IPCC Expert Meeting on Use of Atmospheric Observation Data in emission Inventories

5-7 September 2022

Geneva, Switzerland

INTERGOVERNMENTAL PANEL ON climate change

Task Force on National Greenhouse Gas Inventories (TFI)

Estimating fugitive CH_4 emissions from the detection of plumes using aeroplane flyovers

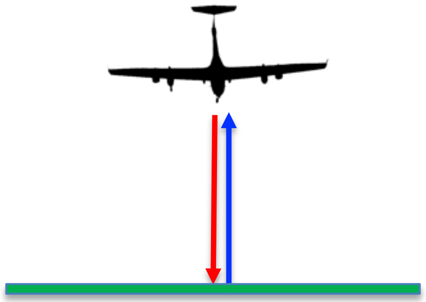
https://www.youtube.com/watch?v=89MtxxM-NTU

Associate Professor Bryce Kelly
The University of New South Wales, Australia

Presentation Focus

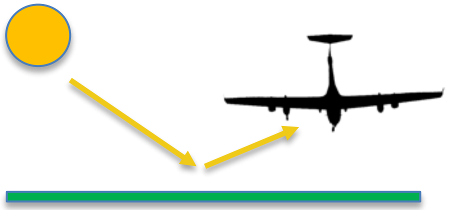
- How we used a regional mass balance emission estimate to "assess and critique" the bottom-up inventory methods for coal seam gas developments in Australia.
- Why the use of isotopes for source attribution and identifying inventory knowledge gaps should be more commonly used.
- Why aircraft-based atmospheric vertical profiles are critical for:
  - satellite verification
  - reducing emission estimate uncertainty and for identifying bias in national and global inverse models of in-situ and satellite observations.

Active Methods
LiDAR



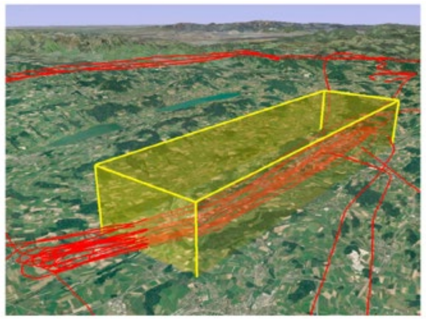
Example: Johnston et al. (2021) – controlled gas releases
Hunter and Thorpe (2017) – oil and gas

Passive Methods
Absorption Spectroscopy using Reflected Sunlight



Example: Sherwin et al. (2021) - controlled gas releases
Krautwurst et al. (2017) – landfills, spectral and mass balance

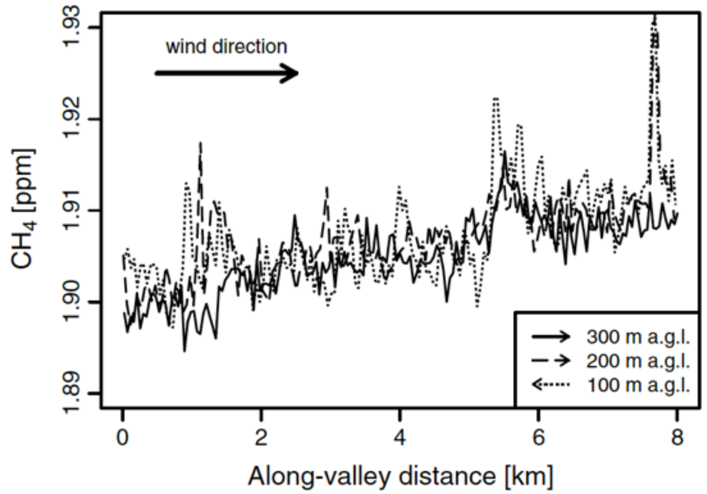
In-Situ Methods
Laser Absorption Spectroscopy

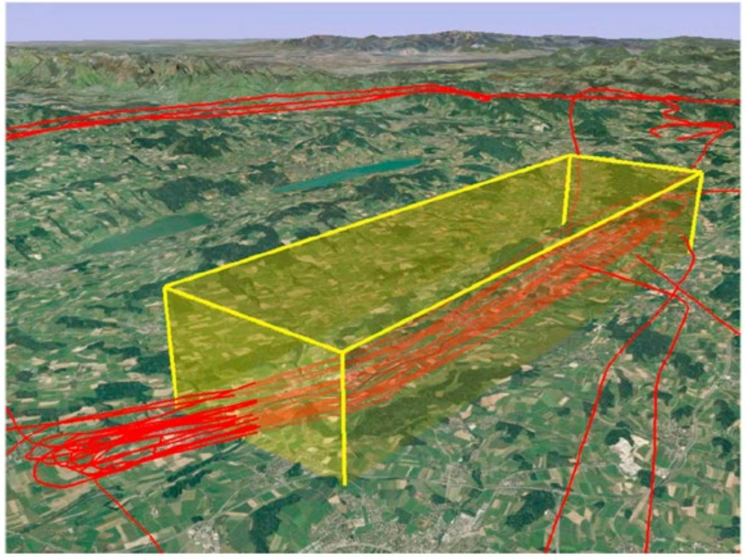


Example: Hillier et al. (2014) - agricultural sources
Alvarez et al. (2018) - oil and gas

Hiller et al. (2014) Aircraft-based CH_4 flux estimates for validation of emissions from an agriculturally dominated area in Switzerland

- Hiller et al. (2014) did one of the earlier BU vs TD studies. This study highlights that multiple measurement methods should be used and/or multiple analysis methods applied.
- They estimated emissions using two of the commonly applied methods:
  - Eddy Covariance, which considers vertical transport by turbulent eddies. This methods is often used for single long flights over wetlands, forests and agricultural regions.
  - Boundary Layer Budget, which quantifies the relative change in concentration into and out of the box (mass balance). This approach is used for many agricultural, urban, and oil and gas studies.
- The results of the Reuss Valley study were:
  Inventory 0.4 < Eddy Covariance 0.62 < Boundary Layer Budget 1.02
  (median μg CH_4 m^{-2} s^{-1})





Flight tracks (red lines) from 7 April 2010 along the Reuss Valley. The yellow box indicates the box used in the boundary layer budget approach. The view is toward northwest.

Aircraft-Based Measurements and Mass Balance CH_4 Emission Estimates
Surat Basin, Australia

UNEP: Methane Science Studies to Generate Accurate, Public Data

In 2015, a series of methane science studies was initiated to improve the understanding of global methane emissions from the oil and gas industry. Through these peer-reviewed studies, scientists continue to investigate and measure methane emissions across the oil and gas supply chain, generating accurate, public information about where and how much methane is leaking. The results of ongoing and future studies will improve understanding of methane emissions at a global level, allowing industry, governments, and other stakeholders to prioritize actions to reduce methane emissions.

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Switzerland

Stefan Schwietzke

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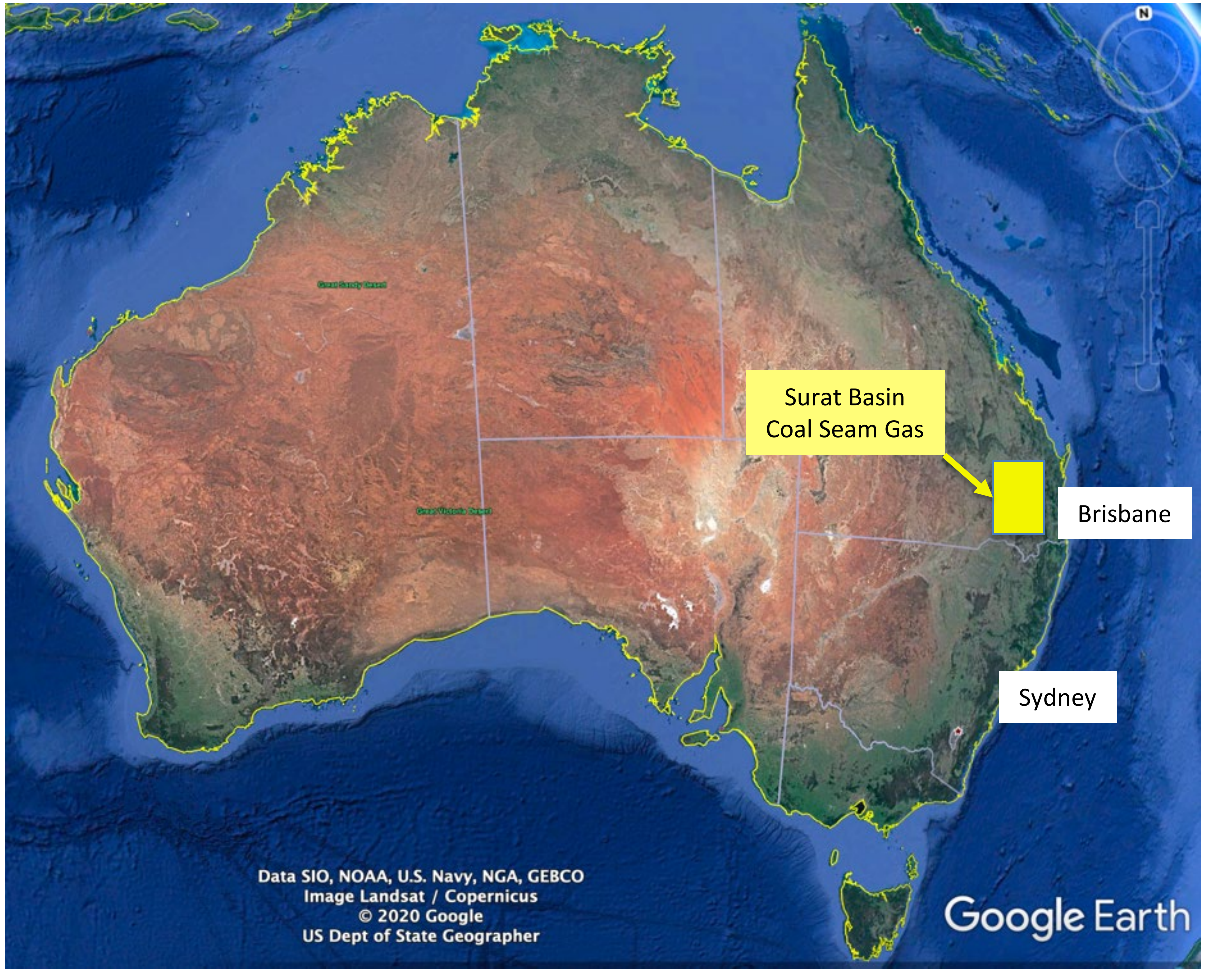
Study Background



The Surat Basin is one of the largest coal seam gas (CSG) developments in the world and is located north-west of Brisbane.

The subregion we surveyed covers an area of approximately 200 km x 200 km.

It is anticipated that when fully developed there will be over 20,000 CGS wells and supporting infrastructure.

In 2018 the total gas produced was 8912 Mm^3.(data.qld.gov.au).

At the start of the project there were limited emission data in the public domain:

- Katestone bottom-up inventory (appendix Luhar et al. 2018, 2020). Nonstandard methods and emission factors.
- CSIRO used the Katestone inventory as a prior for their two-tower inversion study (Luhar et al. 2018).

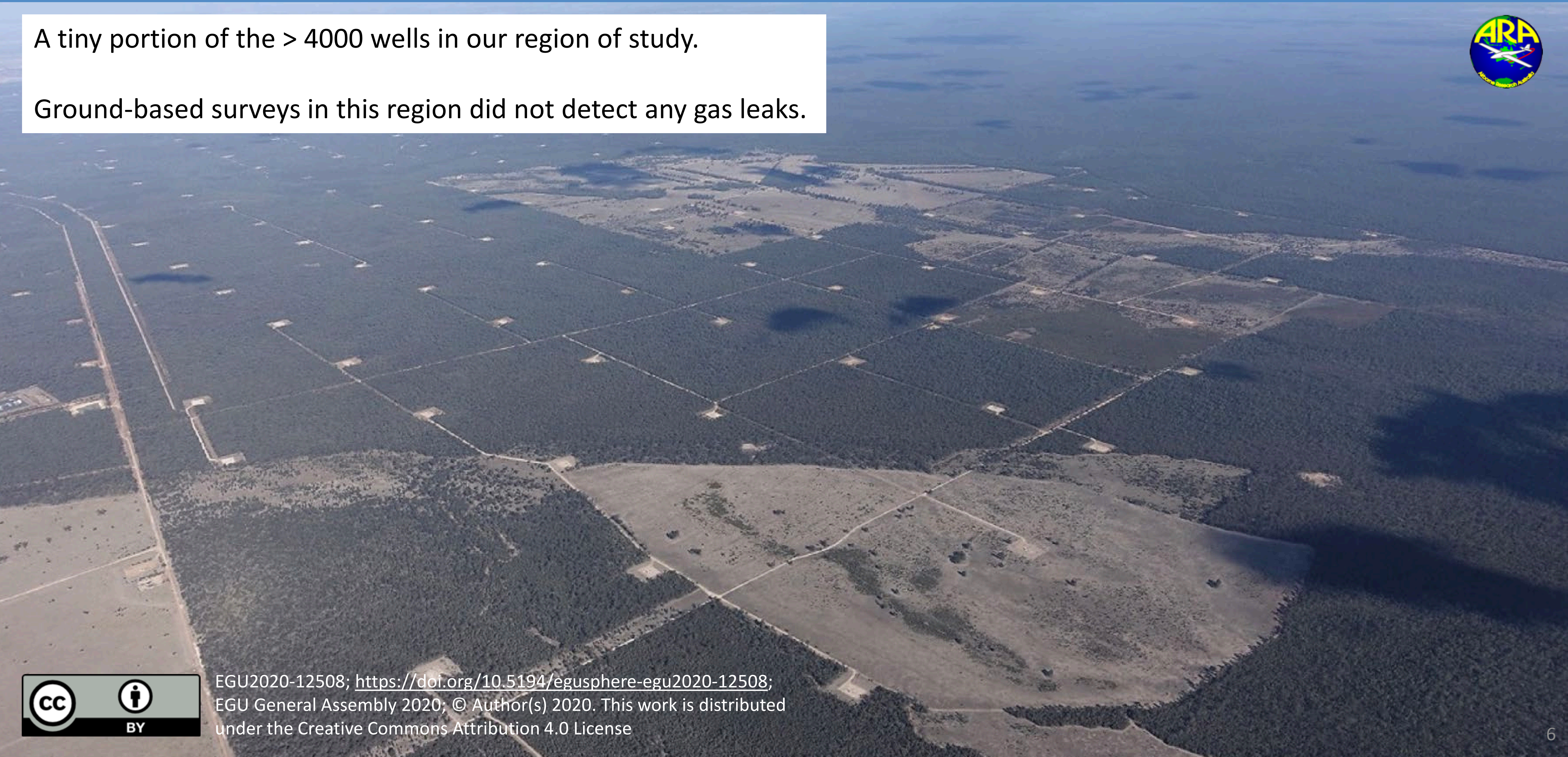
Full details for the study are published in:

Neininger BG, Kelly BFJ, Hacker JM, LU X, Schwietzke S. 2021 Coal seam gas industry methane emissions in the Surat Basin, Australia: comparing airborne measurements with inventories. Phil. Trans. R. Soc. A 379: 20200458. https://doi.org/10.1098/rsta.2020.0458

Background – Gas Wells

A tiny portion of the > 4000 wells in our region of study.

Ground-based surveys in this region did not detect any gas leaks.



