BEAM

BElgian Ammonia assessed using innovative Multi-scale Measurements and Modelling

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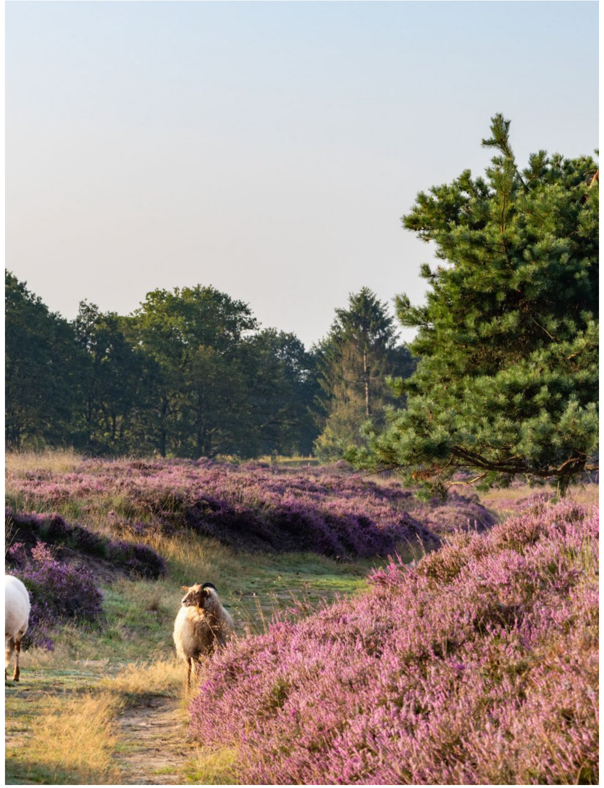
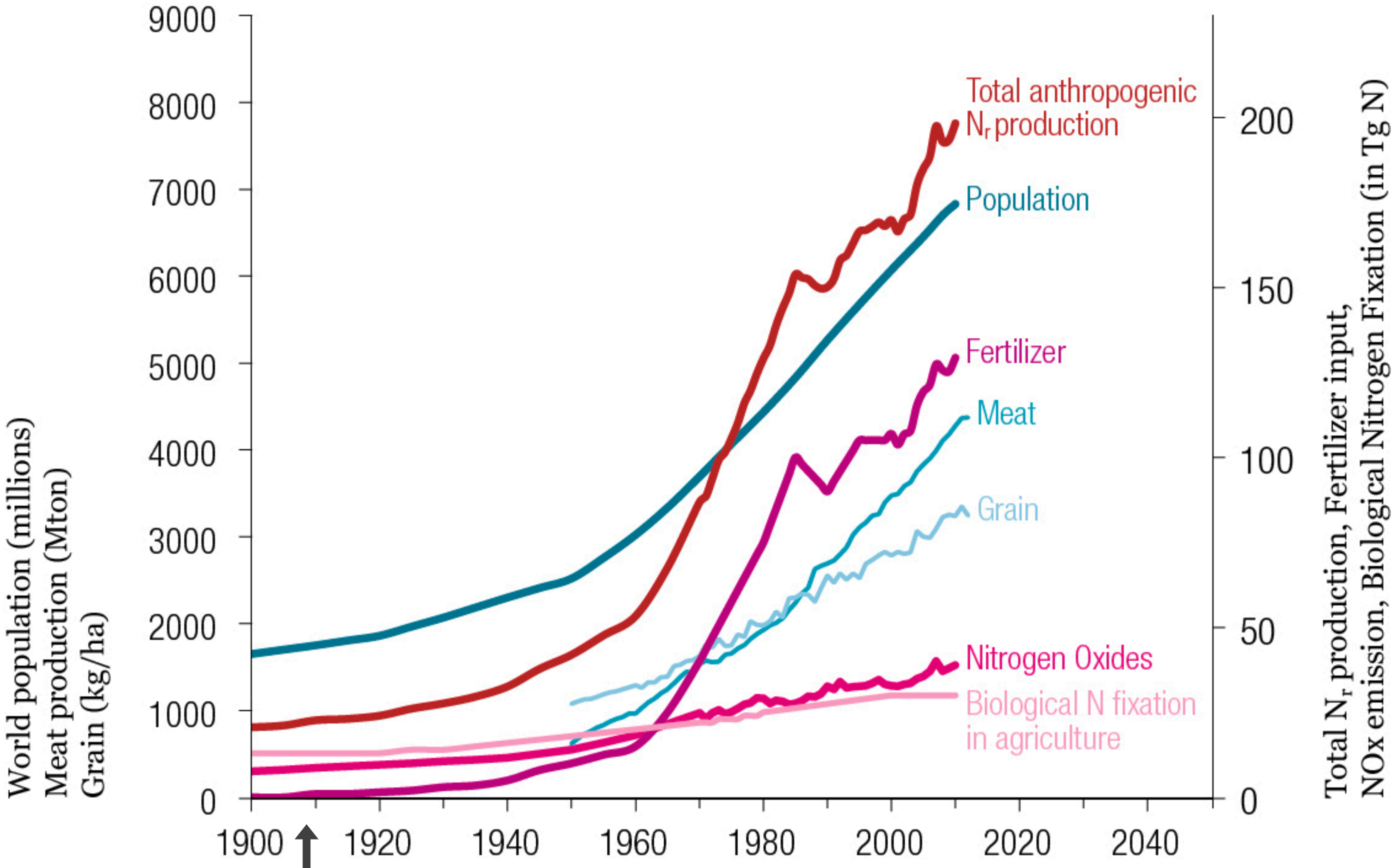
BIRA • IASB

ILVO Flanders Research Institute for Agriculture, Fisheries and Food

KING'S College LONDON



N Cycle Perturbations & Consequences of Excess Nr



(Erisman *et al.*, 2015)

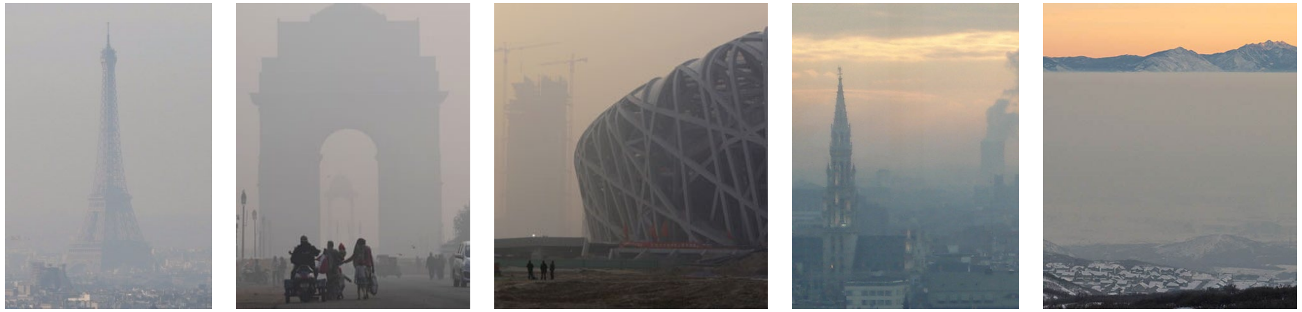
Haber-Bosch industrial process (1908):
$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$

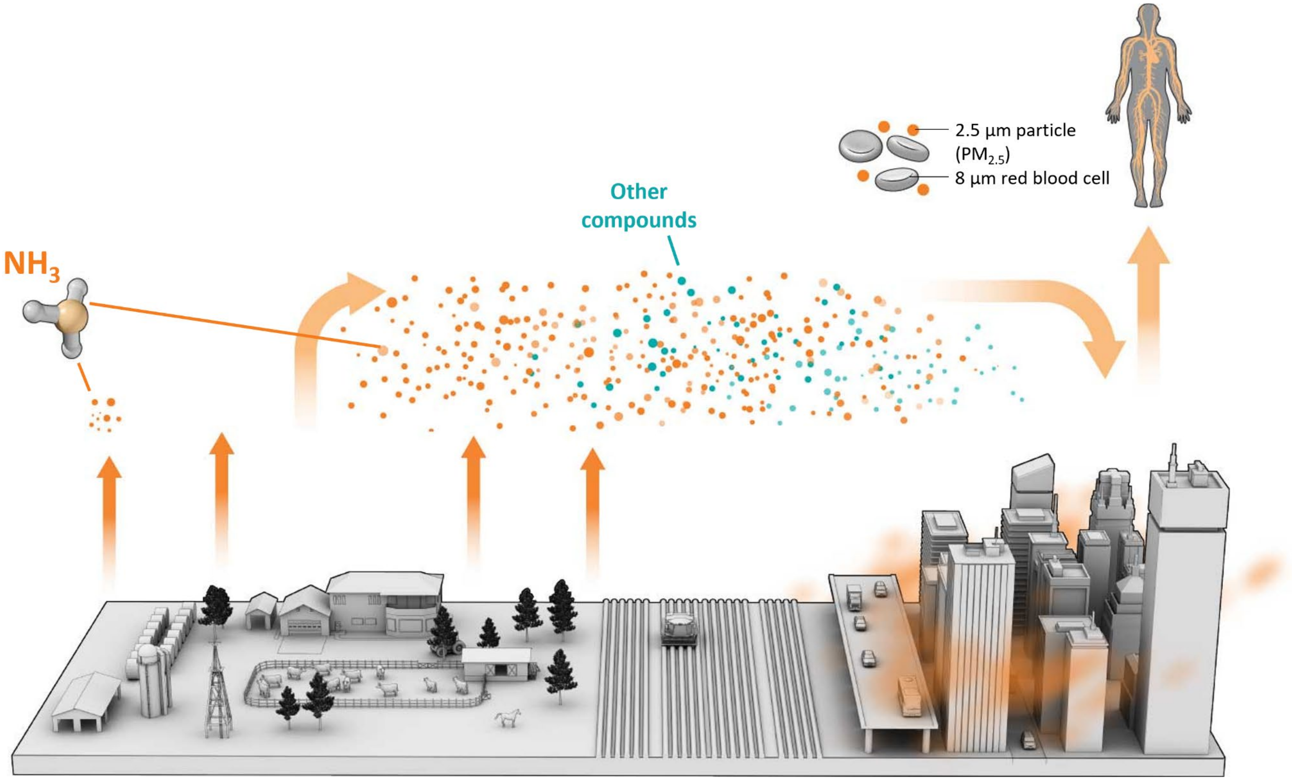
- Ammonia (NH_3) is a main form of reactive nitrogen (Nr) along with nitrogen oxides (NO_x)

