sources, even intermittent sources*
  - *Near-term advances using a variety of techniques could substantially improve estimates for this sector*

Summary Points

- A range of technologies/methodologies will often be needed (*i.e.*, Fox et al. 2019)
- High priority should be given to sectors/sources where the error bounds of observationally-based estimates and inventory estimates do not overlap.
- Need to carefully prioritize resources where they will do the most good