Background – Typical Gas Facilities

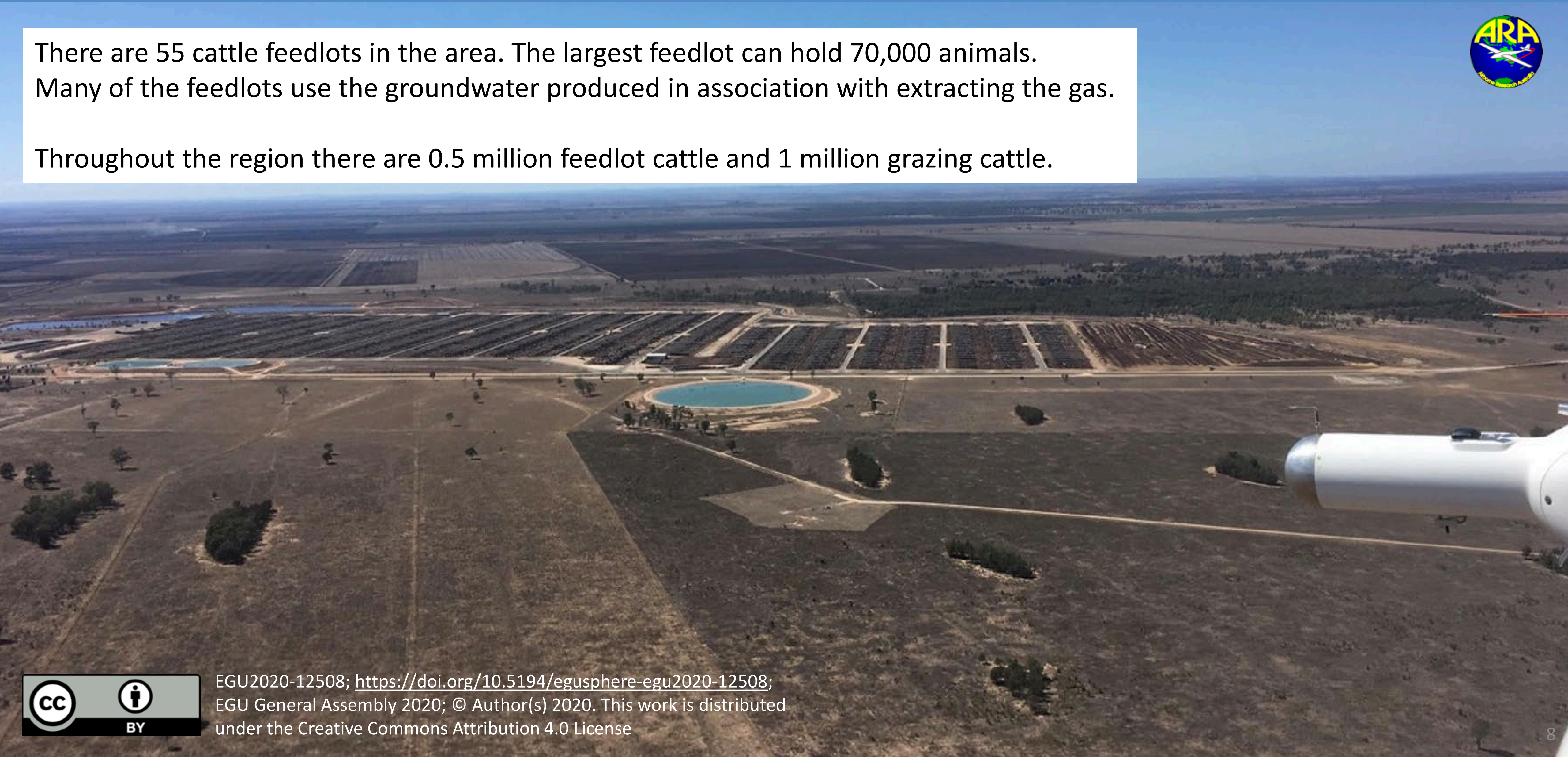
There are 38 CSG facilities: gas compressor stations and processing plants.

In addition to emissions from the CSG facilities, we have mapped emissions from the water pipeline high point vents and the raw water holding ponds.

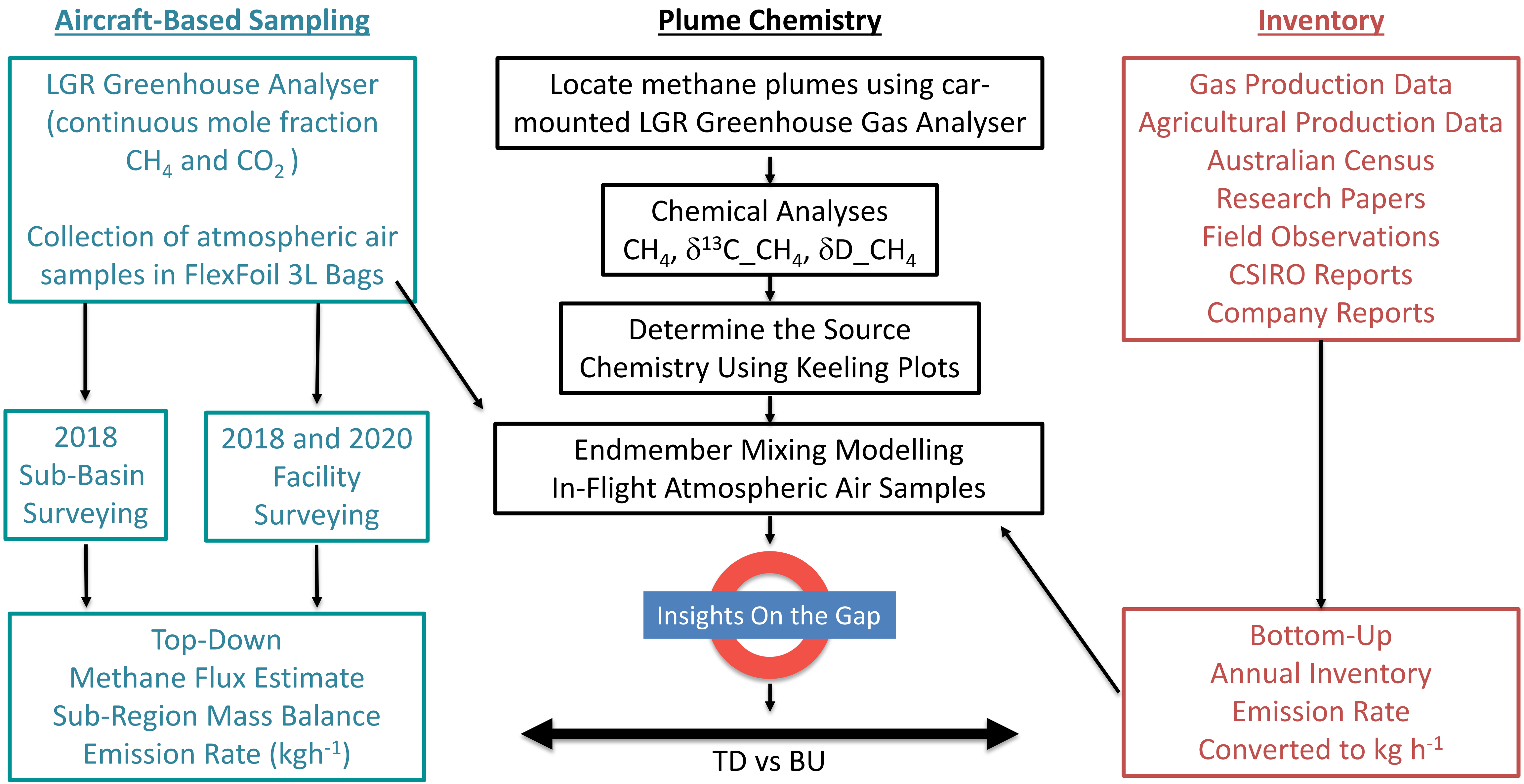
Background – Feedlot

There are 55 cattle feedlots in the area. The largest feedlot can hold 70,000 animals.
Many of the feedlots use the groundwater produced in association with extracting the gas.

Throughout the region there are 0.5 million feedlot cattle and 1 million grazing cattle.



Methodology for Bottom-Up vs Top-Down and Source Apportionment



CH_4 Emission Estimates: Bottom-Up Inventory versus Top-Down Aircraft-Based UNEP, Surat Basin, Queensland, Australia

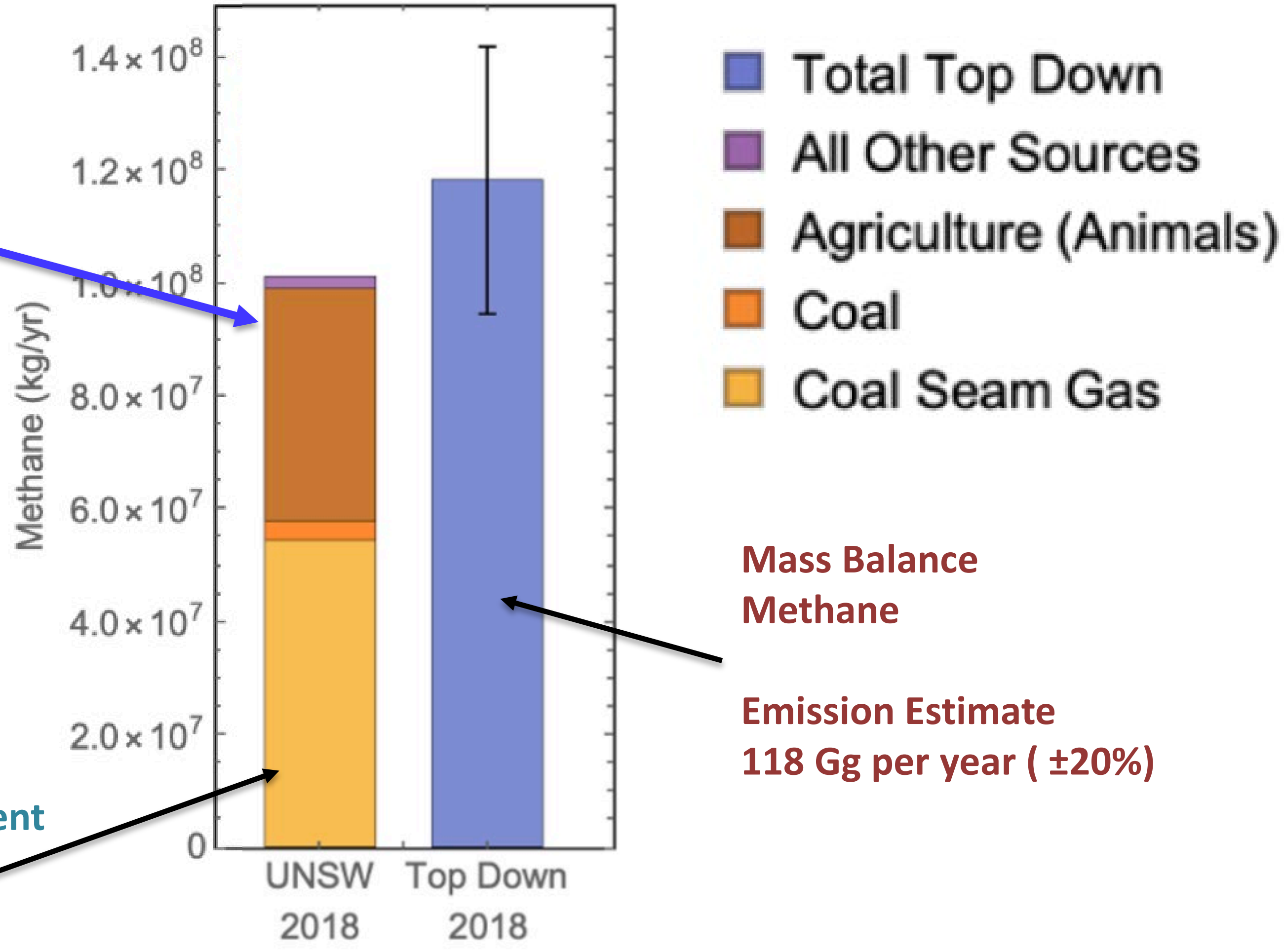
In Australia, there is no block or facility-scale inventory in the public domain.

We used public domain gas and agricultural production data and worked closely with the national inventory team to produce the UNSW Inventory (it is like the National Inventory).

The bottom-up inventory is less than the top-down estimate for the regions, but within the 20% uncertainty bounds of the top-down estimate.

Bottom-Up
IPCC and
Australian Government
Methods

Methane
Emissions
101 Gg per year



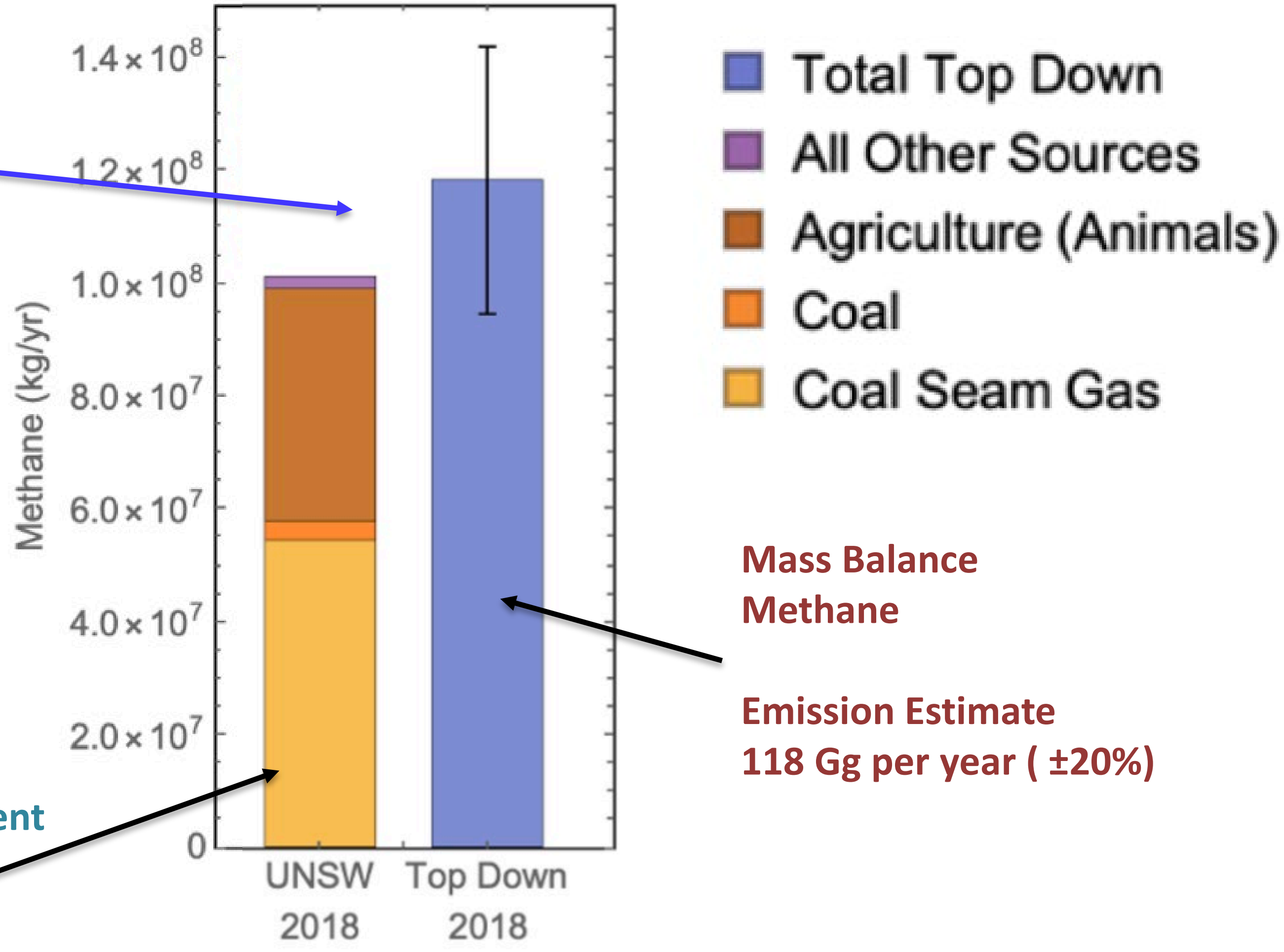
Mass Balance
Methane

Emission Estimate
118 Gg per year (±20%)

Neininger BG, et al. (2021) https://doi.org/10.1098/rsta.2020.0458

CH_4 Emission Estimates: Bottom-Up Inventory versus Top-Down Aircraft-Based UNEP, Surat Basin, Queensland, Australia

I will discuss how we calculated our mass balance estimates of methane emissions from coal seam gas and agriculture.