- Emissions of Nr have increased five to ten-fold since preindustrial times due to our increasing need of food (NH_3) and energy production (NO_x)

- A tipping point was the discovery of the Haber-Bosch process in 1908 which allows synthetic production NH_3 on a massive scale

N Cycle Perturbations & Consequences of Excess Nr





(Adapted from Desai and Cuadra, Science)

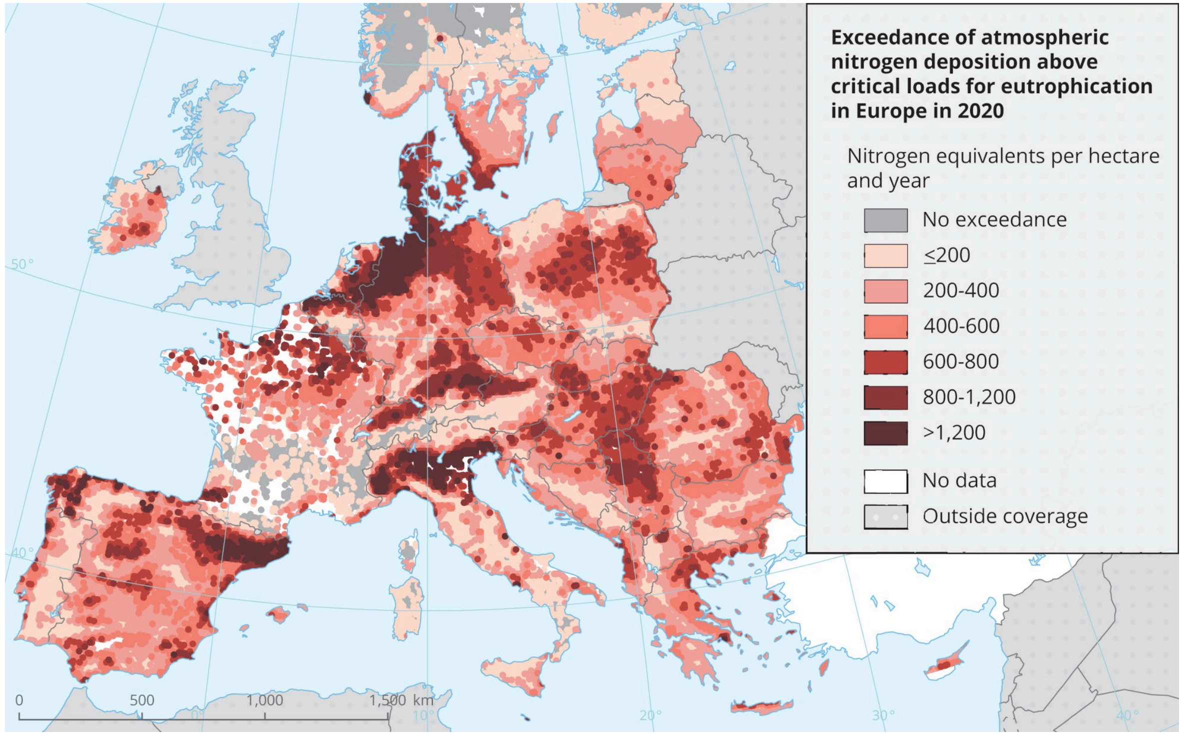
Air Quality

- Nr contribution to $PM_{2.5}$ > 30% in US, Europe and Asia and > 50% in large parts of Europe (Pai et al., 2022; Erisman and Schaap, 2004)
- In EU-27, 96% of the urban population was exposed to $PM_{2.5}$ levels exceeding the WHO threshold in 2020, causing 238000 premature deaths (European Environment Agency, 2022)
- Nr is responsible globally for 23.3 million years of life lost per year, or an annual welfare loss of 420 billion USD (Gu et al., Science 2021)

N Cycle Perturbations & Consequences of Excess Nr

Lake St.Clair, U.S. and Canadian
Satellite view of cyanobacterial bloom, August 2015 (NASA image)

Bellynahone Bog, Northern Ireland
The CAFRE Ammonia Challenge (Cafre)



(adapted from EEA and ESRI)

Air Quality

Soil, Water Quality and Biodiversity

- Excess Nr in soil and water leads to eutrophication and acidification of ecosystems

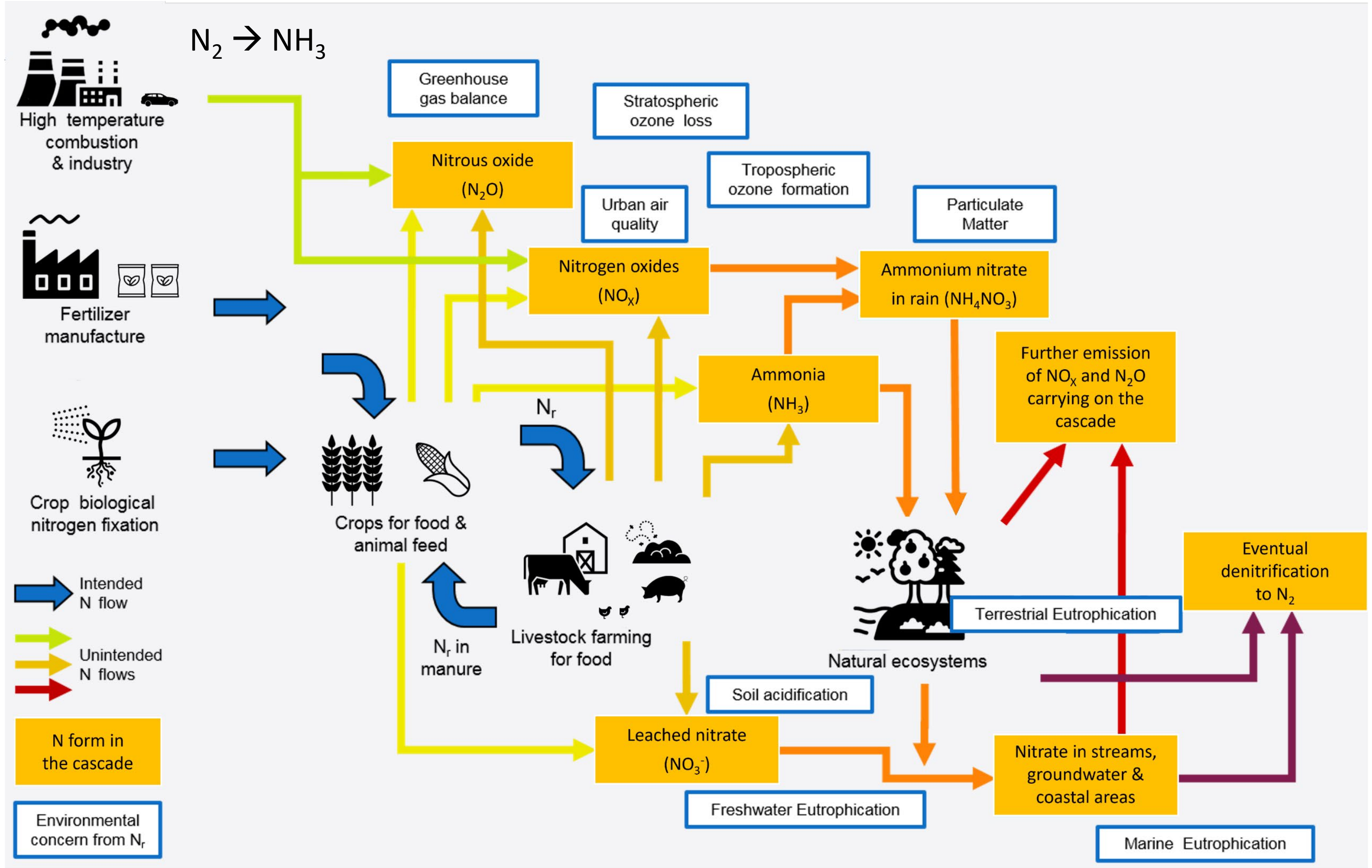
- Eutrophication is one of the major causes of biodiversity loss (next to land use and climate changes)

  Sensitive fauna and flora are gradually outcompeted in areas with excess nitrogen deposition

- In Europe 75% of the ecosystems are exposed to levels of nitrogen outside of the range they can tolerate (European Environment Agency, 2022)

  Projections for the next decade show no/weak improvement, as 58% of the Natura 2000 areas will remain at risk in 2030

N Cycle Perturbations & Consequences of Excess Nr



Adapted from the European Nitrogen Assessment (2011)

Air Quality

Soil, Water Quality and Biodiversity

Climate

These adverse effects of Nr are reinforced by the **Nitrogen Cascade**

N Cycle Perturbations & Consequences of Excess Nr

Nitrogen Crisis

- The Netherlands 2019

  Following a court judgement stating that current legislation was not strict enough to protect Natura 2000 areas, as required by the European Habitat Directive (EHD) (directive 92/43/EEG)