Mass Balance Methane

Emission Estimate 118 Gg per year (±20%)

Bottom-Up IPCC and Australian Government Methods

Methane Emissions 101 Gg per year

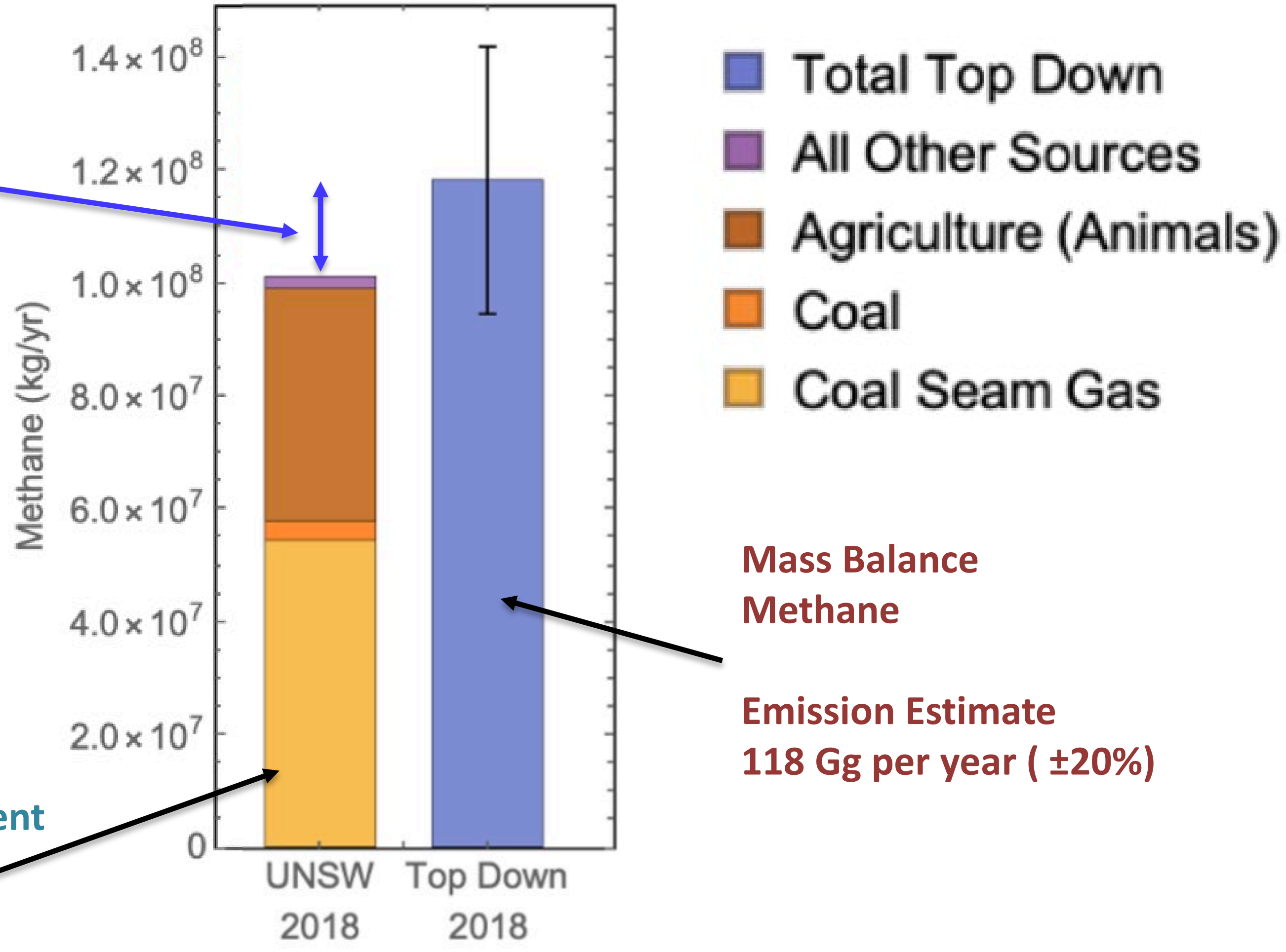
Neininger BG, et al. (2021) https://doi.org/10.1098/rsta.2020.0458

CH_4 Emission Estimates: Bottom-Up Inventory versus Top-Down Aircraft-Based UNEP, Surat Basin, Queensland, Australia

Insights On the Gap

I will also discuss potential reasons for the gap.

We get insights from the:
- subregion mass balance survey
- isotopic composition of methane ($\delta^{13}C_{CH4}$) in in-flight collected atmospheric air samples



Bottom-Up IPCC and Australian Government Methods

Methane Emissions 101 Gg per year

Mass Balance Methane

Emission Estimate 118 Gg per year (±20%)

Neininger BG, et al. (2021) https://doi.org/10.1098/rsta.2020.0458

Does the bottom-up inventory estimate for coal seam gas = the top-down aircraft-based mass balance emission estimate ?

- Australia’s National Inventory Report uses various approved methods for oil and gas, which are based on the best available science and use mostly accessible public data.

- Summarising the methods:

    - Emissions from wells, gathering and boosting stations, and processing plants are a function of tonnes of gas throughput.

    - Emissions from the co-produced water are a function of how many megalitres of water are produced as part of the gas extraction operations.

    - There is also an emissions estimate for each kilometer of pipeline.

    - Coal emissions were estimated from tonnes of coal produced.

    - Waste and urban emissions from annual government reports.

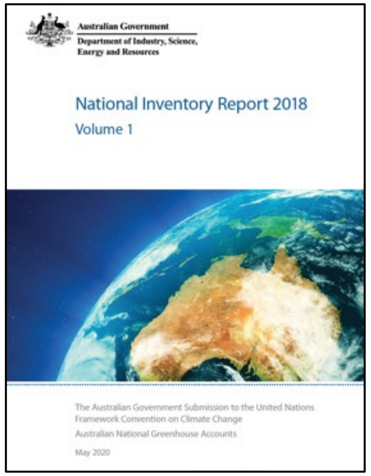


Table 3.44 Fugitive emission factors for natural gas

Inventory category	Unit	Factor		Source
		CO_2	CH_4	
Onshore Natural Gas wells	tonnes of emissions / tonne of gas throughput	0.00013[(a)]	0.000047	Day *et al.* 2014
Offshore natural gas platforms (shallow water)	tonnes of emissions / platform	171.8[(a)]	62.6	US EPA NIR Table A-134 (2016)
Offshore natural gas platforms (deep water)	tonnes of emissions / platform	1,813.9[(a)]	661.1	US EPA NIR Table A-134 (2016)
Onshore coal seam gas wells	tonnes of emissions / tonne of gas throughput	0.00013[(a)]	0.000047	CSIRO 2014
Produced water	tonnes of emissions / Megalitre of water produced		0.31	NGER Method 2 (API 2009)
Gathering and boosting stations	tonnes of emissions / tonne of gas throughput	0.0041[(a)]	0.0015	Mitchell *et al.* 2015
	tonnes of emissions / pipeline kilometre	0.63[(a)]	0.23	NGER Method 2 (API 2009)
Gas processing plants	tonnes of emissions / tonne of gas throughput	Modelled	Modelled	Mitchell *et al.* 2015
Natural Gas Transmission and Storage	tonnes of emission / kilometre of pipeline	0.02	0.41	NGER Method
	tonnes of emission / storage station		370	US EPA NIR Table A-134 (2016)
Natural Gas Distribution	Various	Various	Various	See Table 3.43
LNG storage	tonnes of emission / LNG storage station	2,527.0	921	US EPA NIR Table A-134 (2016)
LNG terminals	tonnes of emission / LNG terminal	3,042.8	1,109	US EPA NIR Table A-134 (2016)
Abandoned gas wells	tonnes of emissions / well		Various	See Table 3.42
Post-meter leakage	Various	Various	Various	See Table 3.47

https://www.industry.gov.au/sites/default/files/2020-05/nga-national-inventory-report-2018-volume-1.pdf

Livestock Emission Factors

For Livestock we used the country-specific tier 2 methods

Table 5.12 Implied EFs – enteric fermentation (kg CH_4/head/year)

Livestock Type	Australia	IPCC Default [(a)]
Dairy Cattle	95	93
Beef Cattle – Pasture	51	63
Beef Cattle – Feedlot	67	63
Sheep	6.7	9
Swine	1.6	1.5

Source: (a) IPCC 2019

Table 5.17 Implied EFs – Methane manure management (kg/head/year)

Livestock Type	Australia	IPCC Default (Oceania)
Dairy Cattle	15	23–31
Beef cattle		
Pasture	2.89	1–2
Feedlot	3.4	1–2
Sheep	0.34	0.19–0.37
Swine	23.24	11–24
Poultry	0.07	0.02–1.4

Source: IPCC 2006, CS = country specific; EF = emission factor; VS = volatile solids.

https://www.industry.gov.au/sites/default/files/2020-05/nga-national-inventory-report-2018-volume-1.pdf

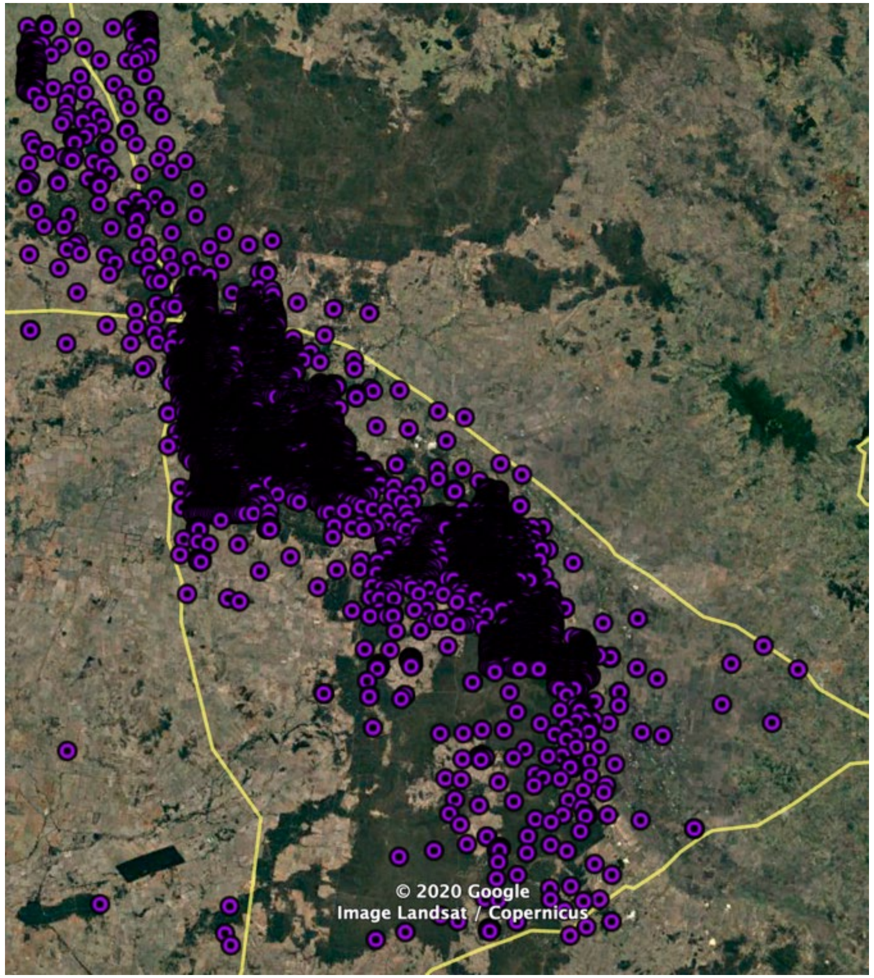
Challenges and Potential Improvements

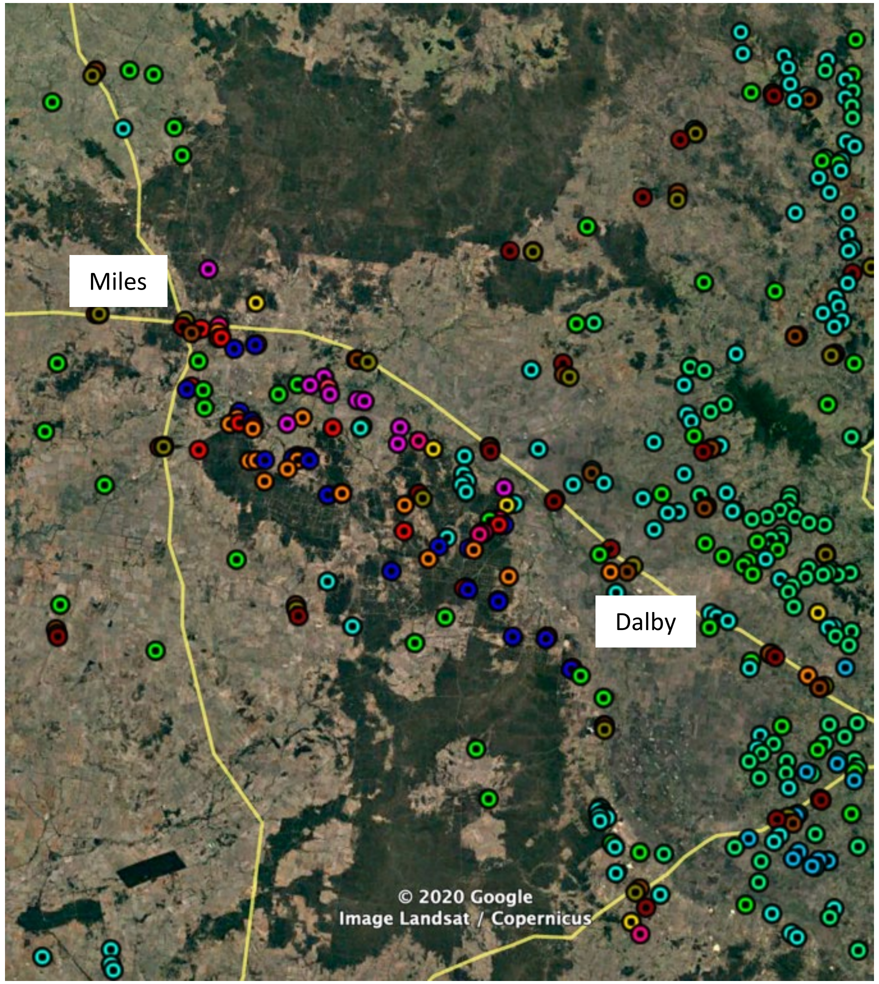
- Where do you position 1 million grazing cattle in the landscape?
- We only had access to yearly animal counts. Ideally, seasonal agricultural bottom-up emissions should be determined.
- There are large agricultural areas in our study where we underestimated emissions. This could be due to emissions from feedlots being underestimated.
- Ideally, inventory uncertainty analyses should be done using Bayesian and Monte Carlo methods.

Inventory – Point Sources of Methane

Over 4600 wells have been drilled in the study region as part of exploration and development operations, and **in 2018 there were approximately 1300 producing wells** in the study area.

392 other methane point sources were identified from Google Earth, government data sets, listed companies' annual reports, and environmental impact statements.





Sources

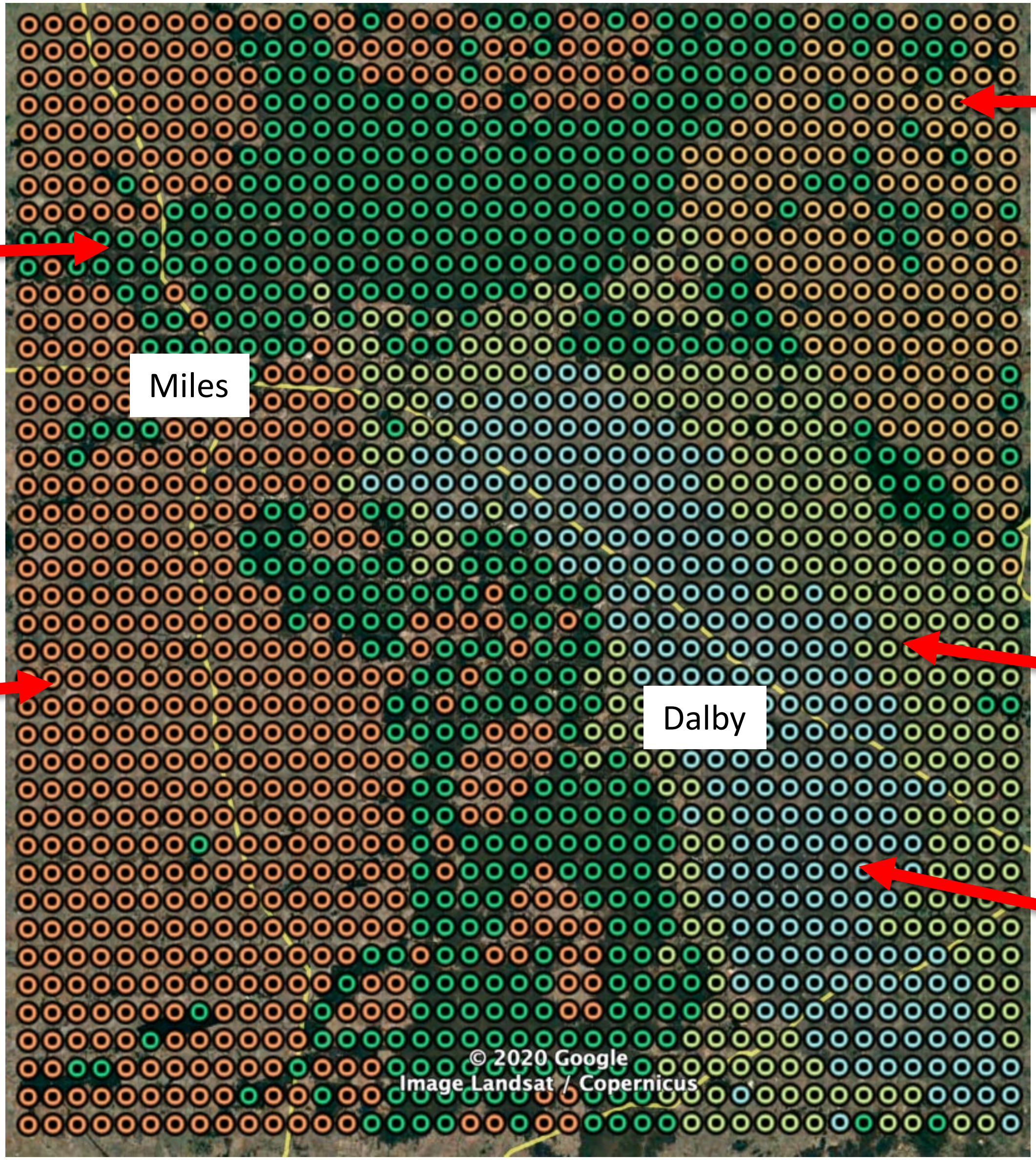
- CSG wells
- CSG processing plants
- CSG compressor stations
- CSG raw water ponds
- Coal mines
- Power stations
- Ground seeps of unknown origin
- Historical exploration wells seeps
- River gas seeps
- Cattle feedlots
- Cattle dairy
- Piggeries
- Poultry farms
- Landfills
- Wastewater treatment plants
- Domestic wood fires

Inventory – Diffuse Sources of Methane

200 km E-W
225 km N-S

Green
Forest, kangaroos
(but we had no estimate for termites)

Dark Orange
Queensland Murray Darling Basin ABS area
Dryland Cropping and Grazing



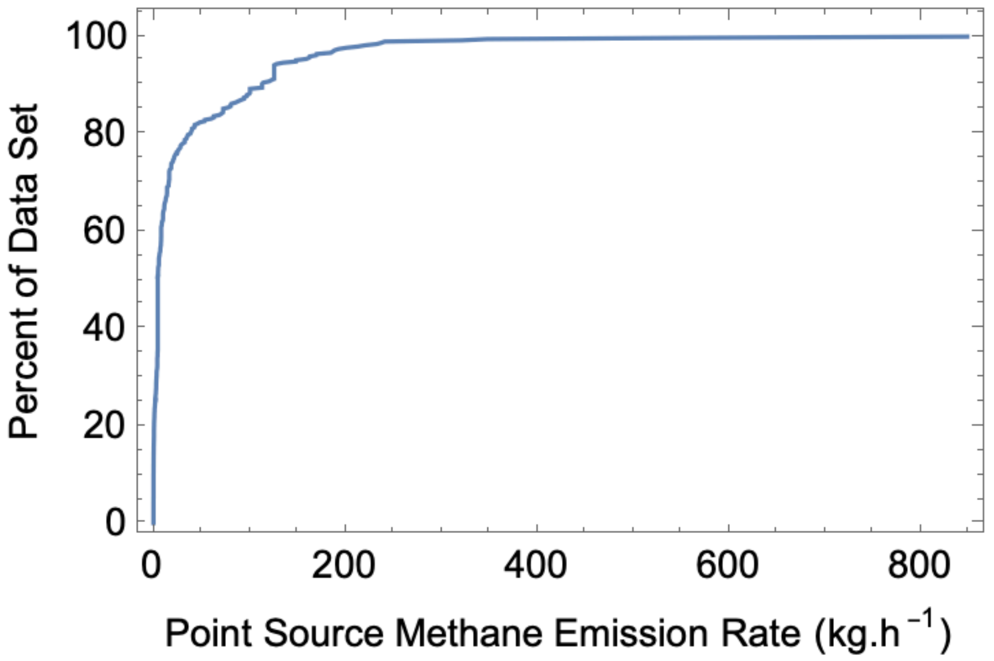
Orange
Burnett Mary ABS area
Dryland Cropping and Grazing

Light yellow
Condamine ABS area
Dryland Cropping and Grazing

Light Blue
Condamine ABS area
Irrigated Agriculture

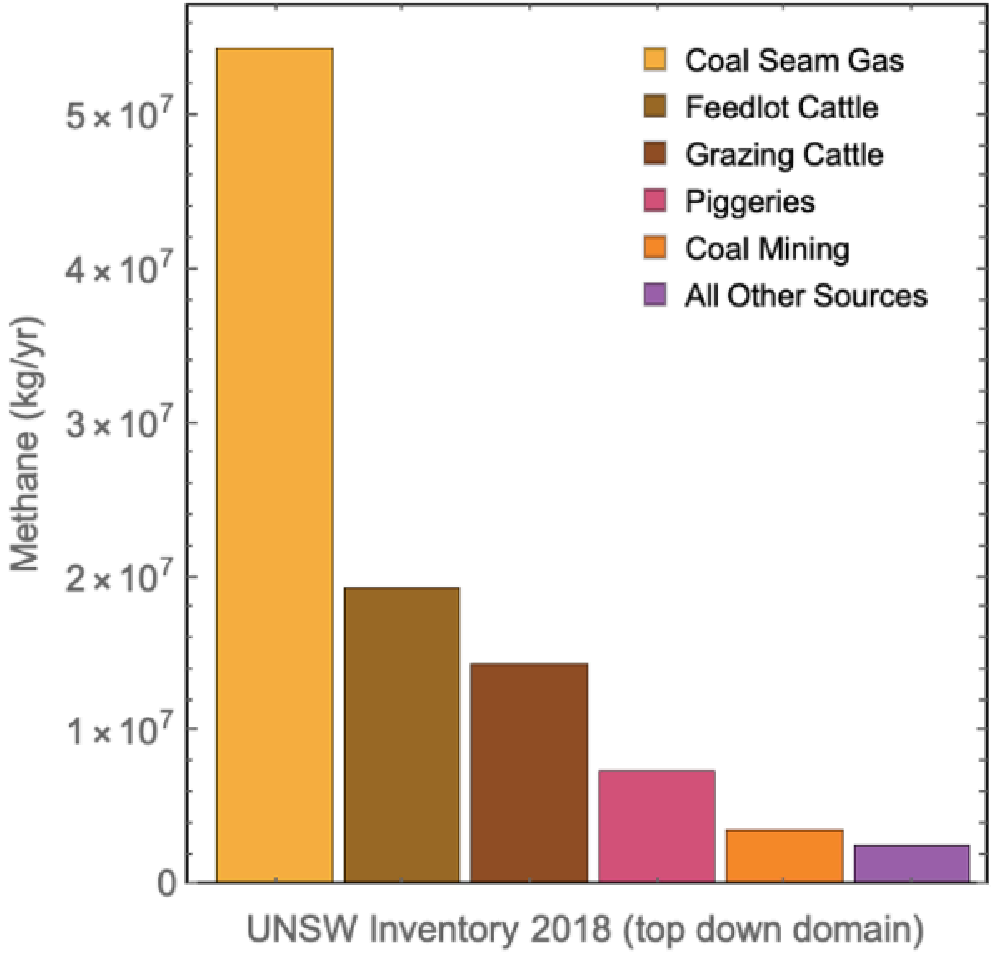
UNSW Inventory Domain

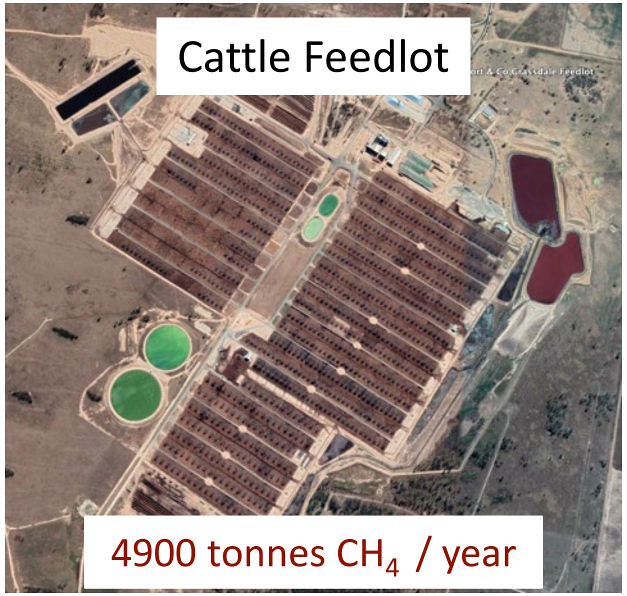
- Within the UNSW inventory domain, 50 % of point sources have an emission rate of less than 4.5 kg h^{-1}. These point sources account for 59 % of the UNSW inventory total.
- The top 10 % have an emission rate exceeding 113 kg h^{-1}.
- The 42 sources in the top 10 % account for 37.7 % of the UNSW inventory total.

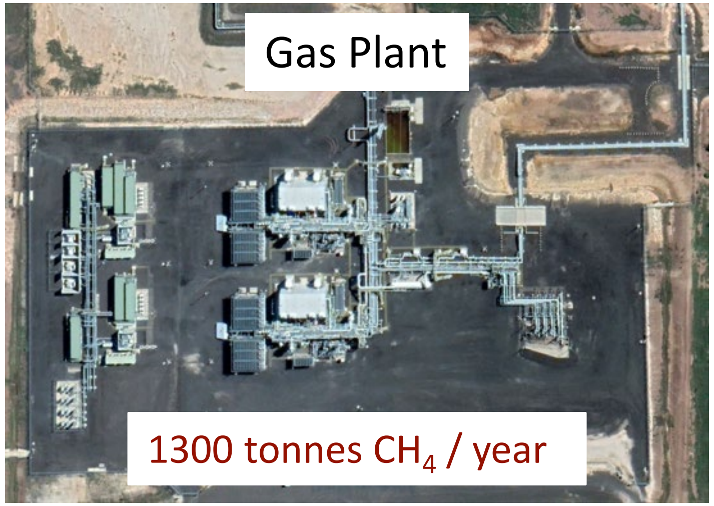


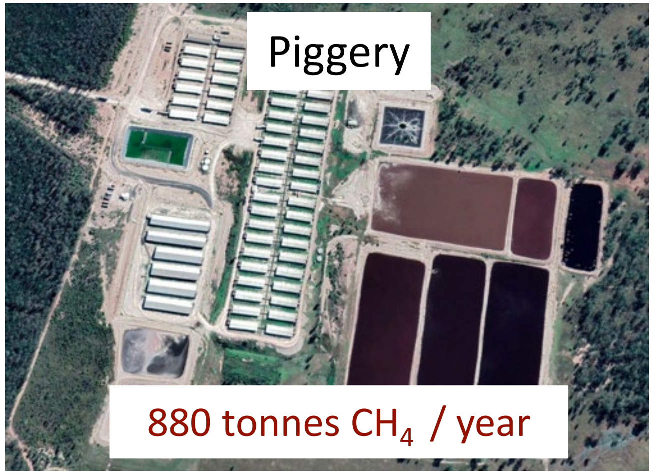
Cumulative probability distribution of CH_4 point source emission rates (kg.h^{-1}) for the 392 point sources in the Surat Basin UNSW inventory domain (this excludes the CSG wells).

Inventory Summary Within the Aircraft Measurement Domain









Neininger BG, et al. (2021) https://doi.org/10.1098/rsta.2020.0458

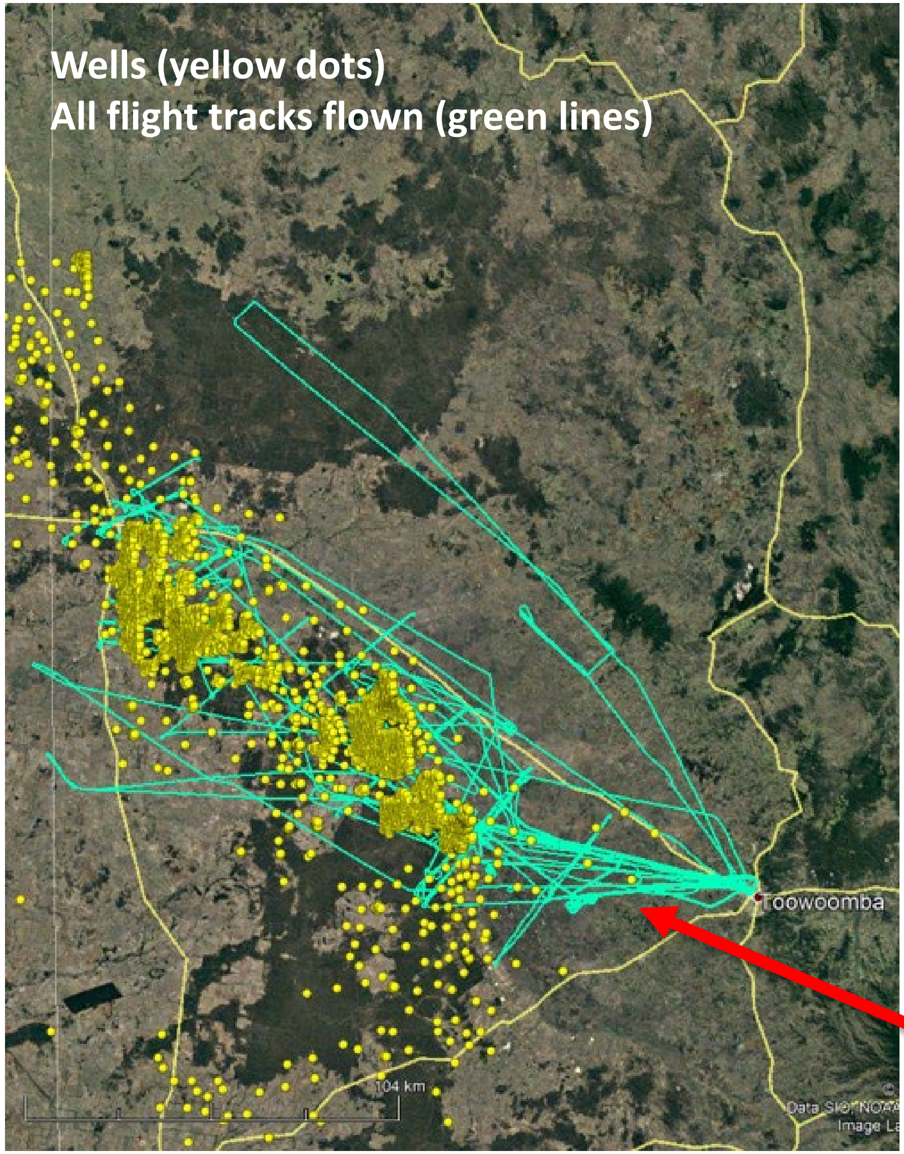
Aircraft Measurement Systems

- We did 13 measurement flights over 15 days.
- Most flights were at 150 to 300 m above ground level and flown at a cruising speed of 150 to 170 km/h.
- Vertical profiles from above the convective boundary layer to 150 m were done at the start and end of each session.