  Huge demonstrations by farmers against potential measures taken to reduce nitrogen emission from the agricultural sector

- Similar situation happened in Flanders early 2023

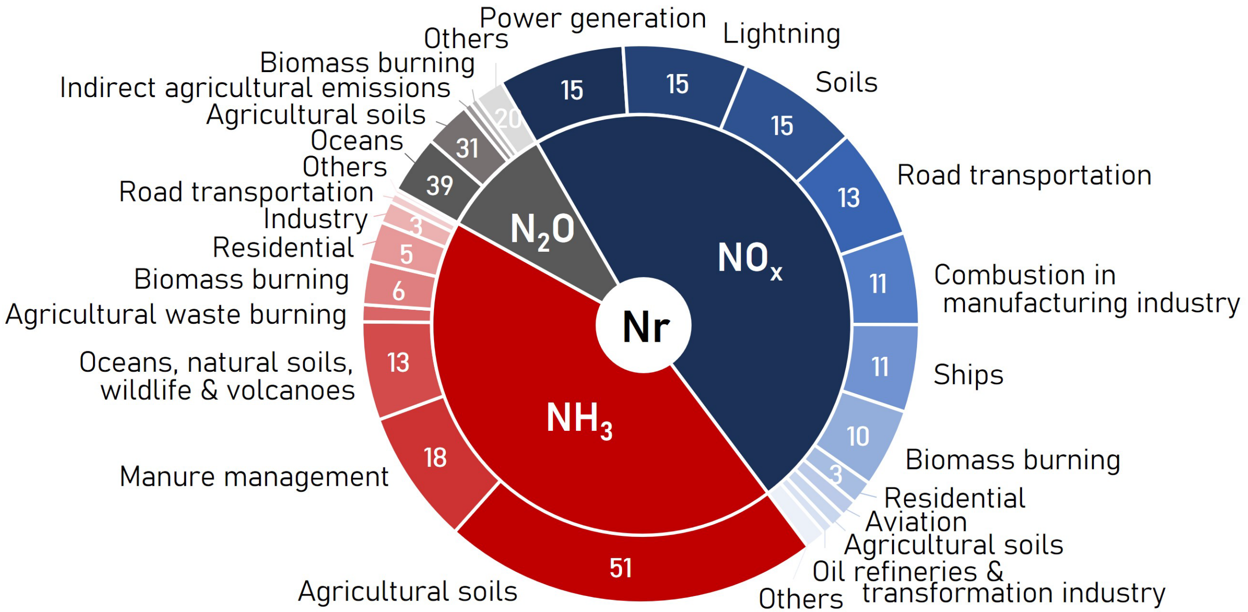
- INEOS – Antwerp (Belgium): In July 2023, the Council for Permit annulled the environmental permit (June 2022) for the construction and operation of the 'Project One' chemical plant arguing that “the Flemish Government's assessment of the potential impact it could have on nearby nature was inadequate”. In January 2024, the permit was granted by the Flemish Environment minister.

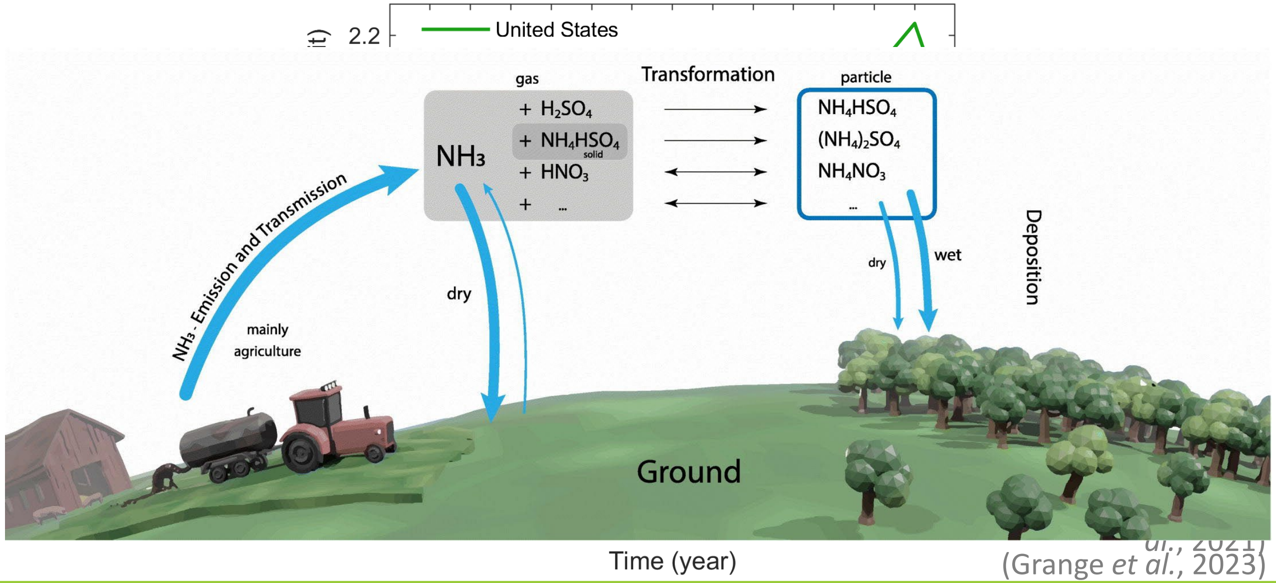
More measurements and monitoring tools are needed to support policy making processes

Ammonia – A major piece of the N cycle

- NH_3 accounts for ~50% of Nr emissions
- It is mainly emitted by agricultural activities (94% in Europe)
- Industrial emissions are underestimated in bottom-up emission inventories
- Projections are highly uncertain and do not show a possible decline
- A recent study found a large increase of atmospheric NH_3 in the major source regions
- Main sinks are deposition and formation of $PM_{2.5}$

  ➡ Short atmospheric lifetime of a few hours
- Highly variable in time and space



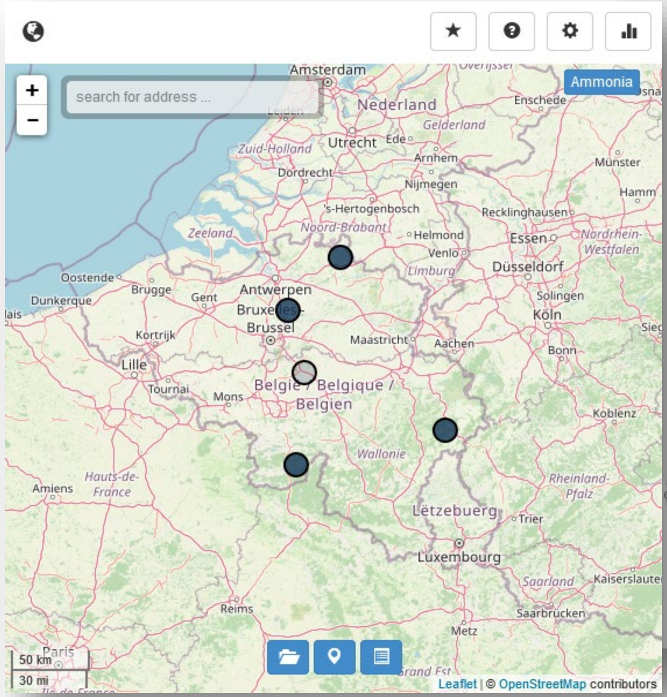


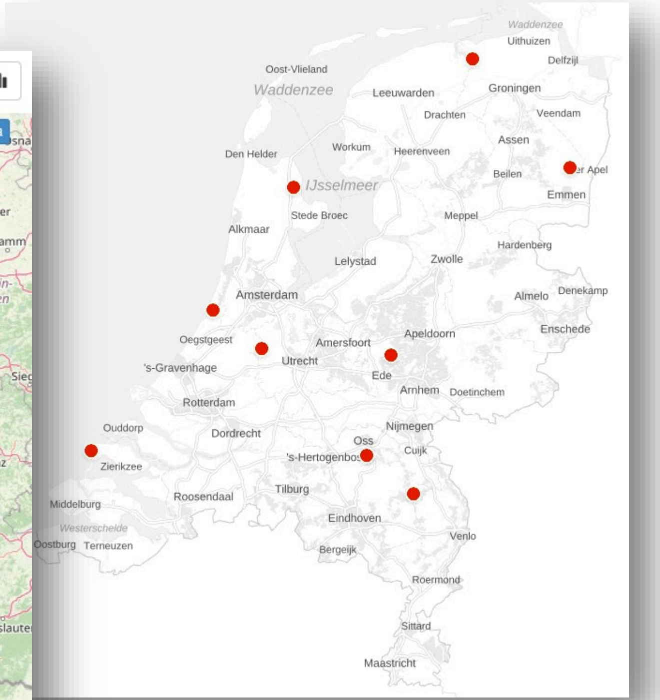
(Grange *et al.*, 2023)

Ammonia – Monitoring Means

www.irceline.be

www.luchtmeetnet.nl





Surface Measurements

- Surface networks are sparse and provide mainly integrated measurement over time
- Few automated monitoring networks providing hourly data
  e.g., Belgium, the Netherlands
- Increasing availability
  - -FTIR: Fourier Transform IR
  - -CRDS: Cavity Ring Down Spectroscopy
  - -DOAS: Differential Optical Absorption Spectroscopy

(DOAS at Cabauw tower, E. Dammers)

(CRDS, NOAA)

(Quantum cascade laser, M. Zondlo)

(TELOPS, L. Noppen)