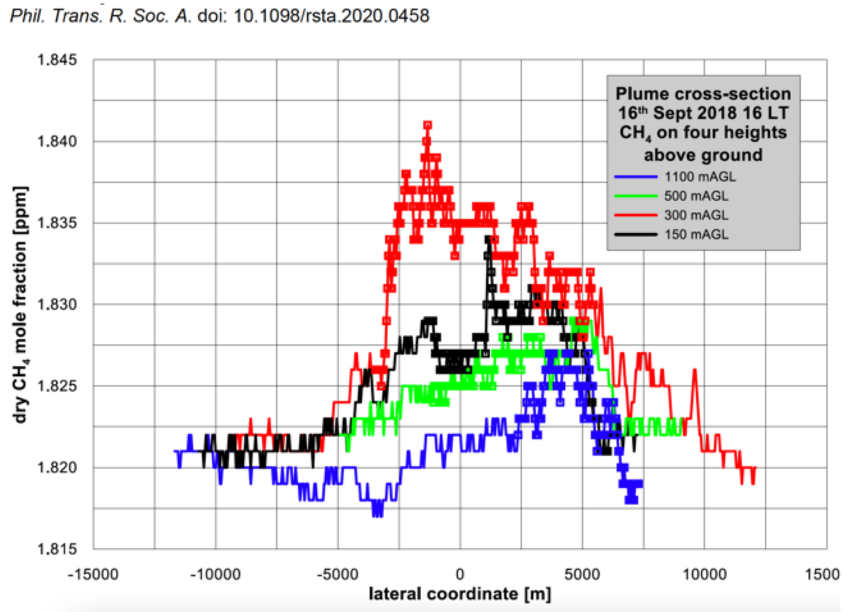
MetPod with the 3D-turbulence probe and internally mounted LiCOR LI-7500 (CO_2) and MetOne particle counter mounted on one of the wing pylons

LGR greenhouse CH_4 and CO_2 analyser and pump

Aeroplane Campaign

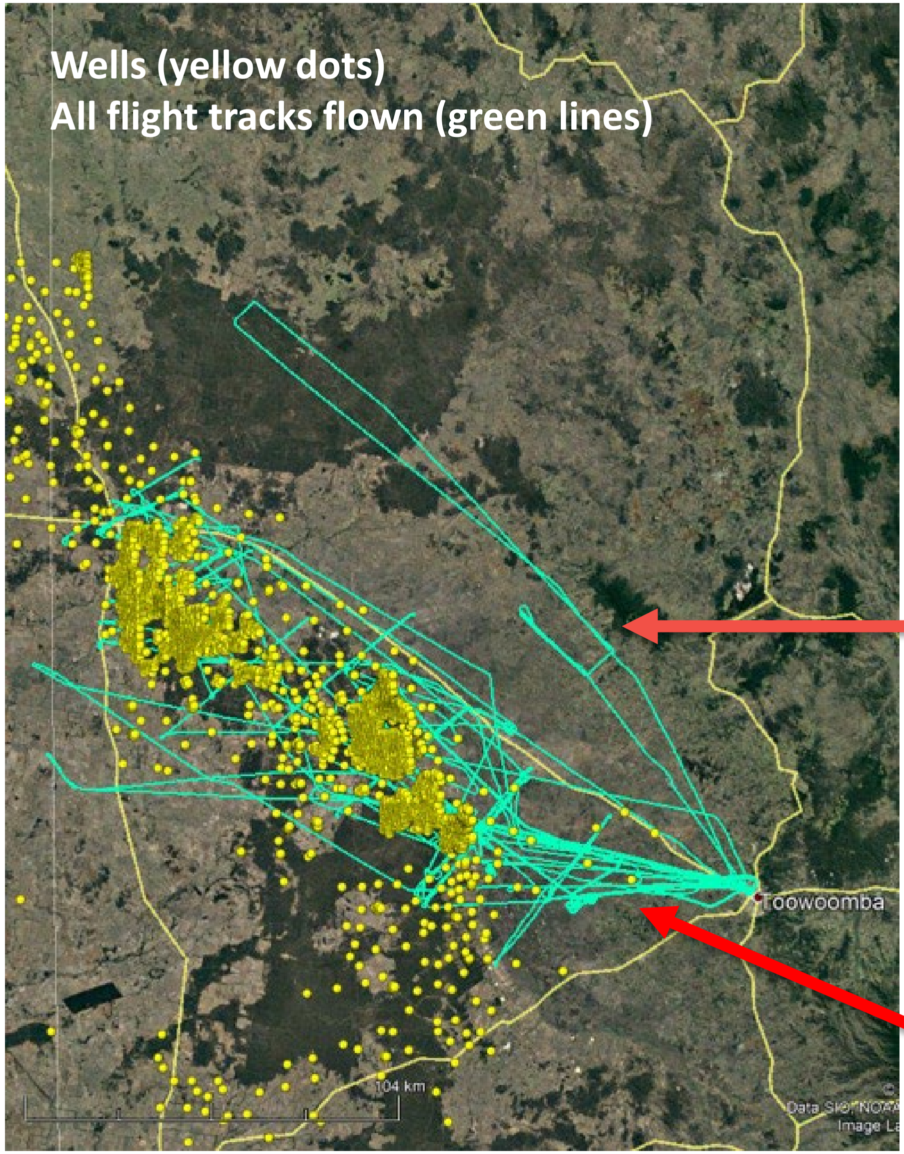


- The maximum methane enhancement above background recorded was 40 ppb.
- Even at this low level of methane enhancement the isotopic composition of methane proved to be a useful tool for verifying the upwind inventory and identifying inventory knowledge gaps.



- The cyan lines are the flight tracks. Having overlapping mass balance subregions is critical to reducing the uncertainty in the emission estimate.

Aeroplane Campaign



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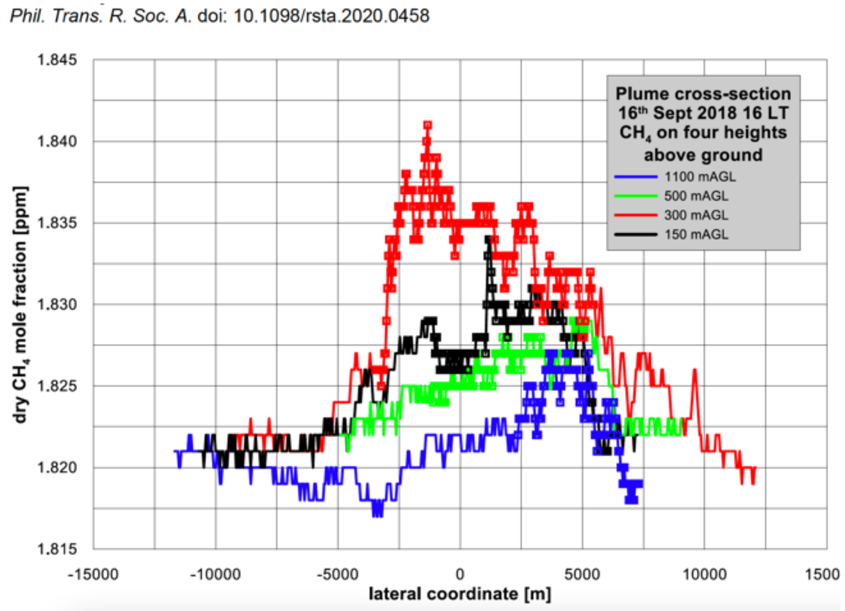

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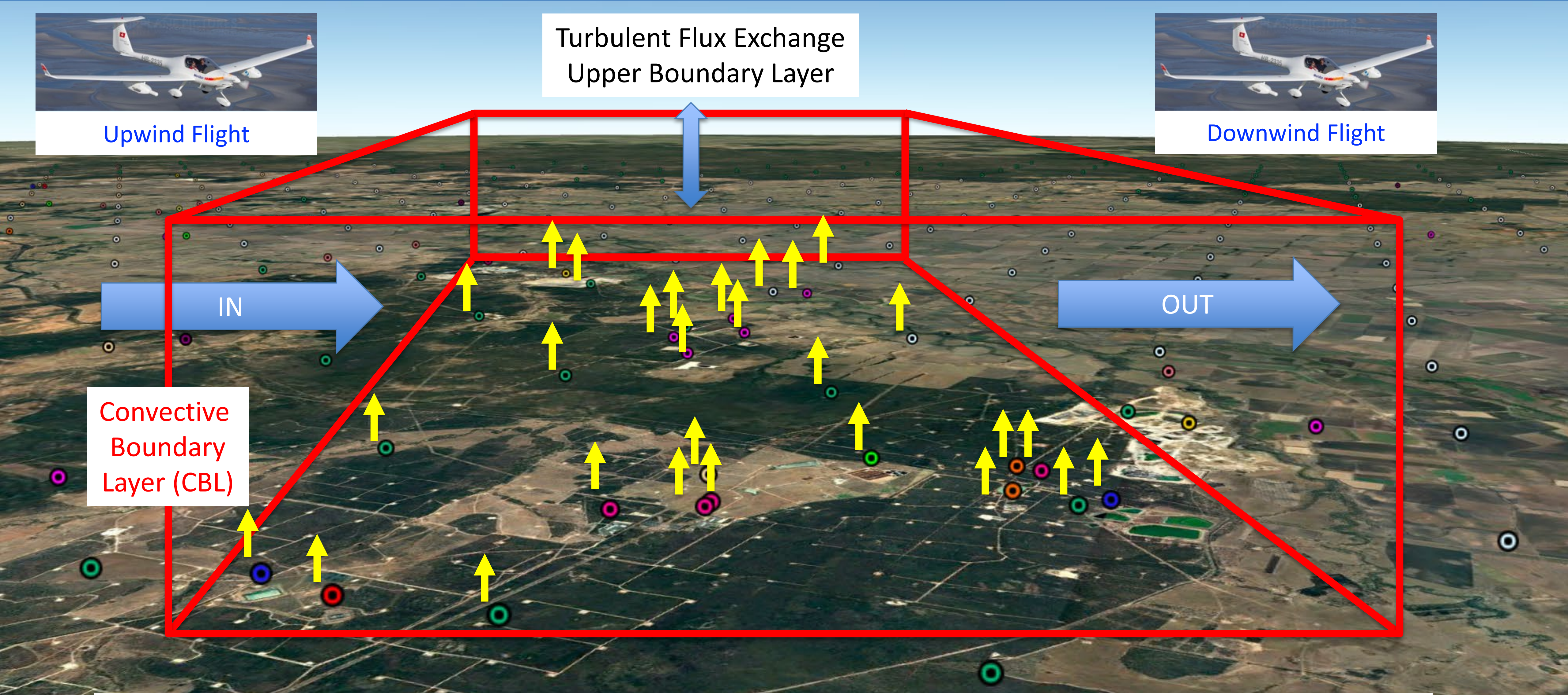
In-Flight Measurements of Atmospheric Methane Mass Balance – Rate of Methane Emissions (kg h^{-1})



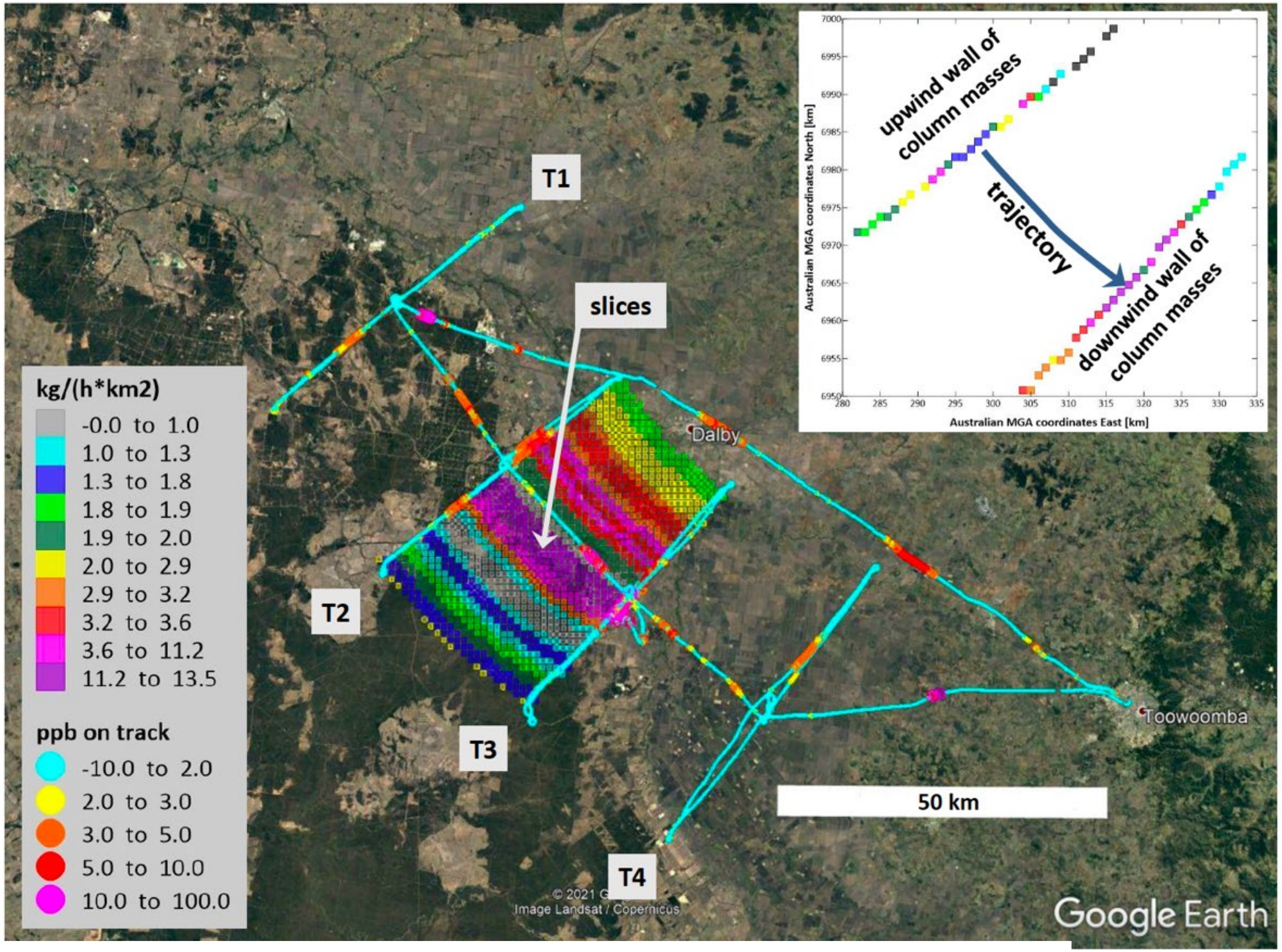
Flying heights: survey lines 150 m, 300 m, 500 m above ground level, plus CBL measurement surveys to >2 km

32 Subregion Mass Balance BU vs TD

The light blue lines are the flight tracks at 150 and 300 m above the ground. The coloured bands show the CH_4 emission estimates between the upwind and downwind tracks.

Mass Balance Uncertainties:

- Timing of the upwind and downwind tracks and alignment with an air mass,
- Alignment of the upwind background CH_4 with the downwind enhanced CH_4,
- Data smoothing intervals,
- Convective boundary layer stability or expansion between upwind and downwind tracks,
- Temporal uniformity of emissions.



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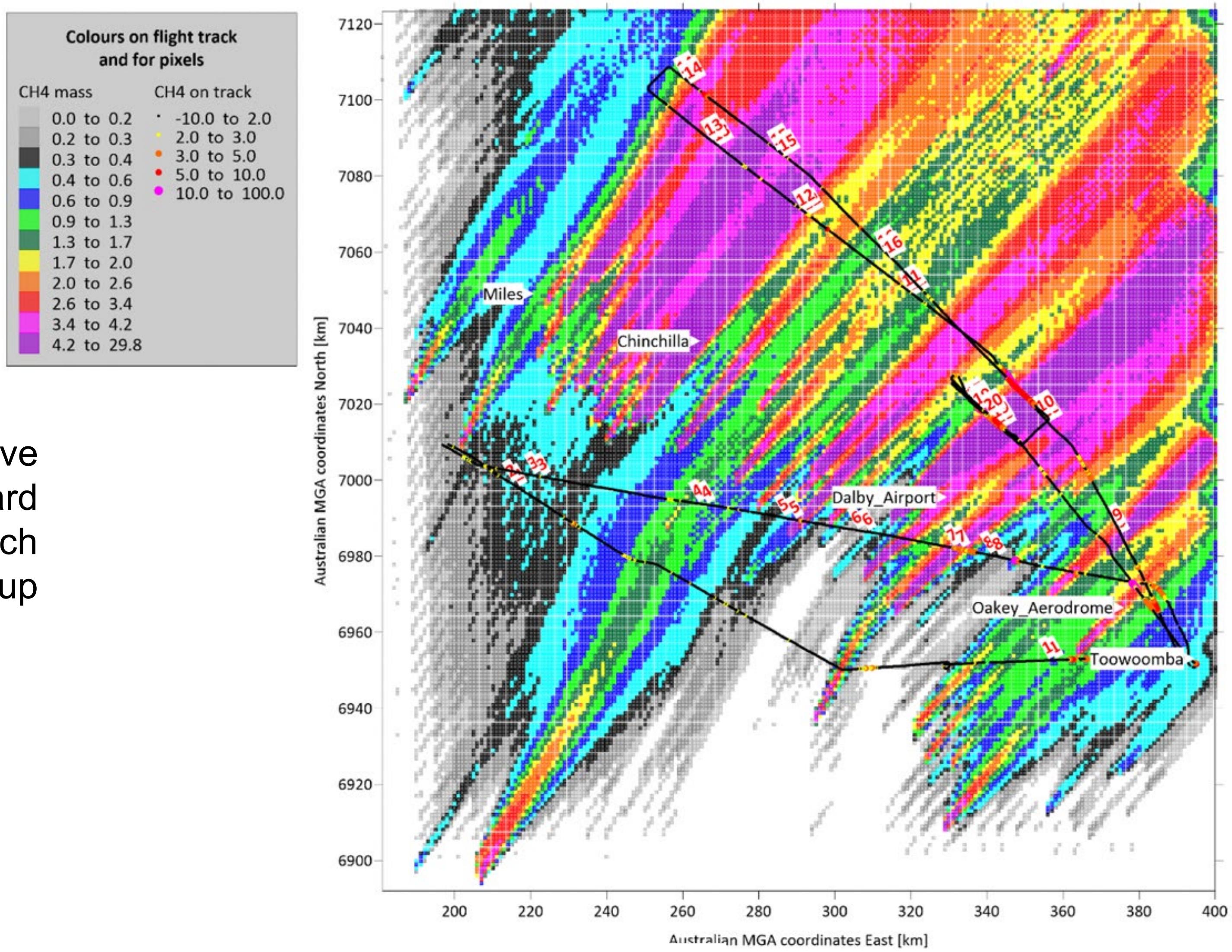
Inventory Plume Dispersion Modelling – 16^{th} September 2018



Mass distribution of CH_4 within the Convective Boundary Layer. This is calculated by forward modelling the emission rates (in kg/h) for each source specified in the UNSW bottom-up emission inventory.