Ammonia – Monitoring Means

Surface Measurements

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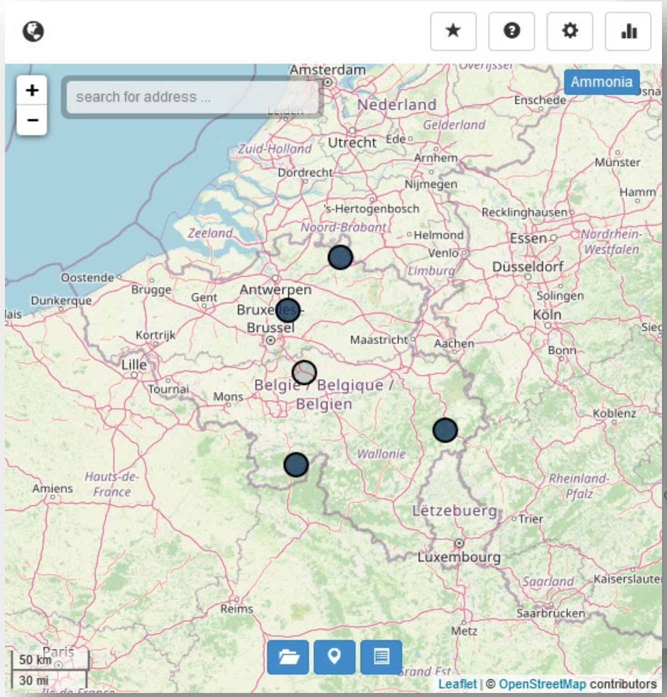

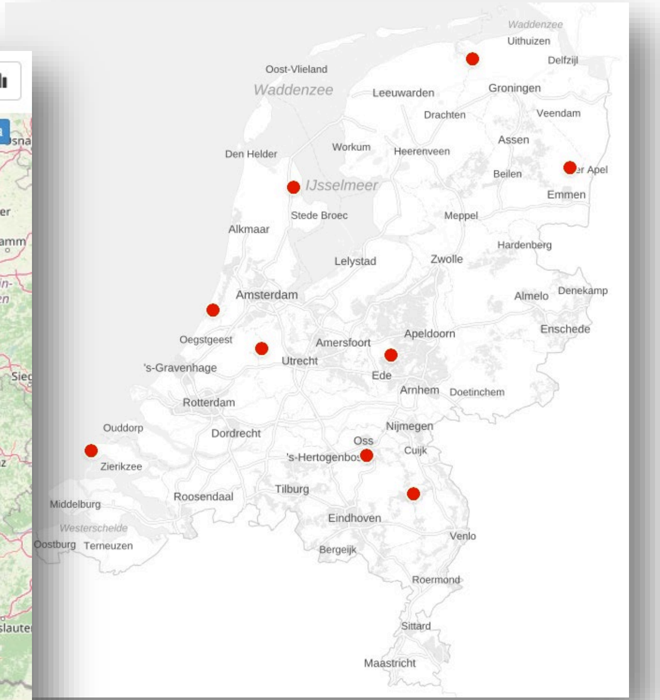

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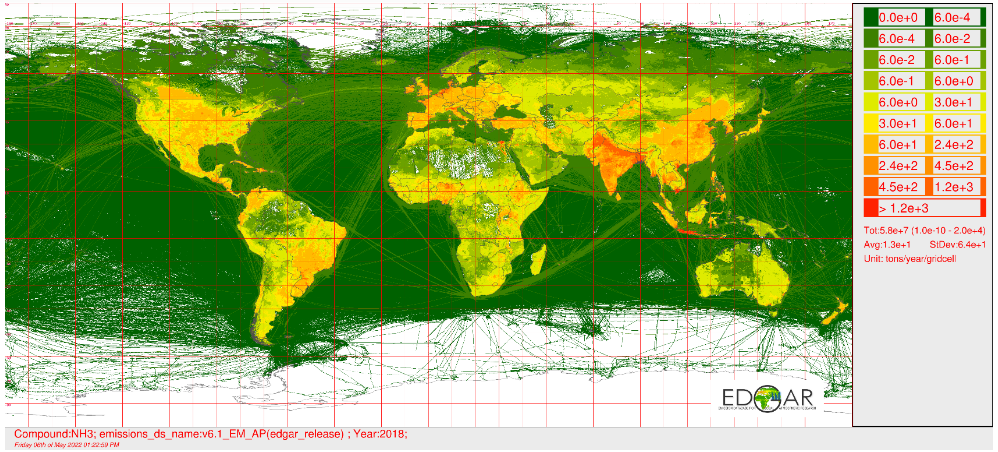
Models

- Highly dependent on the timing and gridding of emissions used as input

- Limited by the lack of reliable inventories (and observations)

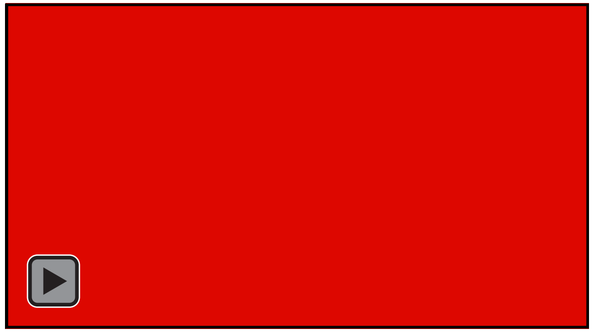
  Magnitude

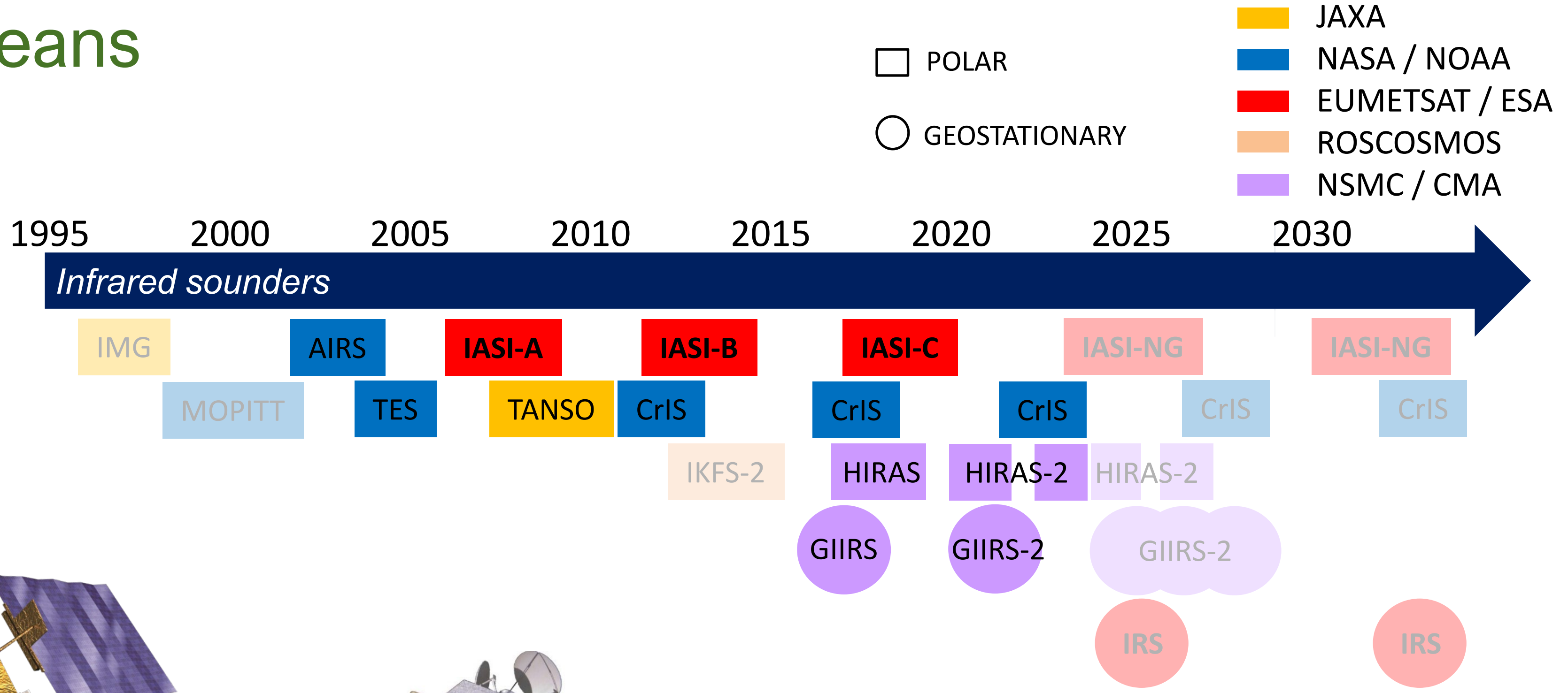
  Timing

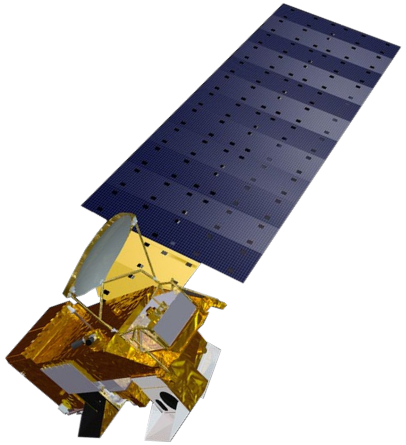


Ammonia – Monitoring Means

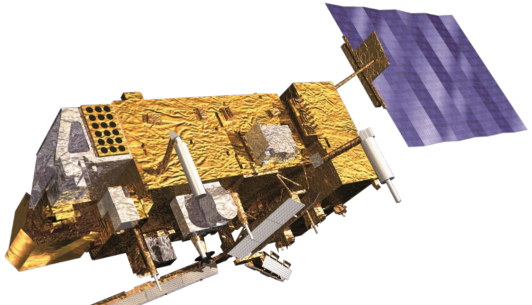
Space Component



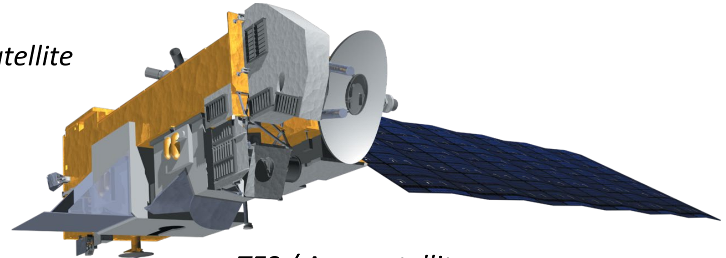




AIRS / Aqua satellite

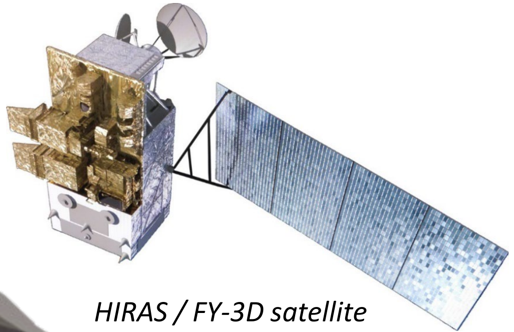


IASI / Metop satellite

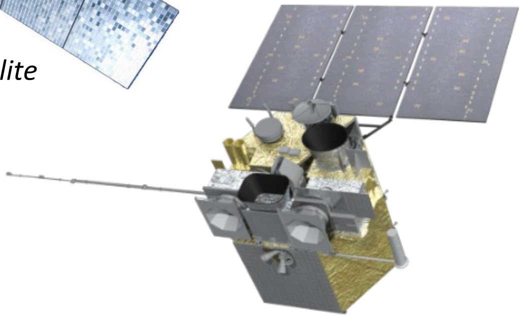


TES / Aura satellite

CrIS / Suomi NPP satellite



HIRAS / FY-3D satellite

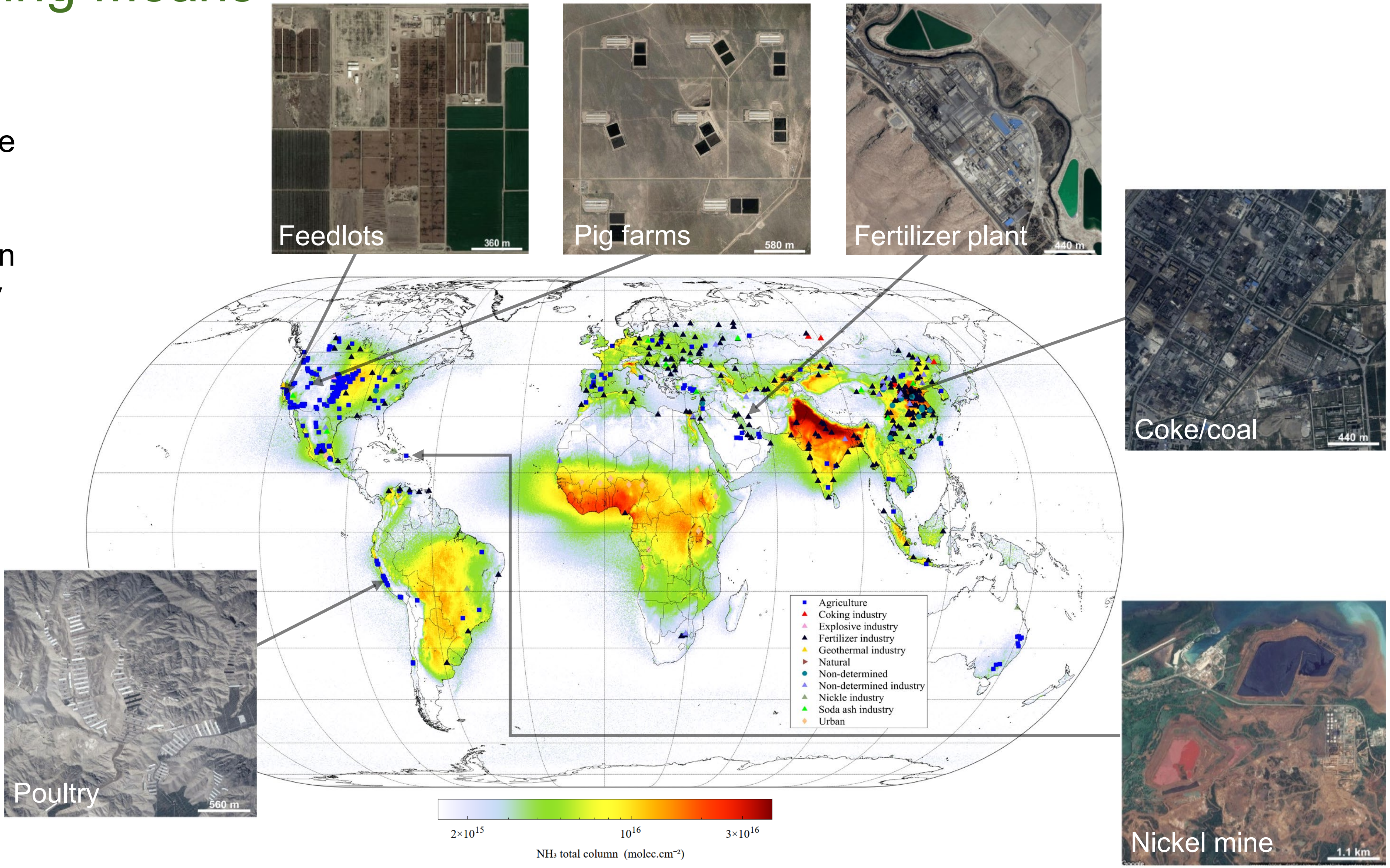


IRS / MTG-S satellite

Ammonia – Monitoring Means

Space Component

- Polar orbiting satellites provide (bi-)daily global distributions
- New insights to NH_3 emission spatial and temporal variability



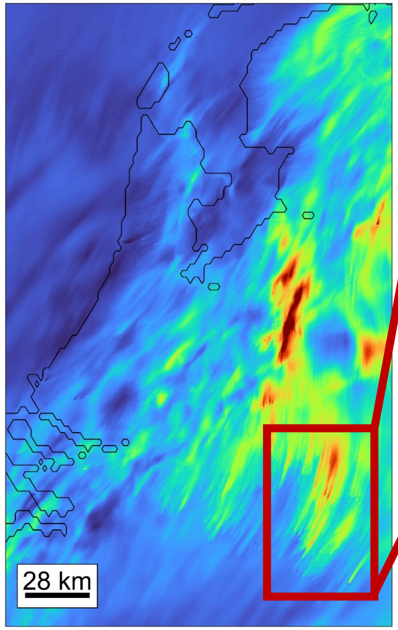
(Van Damme et al., Nature 2018; Clarisse et al., AMT 2019; Clarisse et al., AMT 2023)

Ammonia – Monitoring Means

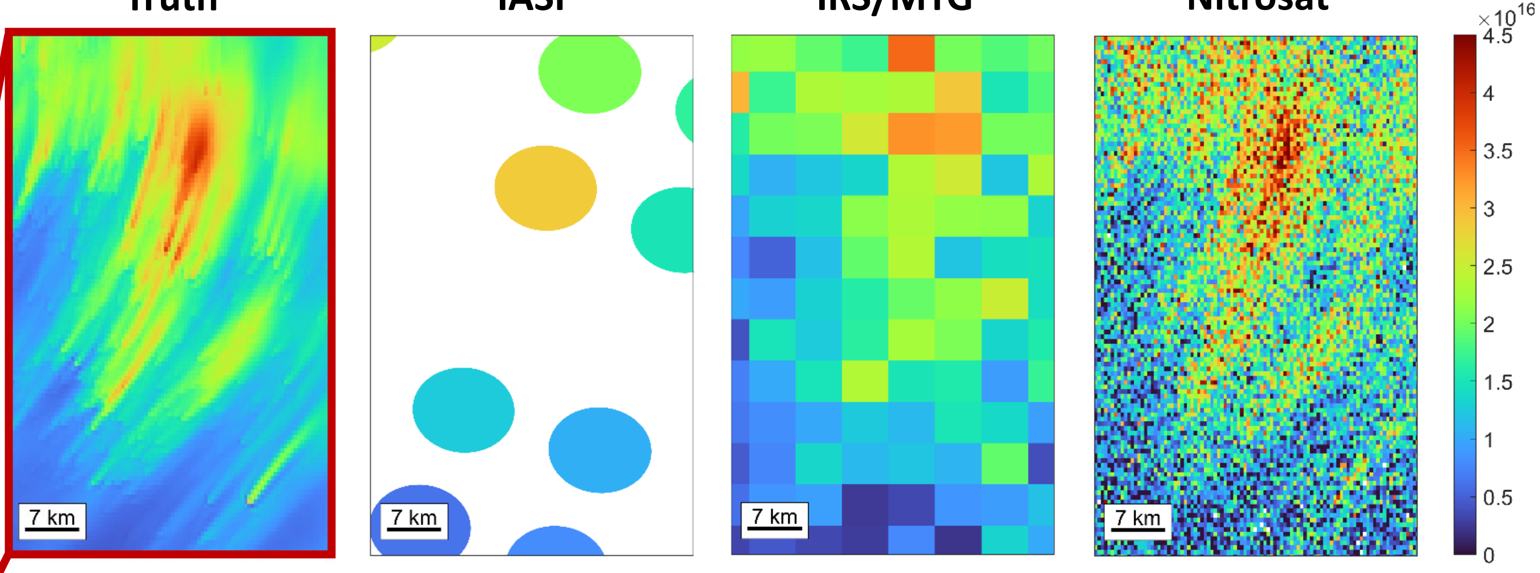
Space Component

- Polar orbiting satellites provide (bi-)daily global distributions
- New insights to NH_3 emission spatial and temporal variability

Scientific return from current satellite missions is limited by their overpass time (1-2 per day) and their spatial resolution (~12 km at best)

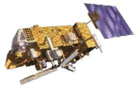


Modelled **"Truth"** | *Polar* **IASI** | **2025** *Geostationary* **IRS/MTG** | ~~**2031**~~ *Polar* **Nitrosat**



15.06.2018
0.4×0.7 km²
1pm

12-30 km
1-2 per day



Gapless coverage
6-7 km
Every 30 min!