Neininger BG, et al. (2021) https://doi.org/10.1098/rsta.2020.0458

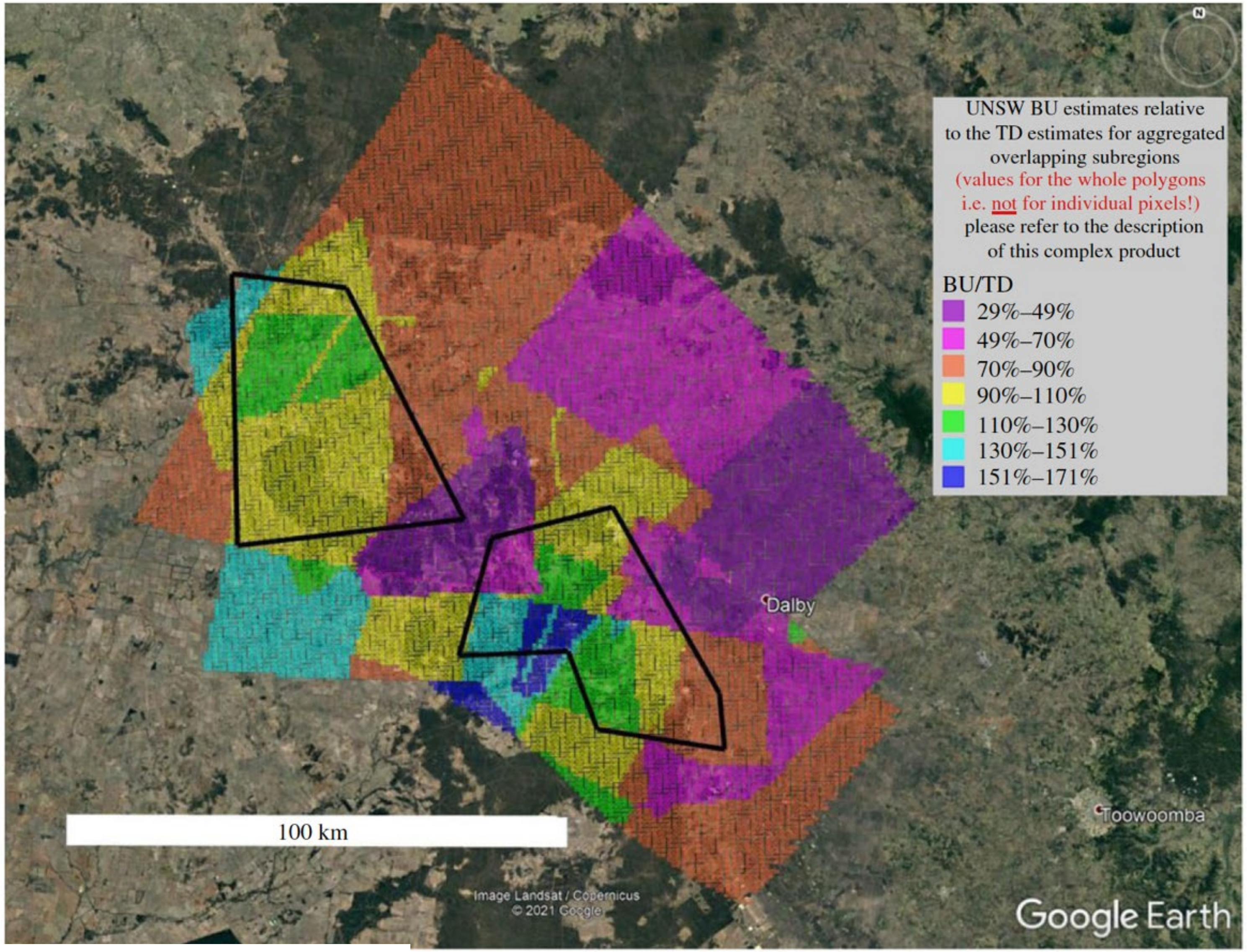
32 Subregion Mass Balance BU / TD

This 'patchwork' covers the TD domain and shows the percentage of UNSW inventory mass balance (BU) / the airborne measurement mass balance (TD).

The two CSG clusters are represented by the black polygons.

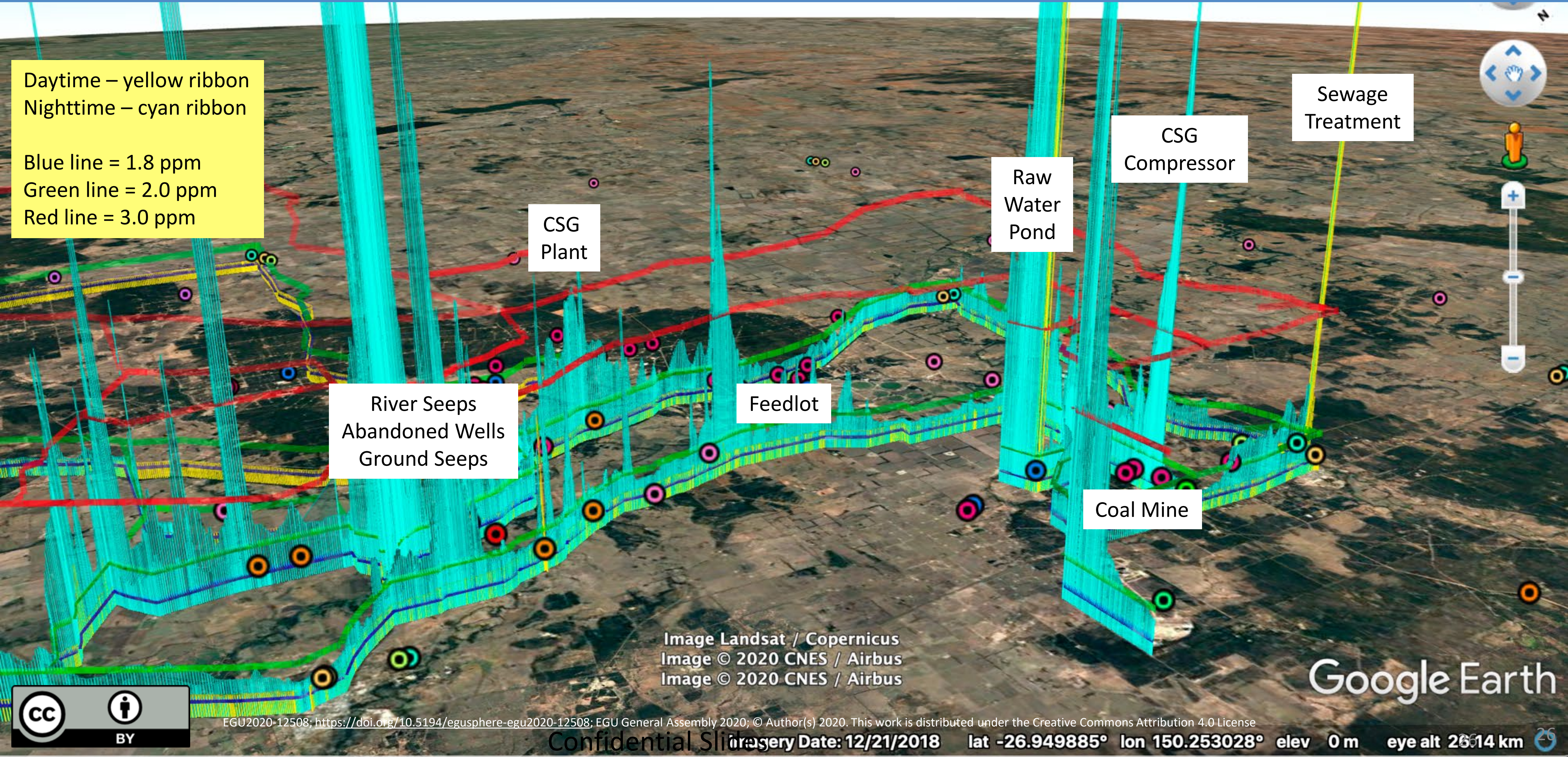
The yellow and green areas (BU/TD = 90 to 130 %) overlap with the coal seam gas production regions.

The poorer quality agreement between the BU and TD emission estimates mostly overlap with the agricultural districts. We are missing emissions from agriculture.



Neininger BG, et al. (2021) https://doi.org/10.1098/rsta.2020.0458

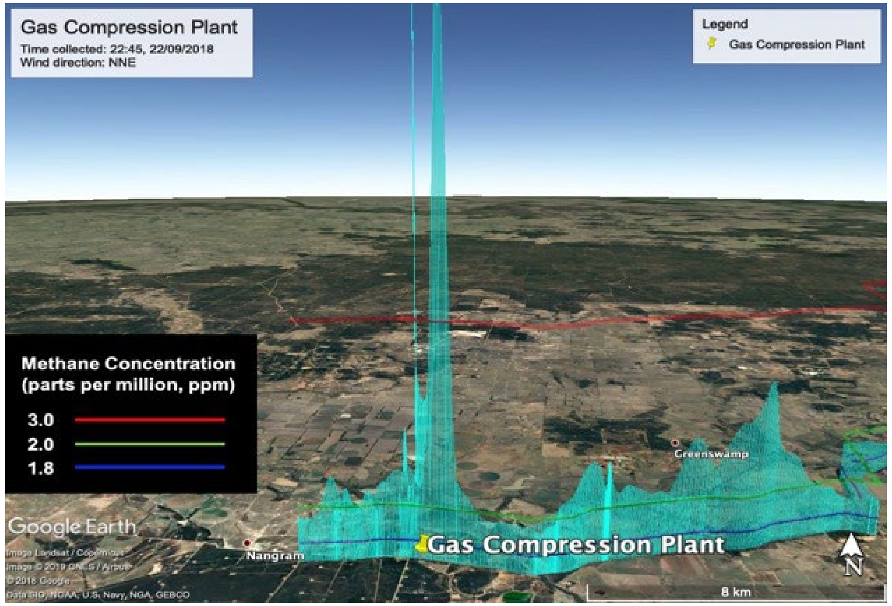
When you have multiple sources you need chemical tracers for source attribution and to identify inventory knowledge gaps

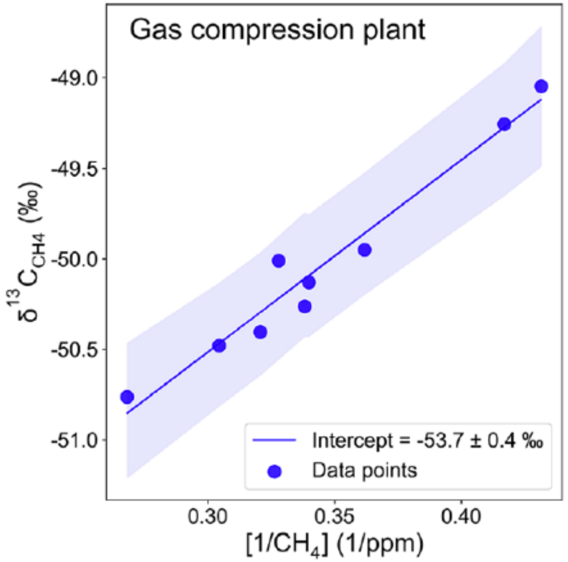


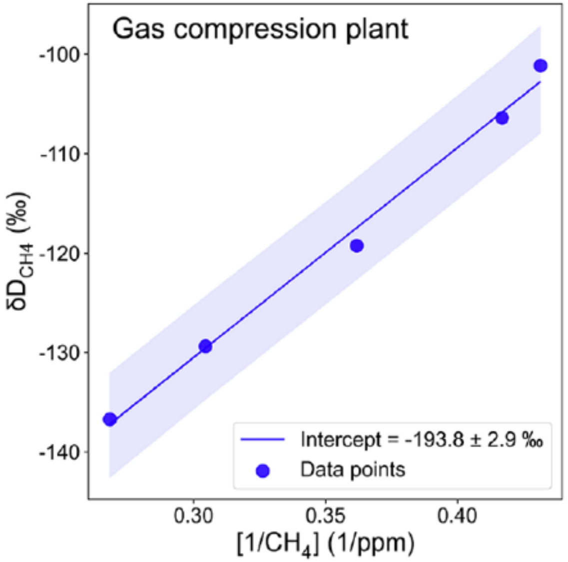
Coal Seam Gas (CSG)-Processing (Talinga Gas Facility)

The Talinga Gas Facility consists of 12 Waukesha Gas Engines coupled to Ariel Screw Compressors, which process first stage compression of raw coal seam gas from the surrounding gathering field network.
www.valmec.com.au

Plume maximum CH_4 11.3 ppm
$\delta^{13}C_{CH4}$ = -53.7‰
δD_{CH4} = -194‰





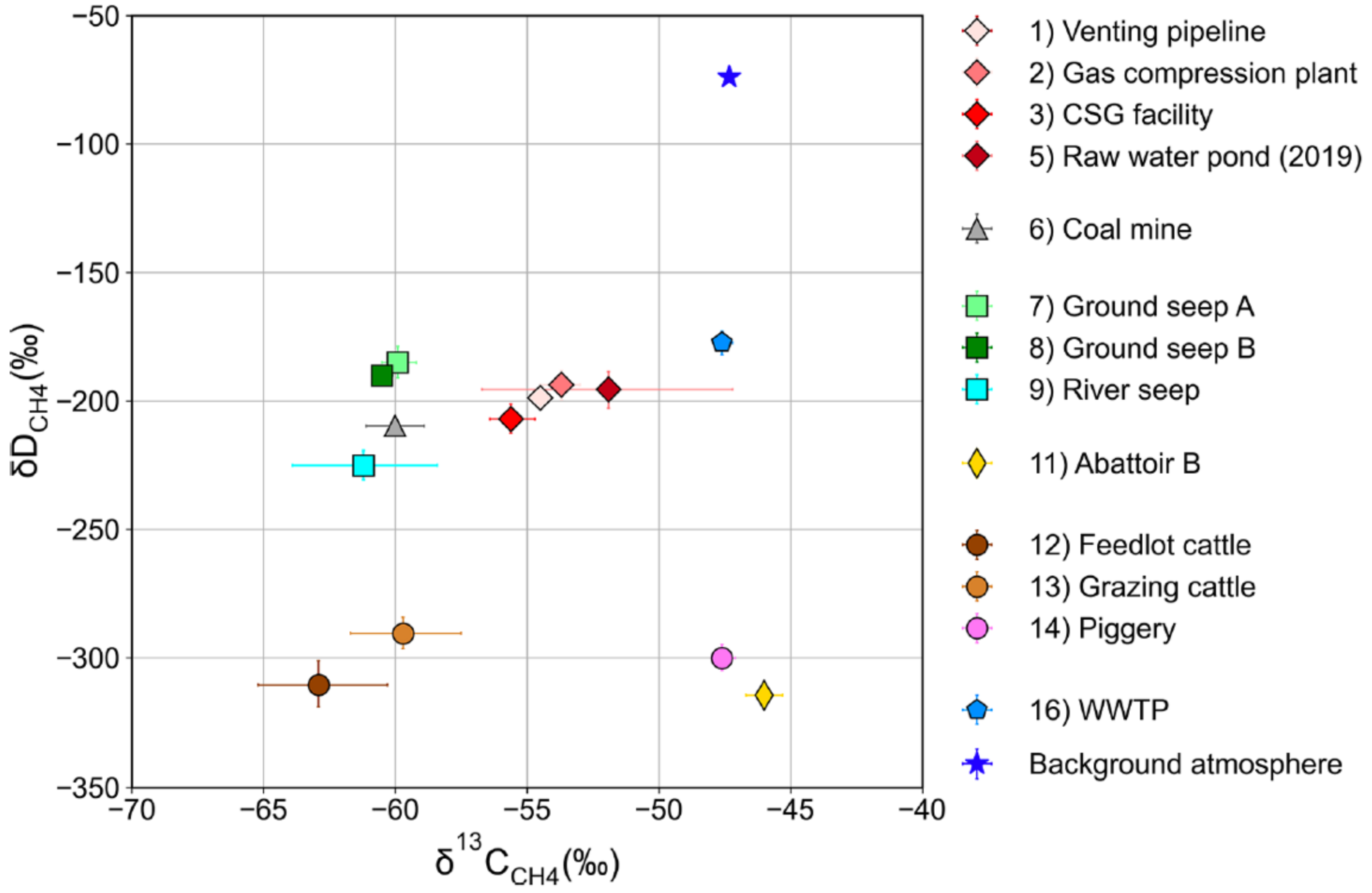


Lu et al. (2021) https://doi.org/10.5194/acp-21-10527-2021

Dual Isotope Plot

The scatterplot of δD_CH_4 vs $\delta^{13}C\_CH_4$ highlights good separation of sources based on the chemistry of the plume samples.