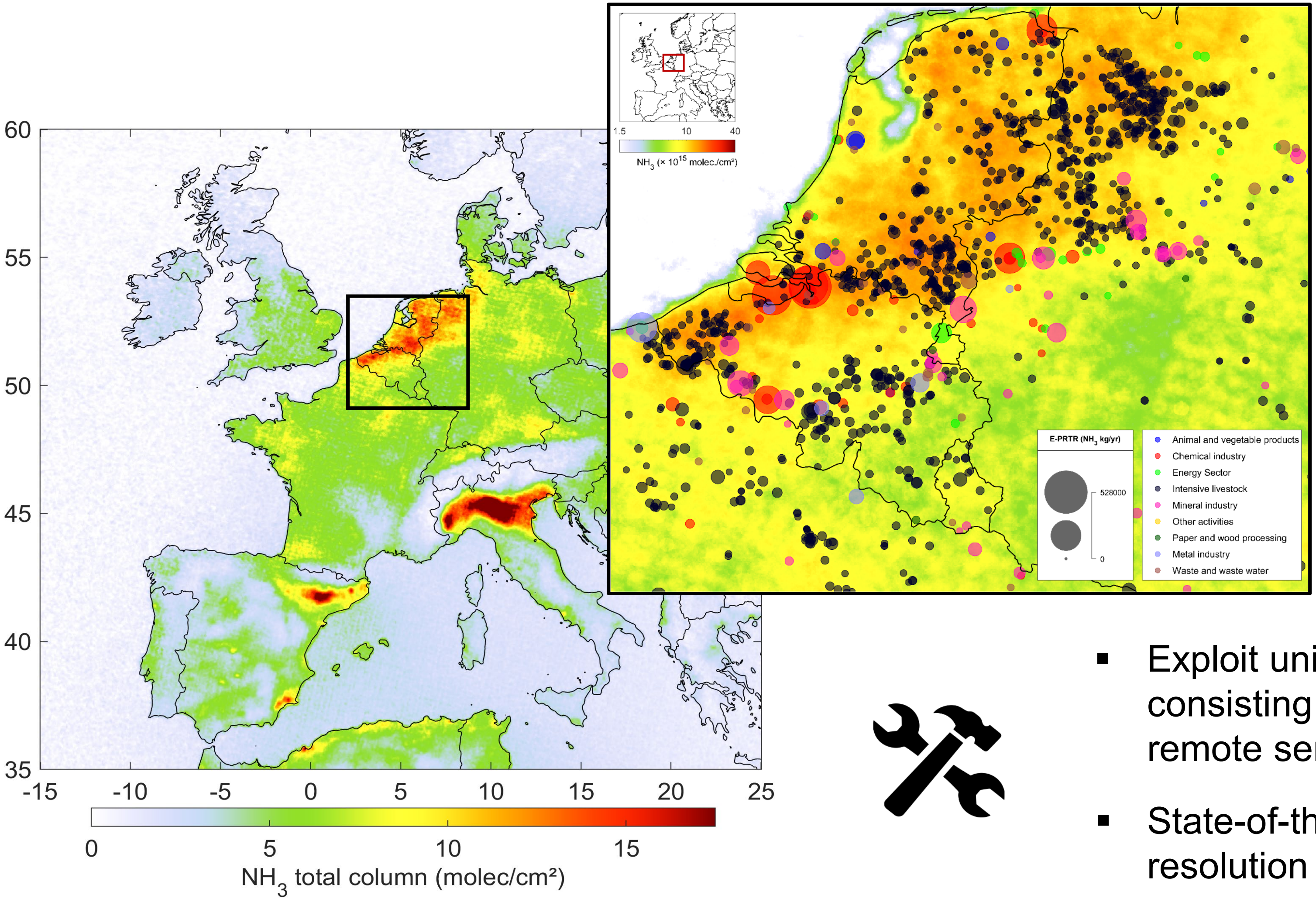
Gapless coverage
600 m
>once a month

Nitrosat

NH_3 monitoring from space is entering a new era, due to the advent of geostationary satellites and satellites offering increased spatial resolution

BEAM

Better quantify and understand the sources and processes driving atmospheric NH_3 agricultural and industrial emissions and subsequent deposition in Belgium



→ Flanders and the Netherlands are characterised by the largest livestock unit density in Europe

→ European regions where critical loads for eutrophication are exceeded most

- Exploit unique set of complementary monitoring techniques, consisting of in-situ measurements on-ground and infrared remote sensing from ground, aircraft and satellites
- State-of-the-art modelling at very high spatial and temporal resolution will allow upscaling and bridging the different measurement scales

BEAM - Scientific Objective 1

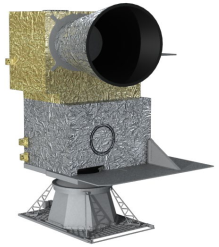
To develop an NH_3 dataset at high spatial (6-7 km) and temporal (daily, every 30 minutes) resolution over the entire European domain, based on observations of the IRS satellite sounder

- Neural network retrieval of NH_3 building on IASI / GIIRS heritage (Clarisse et al., AMT 2023)

→ **First NH_3 geostationary dataset over Europe**

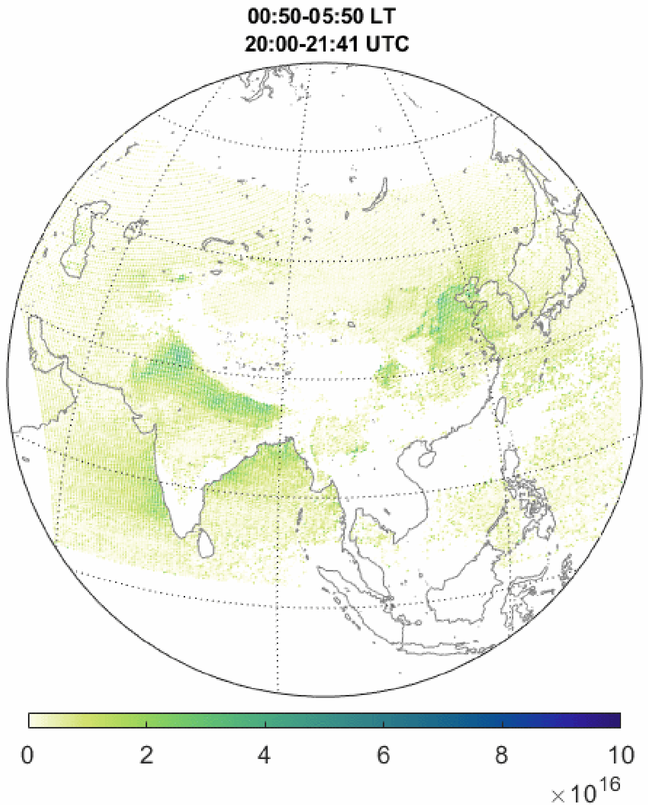
BEAM - Scientific Objective 2

To characterise the NH_3 spatiotemporal variations over Europe, from seasonal to diel variations and from the country to the regional scale