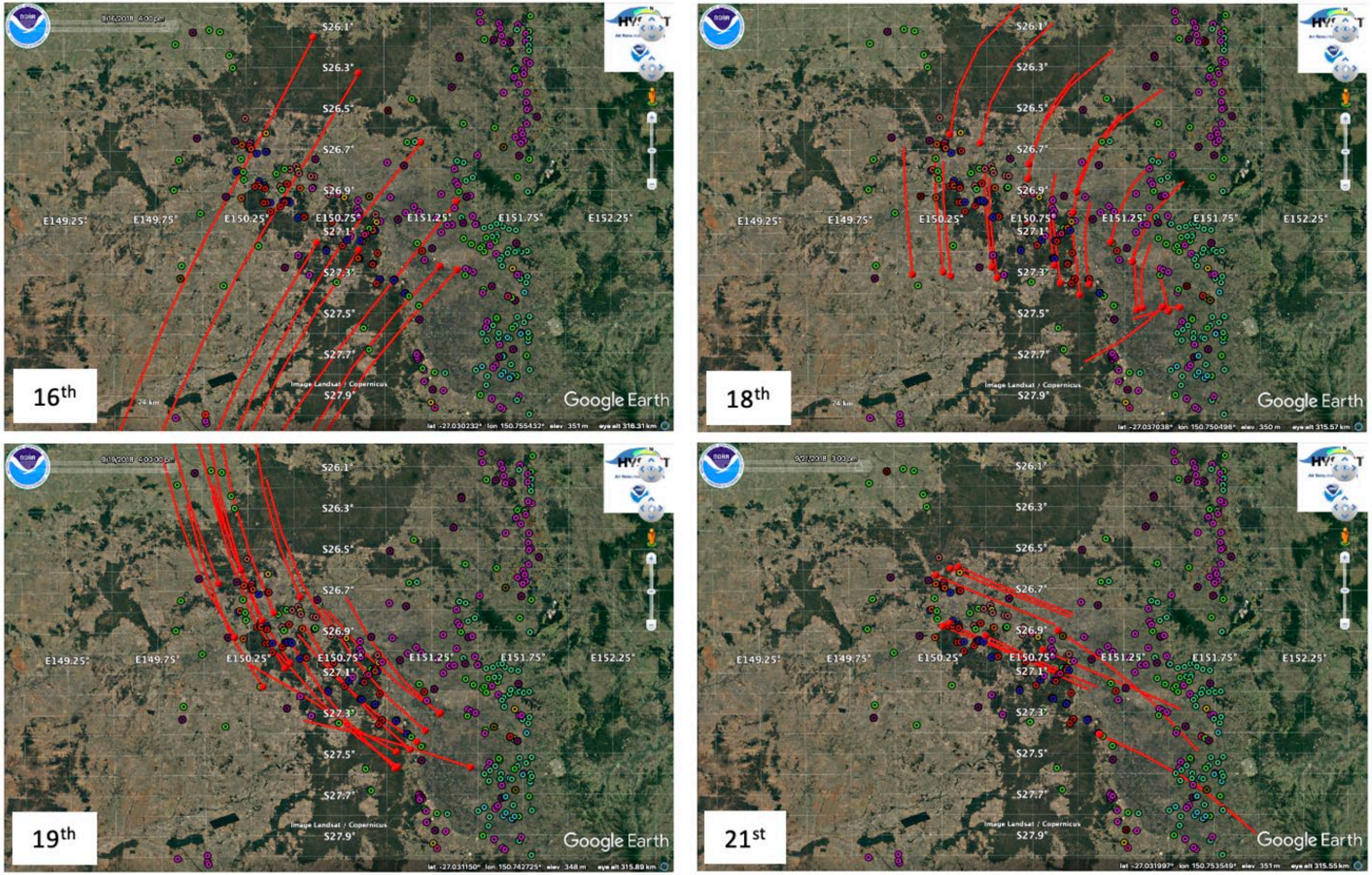
It is clear in the graph that CSG activity emissions and cattle emissions form distinct clusters. When there is clear end-member chemistry we can use mixing models to apportion contributions.



Lu et al. (2021) https://doi.org/10.5194/acp-21-10527-2021

The ethane content of most Australian gas is < 1%

In-Flight Atmospheric Air Samples
Back trajectories for the 49 air samples were determined using Hysplit



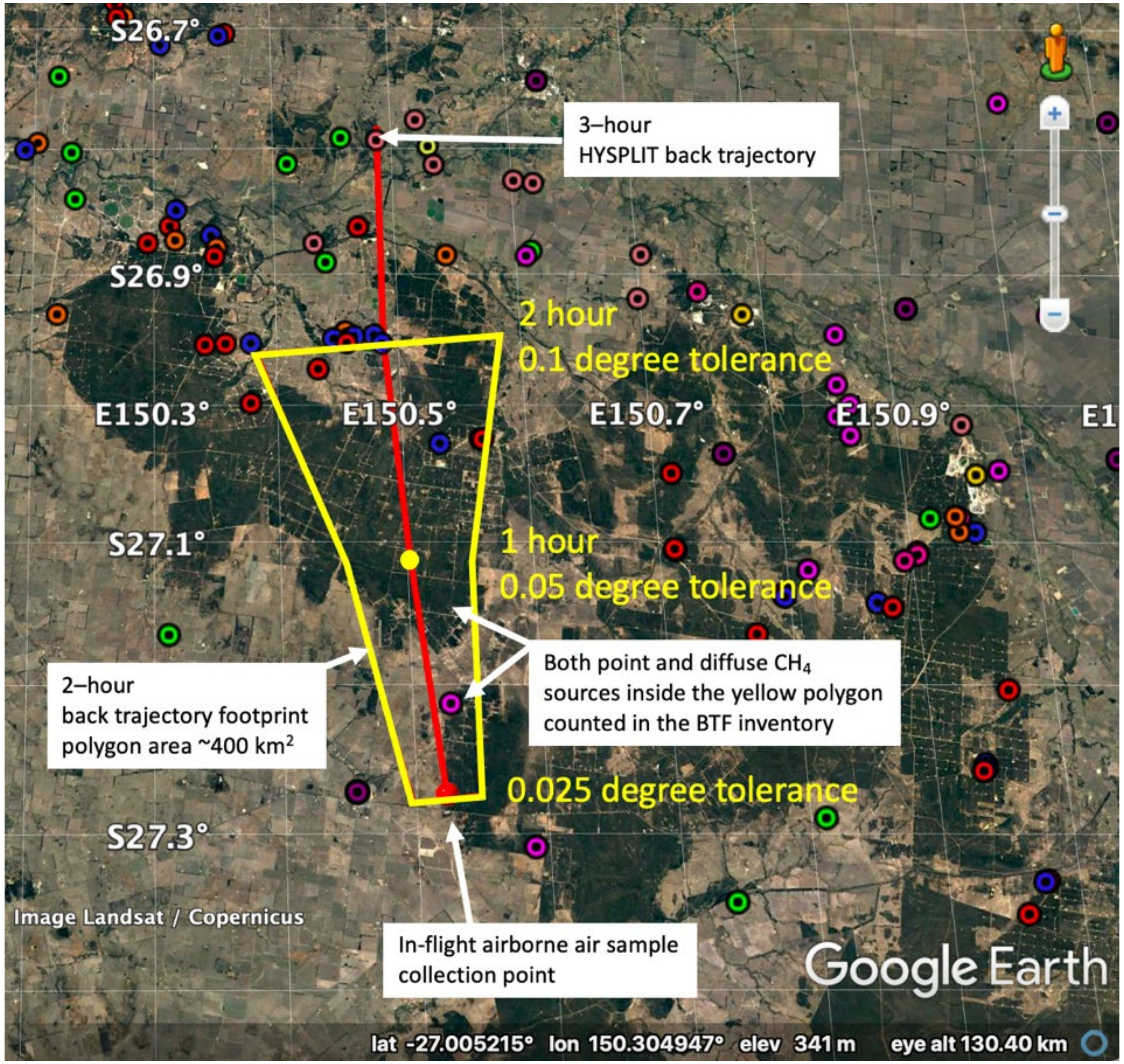
Point Sources

- CSG processing plants
- CSG compressor stations
- CSG raw water ponds
- Coal mines
- Power stations
- Ground seeps
- River gas seeps
- Cattle feedlots
- Cattle dairy
- Piggeries
- Poultry farms
- Landfills
- Wastewater treatment plants
- Domestic wood fires

Kelly et al. (2022)
under review acp-2022-552

In-Flight Atmospheric Air Samples (FlexFoil Bags)
Isotope Mixing Modelling for Source Apportionment

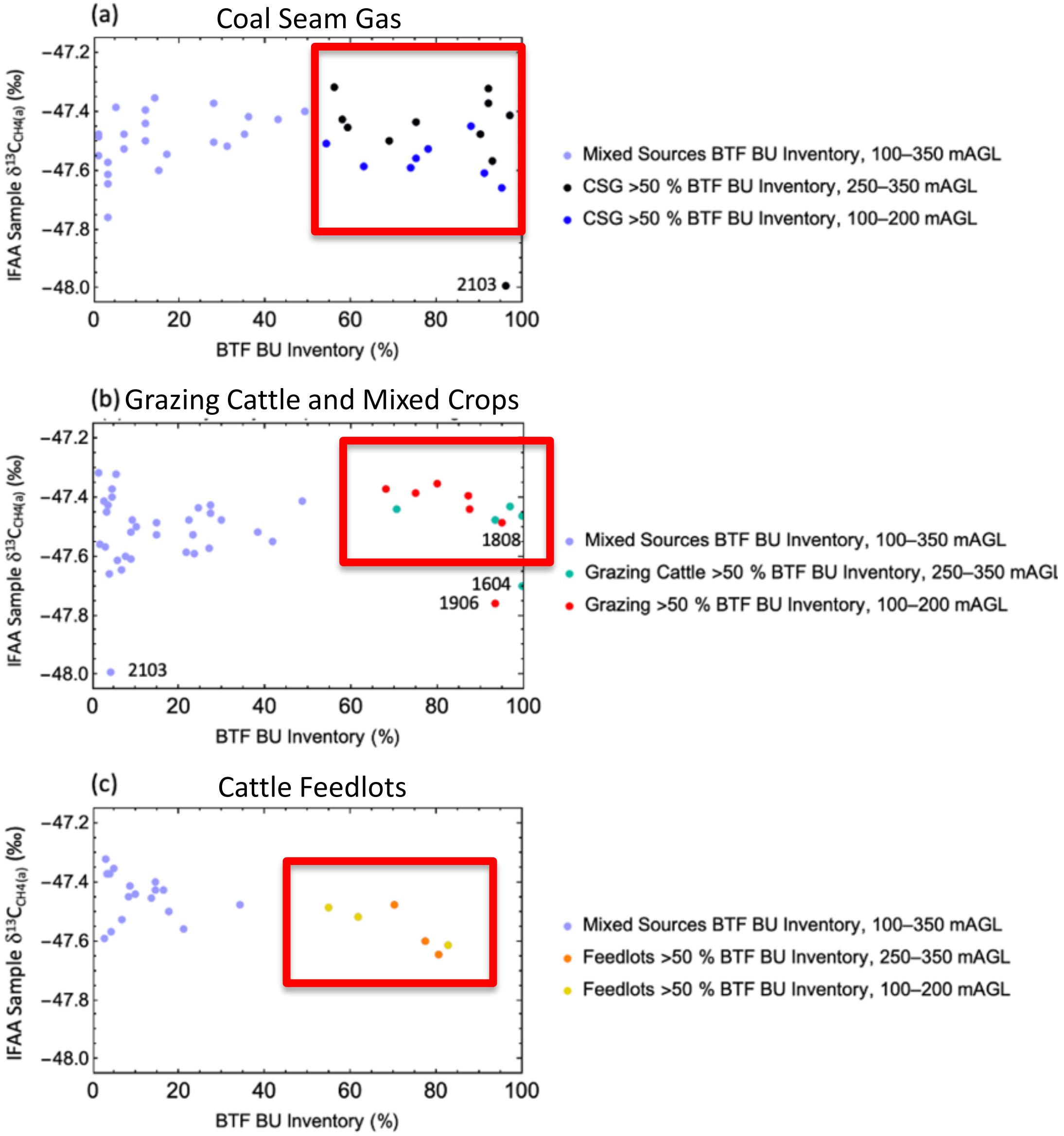
Does the chemistry of the atmospheric air sample match what is expected from the upwind inventory?