GIIRS instrument on-board FY-4A satellite

April



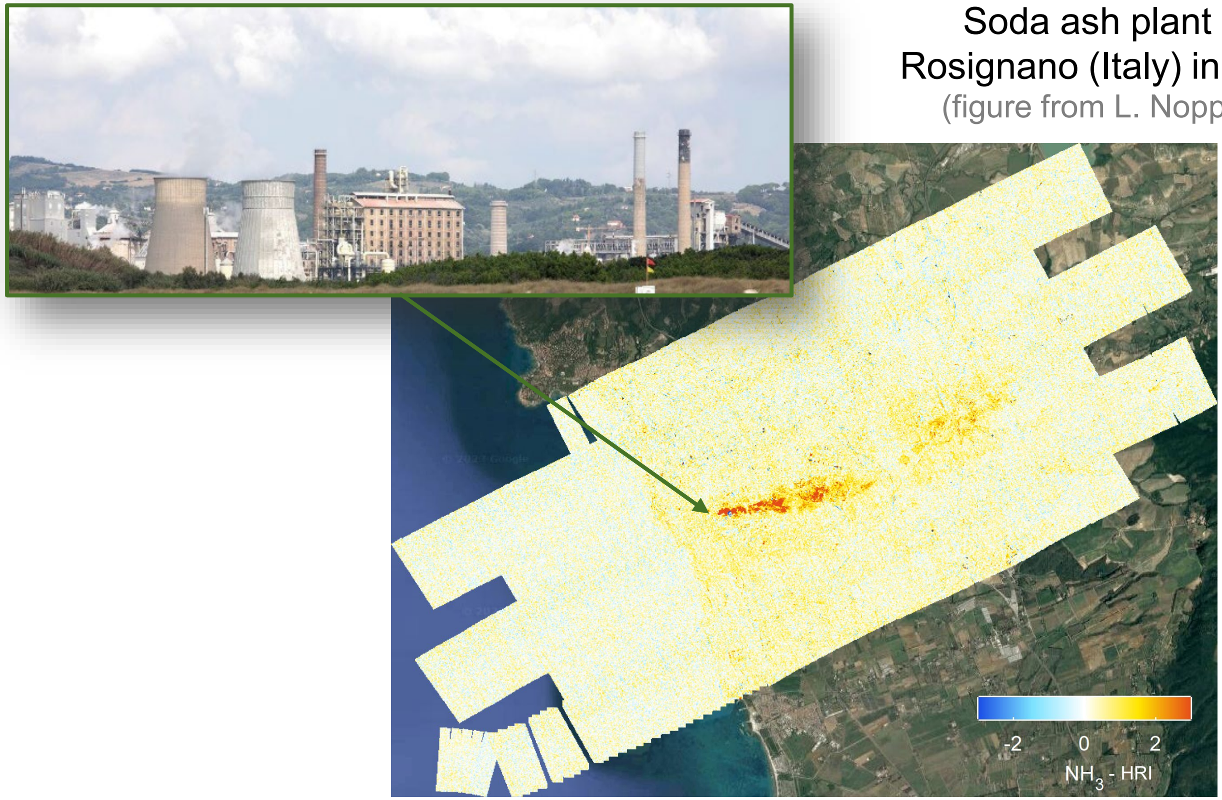
(Clarisse et al., GRL 2021)

BEAM - Scientific Objective 3

To survey regional NH_3 at hyperspatial resolution (below 5 m) over key sites in Belgium and/or the Netherlands

- Infrared imagers such as TELOPS mounted on an aircraft give new opportunities to investigate NH_3 sources
- 7-8 survey flights (30 h) will be set up over the target sites
- Derivation of fluxes using well-established techniques (e.g., transect method) (Noppen et al., RSE 2023)

Soda ash plant in Rosignano (Italy) in 2022
(figure from L. Noppen)



BEAM – Specific Target Sites

1. Concentrated animal feeding operations (CAFOs)

Clusters of CAFOs either in West Flanders or Northern part of the Antwerp Province are responsible for large NH_3 emissions. Both provinces are characterised by the largest livestock unit density in Europe. While open cattle CAFOs have been surveyed in the US, European-style enclosed livestock housings (pigs, chickens) have not, and are the dominating source of NH_3 emissions in the lowlands.

2. Harbour of Antwerp

The harbour of Antwerp, and the associated industrial park is home to several large chemical companies that report significant NH_3 emissions. Satellite distributions of NH_3 are notoriously difficult to analyse over harbours because of the large number of densely packed sources, and the typically high coastal wind speed. The hyperspatial resolution offered by aircraft measurements will therefore offer a view of the sources over the region that remains otherwise unavailable.

3. Kalmthout Heath

The Kalmthout heath is one of the oldest and most valued nature reserves in Flanders. Protected since 1941, the Kalmthout Heath consists of an area of marsh, heath, old inland dunes and woodlands, partly bordering the delta of the river Sheldt. Surrounded by NH_3 sources, it suffers from nitrogen influx towards its fragile ecosystems. The surveyed areas will include a large part of the heath, together with its dominant source region upwind (which will be determined after careful analysis of modelled and satellite data).

4. Fen area of Turnhout

The fen area of Turnhout (2208 ha) covers 11 protected habitats and 18 protected species and is coded as a Special Protection zone for Nature Conservation in the European Union (SBZ-H BE2100024). It has a varied landscape of heath on sand dunes, dry and wet heath, fens and woods. The survey area will also cover a historical official monitoring site of the VMM ("Vlaamse Milieu Maatschappij" which guards the air, water and climate quality in Flanders).

BEAM - Scientific Objective 3

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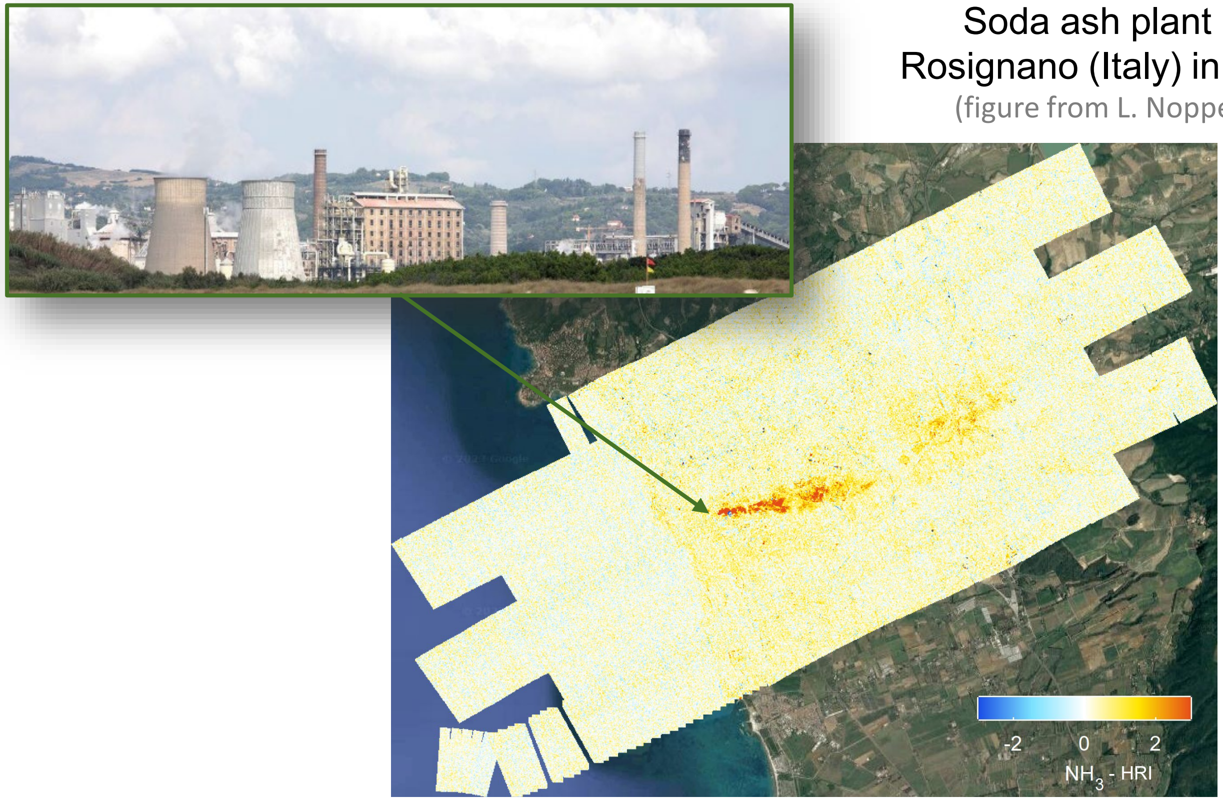
Soda ash plant in Rosignano (Italy) in 2022
(figure from L. Noppen)



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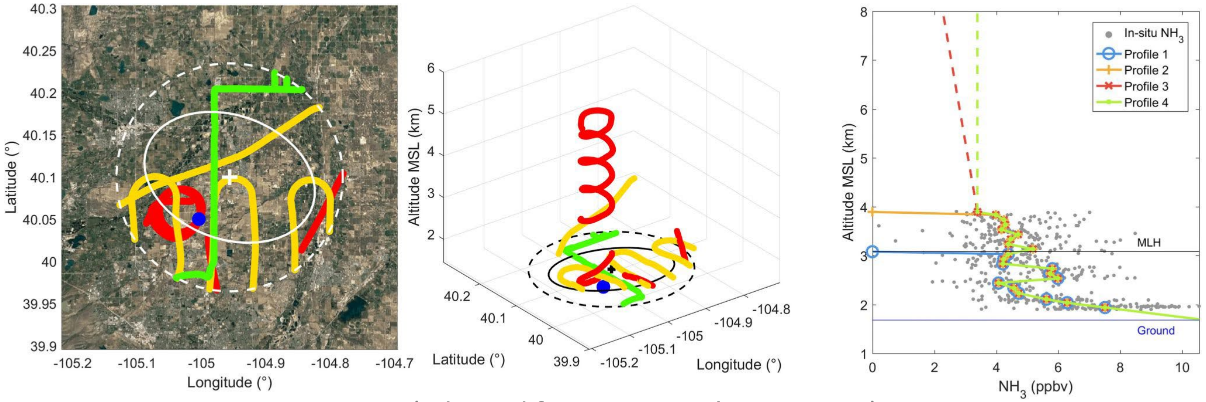
BEAM - Scientific Objective 4

To provide constraints on NH_3 vertical profiles

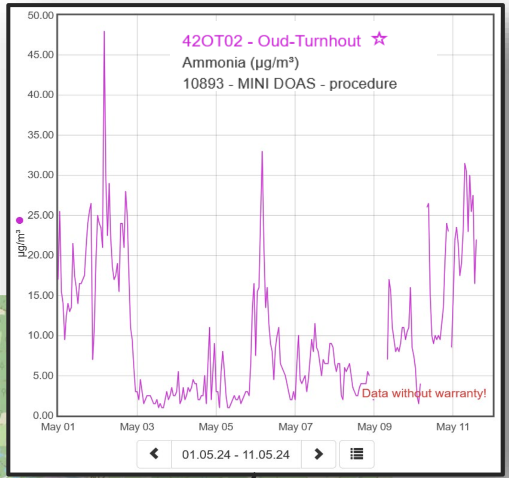
- A major uncertainty resides in the vertical distribution of NH_3 in the atmosphere
- A series of profiles will be measured during the spiral flights with the MIRO gas analyser, combined with ground-based measurements (TELOPS)