Kelly et al. (2022)
under review
acp-2022-552

Inventory Verification

For samples where one source type represented >50% of the upwind inventory we analysed the data using multi Keeling model regression with shared background air ($CH_{4(b)}$ and $\delta^{13}C_{CH4(b)}$)



Kelly et al. (2022) under review acp-2022-552

Back Trajectory Inventory Check

Grazing cattle and forest districts >50 % of the upwind inventory

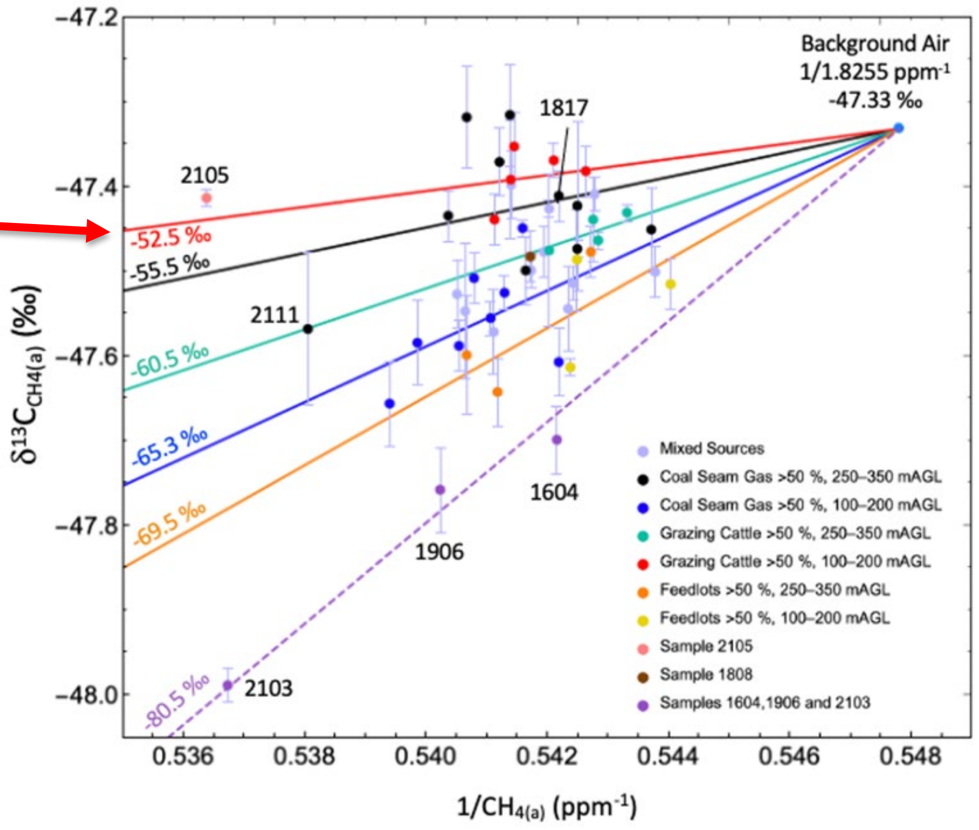
Airborne samples

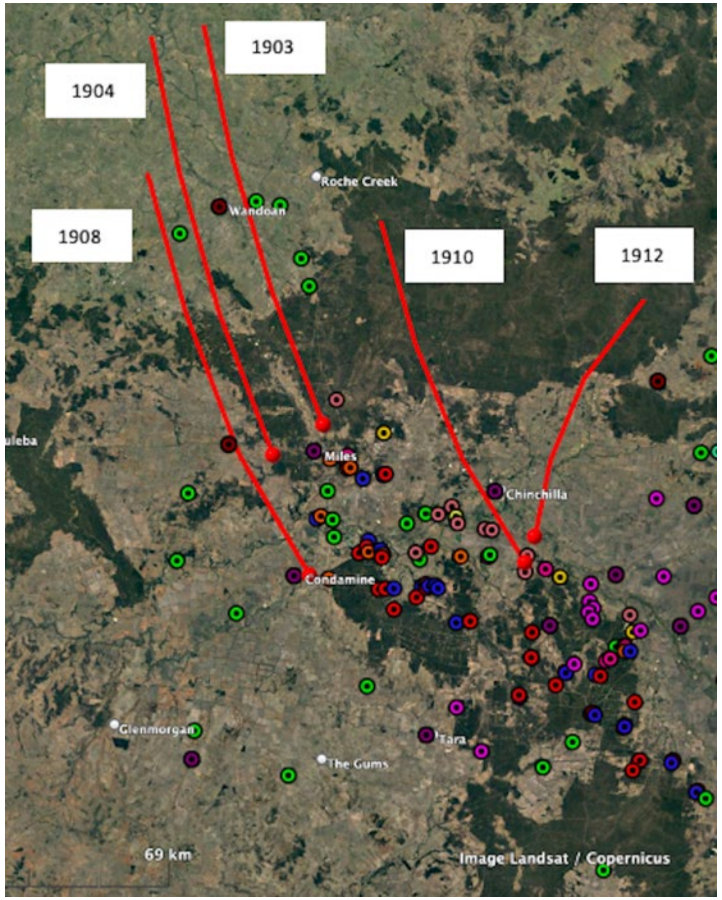
$\delta^{13}C_{CH4(s}$ −52.5 ‰ (CI 95 % ± 18.8 ‰)

Expected from inventory

$\delta^{13}C_{CH4(s)}$ −61.7 ‰ to −57.5 ‰

The relatively high permil value suggests CSG emissions entering from the northern western gas field.

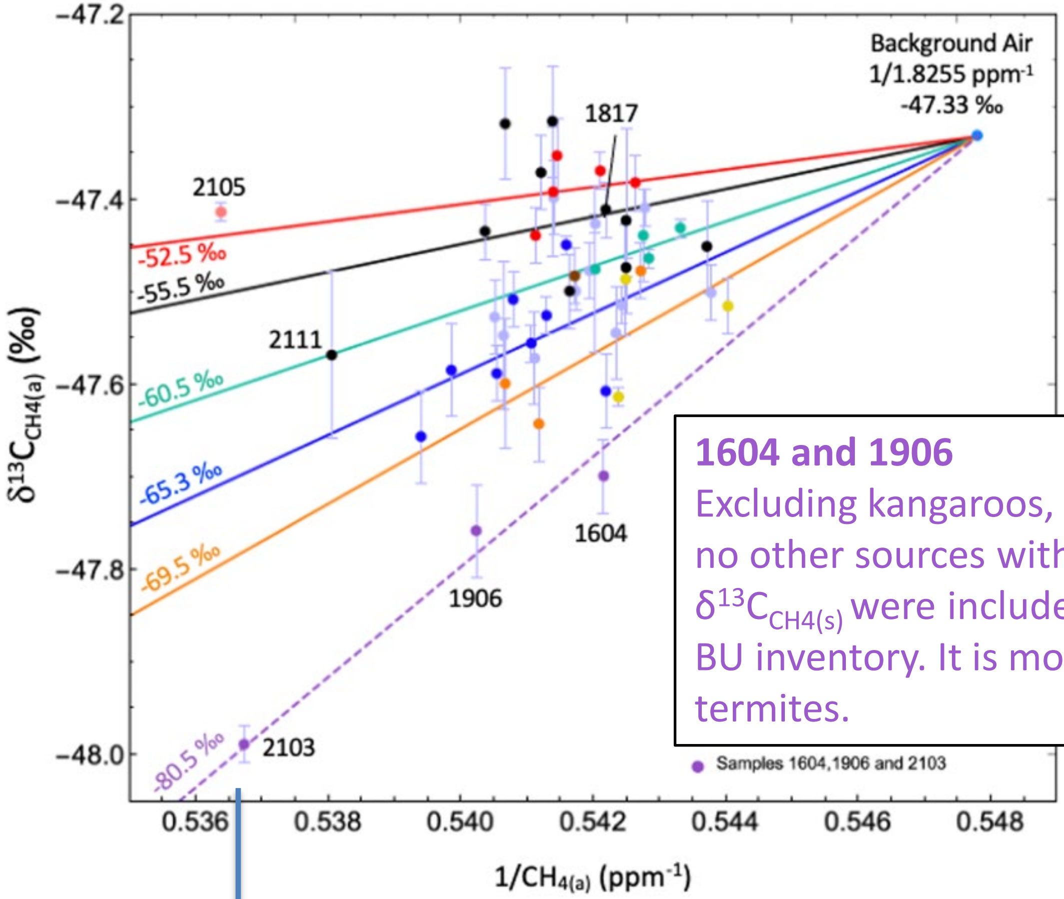




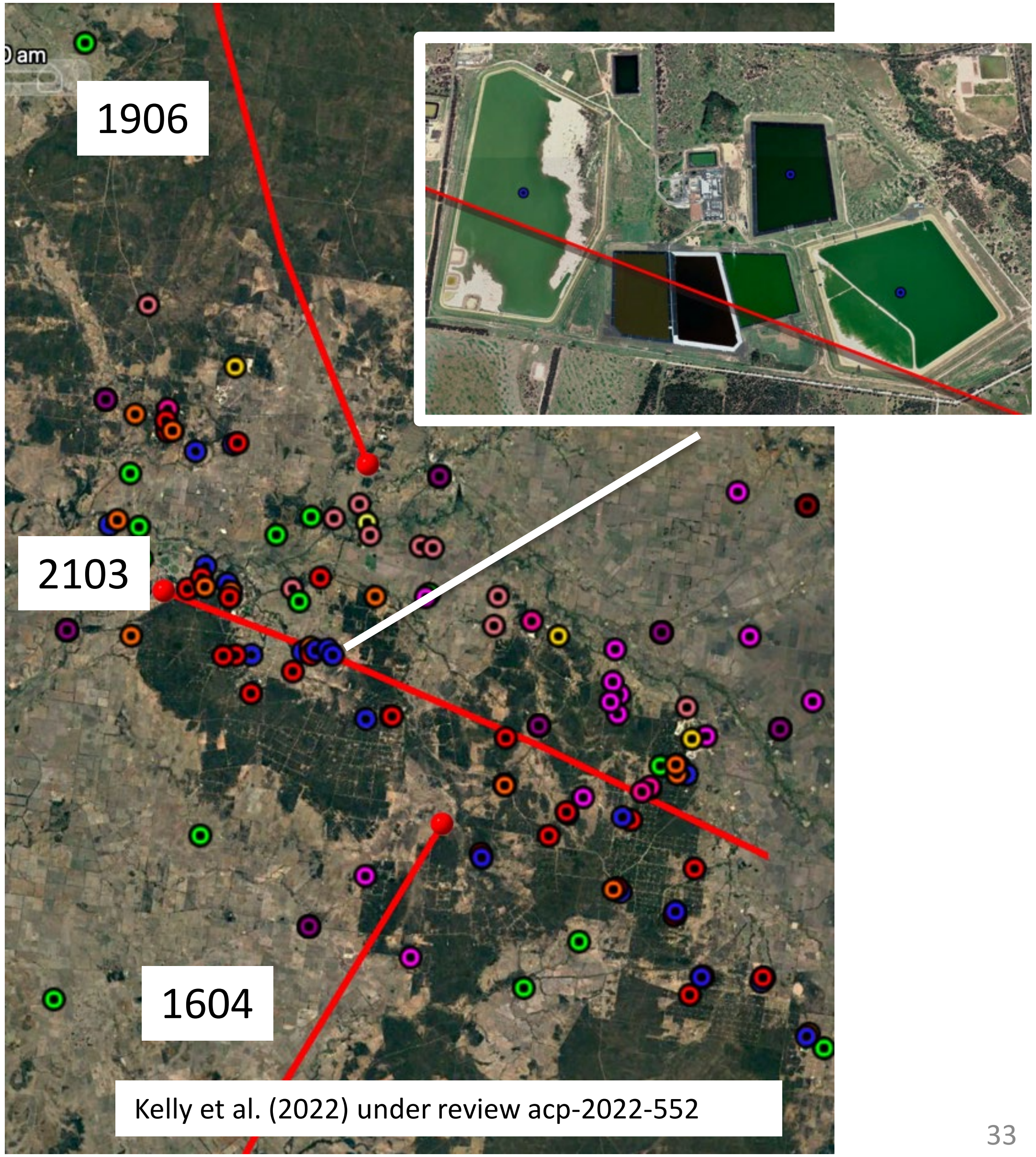
Insights On the Gap

Kelly et al. (2022) under review acp-2022-552

Back Trajectory Inventory Check



1604 and 1906
Excluding kangaroos, no other sources with this very $\delta^{13}C_{CH4(s)}$ were included in the BU inventory. It is most likely termites.



Kelly et al. (2022) under review acp-2022-552

2103 Downwind of CSG brine pond. No emissions from these ponds were included in the BU inventory. Is this due to the brine ponds or termites?

Insights On the Gap

Kelly et al. (2022) under review https://acp.copernicus.org/preprints/acp-2022-552/

The Future

Jacob et al. (2022) https://doi.org/10.5194/acp-2022-246

https://ghginstitute.org/ipcc/

https://www.industry.gov.au/sites/default/files/April%202021/document/national-inventory-report-2019-volume-1.pdf

<u>Satellite Measurements</u>

Continuous Measurements

(cloud cover and column averaging will be a limitation)

<u>Aircraft Measurements</u>

Regional and Facility Scale Emission Estimates

Satellite Verification

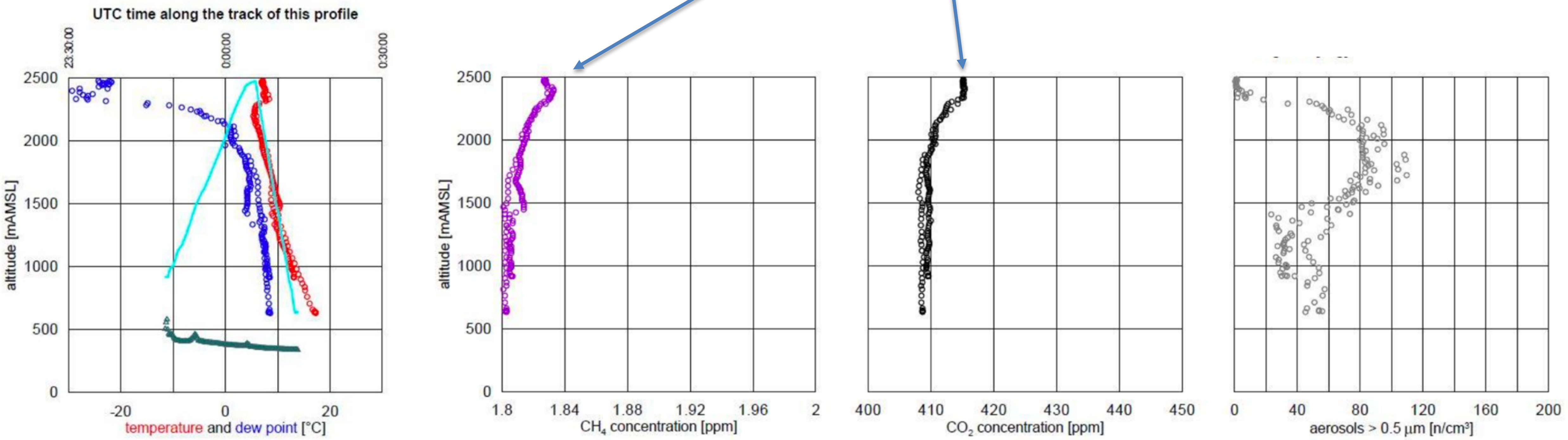
<u>Inventories</u>

Spatially and Temporally Varying

Seasonal Inventories

Satellite Verification Using Aircraft Vertical Profiles
An example vertical profile from the Surat Basin

Note the higher mole fractions for CH_4 and CO_2 above the boundary layer



When analysing the satellite total atmospheric column data sets how do you account for the higher concentration of greenhouse gases in the higher altitude atmospheric layers?

Neininger BG, et al. (2021) https://doi.org/10.1098/rsta.2020.0458

For Discussion

The focus of aircraft-based campaigns

- Aircraft-based in-situ measurements are helpful for reducing emission estimate uncertainty and for identifying bias in national and global inverse models. How do we facilitate greater use of aircraft-based measurements in inverse modelling studies?

- Tallying emission measurements from components within a facility will never equal the emissions from the complete facility. Could it be made a requirement that facility owners perform aircraft-based spot checks?

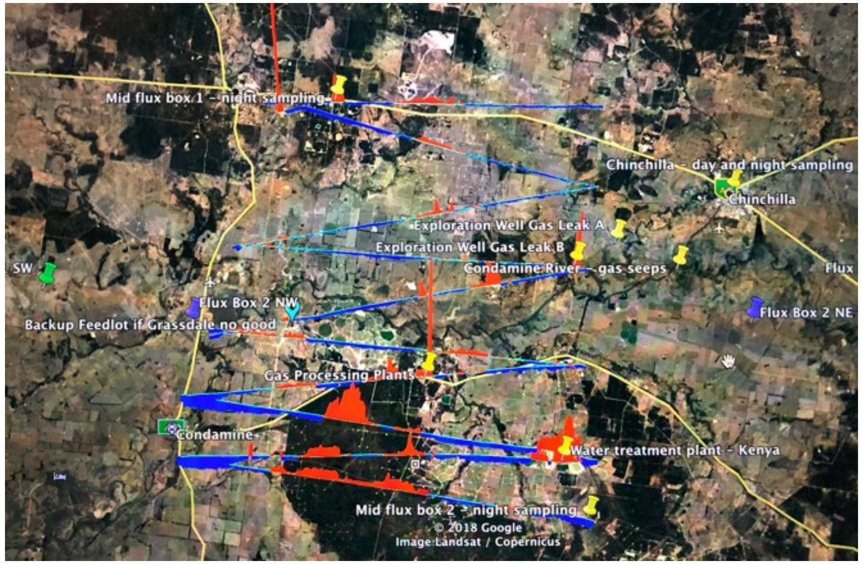
Kelly et al. (2022) under review https://acp.copernicus.org/preprints/acp-2022-552/

For Discussion

<u>The focus of aircraft-based campaigns</u>

- There are no international standards for the use of tracer gas surveys for source attribution and to identify source knowledge gaps. Has the science matured enough to develop good practice guidelines?

- If there is to be increased use of satellite and aircraft-based methods in inventory development, don't we need better data on non-reportable sources?



Aircraft-Based Surveys
An Efficient Way To Verify and Refine Emission Inventories

Aircraft-based methods are a fast way to locate unknown sources and verify inventory methods, from small-scale facilities to regions that cover thousands of square kilometers.

Of high importance, the emission estimates give reassurance to governments, industries and the community.

From large aircraft to drones, airborne surveys can be used to track Net Zero goals.

https://www.metair.ch/index.php/de/

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