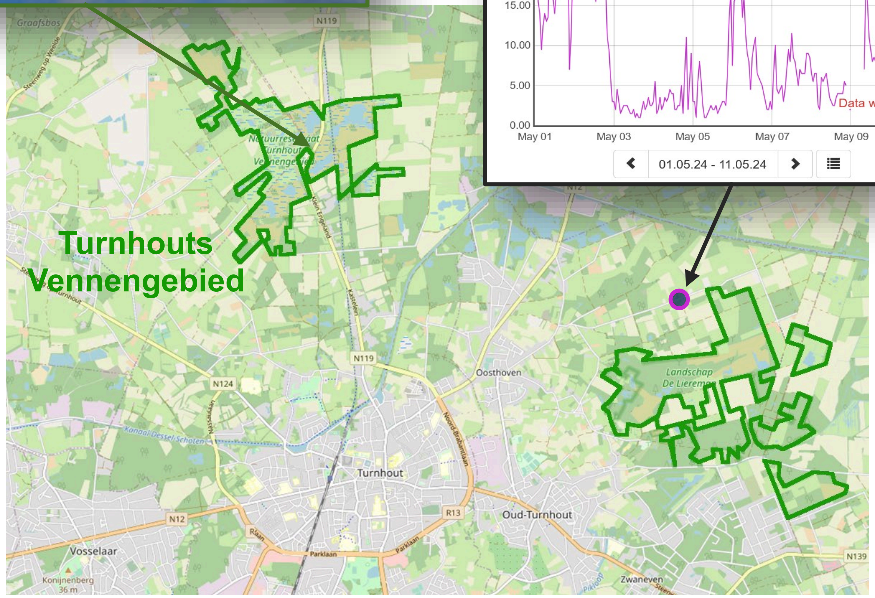


(adapted from Guo et al., GRL 2021)

BEAM - Scientific Objective 5

To characterise local source contributions to point source measurements





- Investigation of the main sources influencing nitrogen deposition to the fen area of Turnhout ("Turnhouts Vennengebied")

  →Current legislation fails at protecting such area from too high N inputs

- Assessment of the representativity of Oud-Turnhout measurement site

  → High variations in measured NH_3 concentrations are reported

  → Unclear which emission sources contribute to these high levels

- Ground-based measurements will be deployed (open-path lasers, potentially also a ground-based TELOPS imager)
- Satellite data will be used to identify location of the main sources
- A survey flight will also cover the target region
- Comparison with WRF-Chem models at hyperfine spatial resolution

Open-path laser (ILVO)

TELOPS (KCL)

BEAM - Scientific Objective 6

Identify strengths and weaknesses of models in simulating the spatio-temporal distribution of NH_3 and related compounds

BEAM - Scientific Objective 7

To derive a highly resolved top-down emission inventory over Belgium and the Netherlands

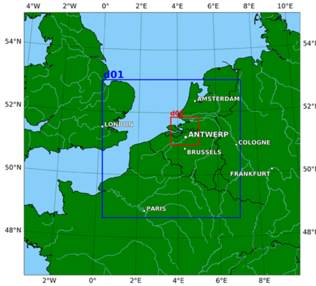
- Application of windrotated supersampling techniques together with exponential modified Gaussian (EMG) fits in Belgium and the Netherlands (IRS dataset)

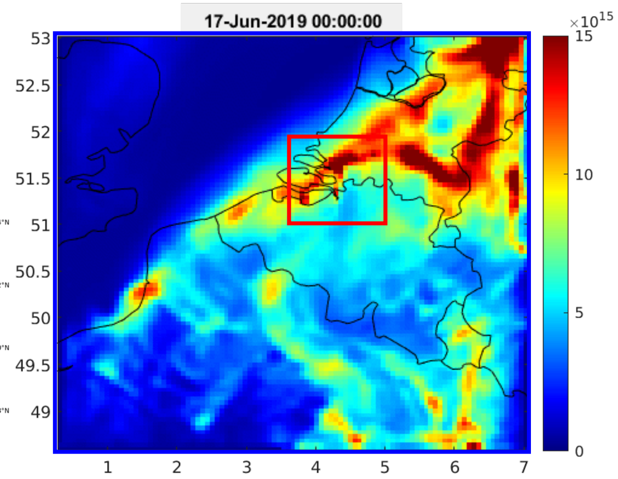
  → Catalogue of large point source emitters

- A mass balance approach will be designed to provide gridded emission updates in the WRF-Chem model

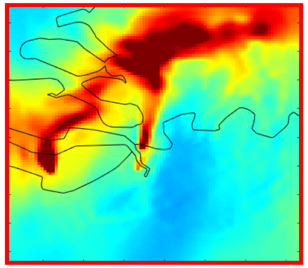
  → Gridded inventory characterizing the larger area sources and smaller unresolved clusters of point sources

→ **BEAM emission inventory**



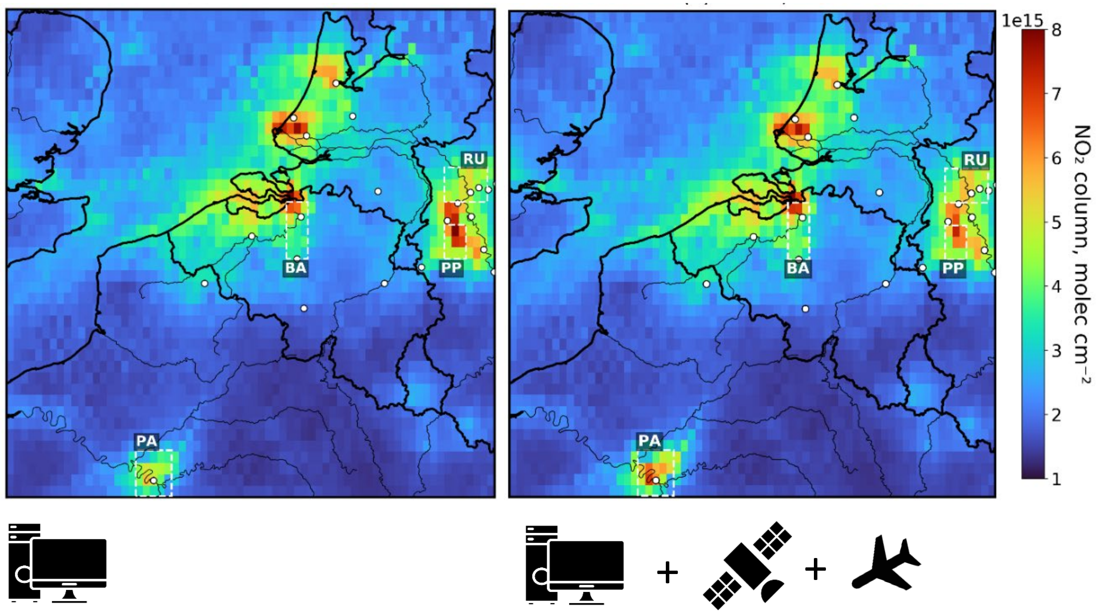


d01 - 5×5 km²



d02 - 1×1 km²

Example of NO_2



(Poraicu et al., GMD 2023)

BEAM - Scientific Objective 6

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BEAM emission inventory

BEAM - Scientific Objective 8

Establish the NH_3 trends (2008-present), assess their causes and estimate their consequences for air quality and NH_x deposition over Belgium and the Netherlands

- Evaluation of a trends re-assessment from IASI data record (2008-present) against WRF-chem dedicated model runs for 2008, 2013, 2018 and 2023

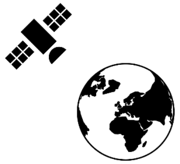
BEAM - Scientific Objective 9

Quantify the contributions of NH_3 and NO_x emissions to nitrogen deposition over Belgium and the Netherlands

BEAM - Scientific Objective 10

Validation of BEAM datasets and main findings

BEAM – Partners, Expertise & Complementarity



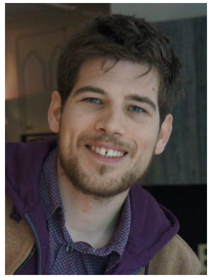
ULB

Infrared remote sensing, Satellite retrievals, Ammonia sources, budgets and monitoring techniques, Nitrogen cycle

Lieven Clarisse

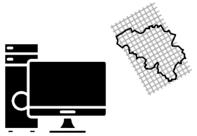
Pierre Coheur

Postdoctoral Researcher



Martin Van Damme

Master Students



BIRA • IASB

Atmospheric models, Inverse modelling of emissions, Chemical mechanism development, Emission inventories

Jean-François Müller

Jenny Stavrakou

Antoine Pasternak

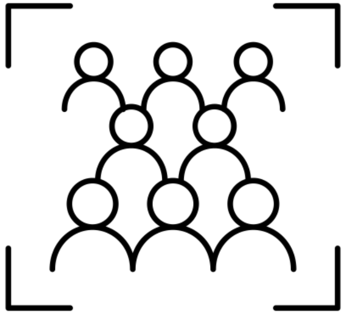
ILVO
Flanders Research Institute for Agriculture, Fisheries and Food

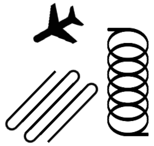
Monitoring of emissions from livestock housings, On-farm experiments, Gas analyser, Support to policy-making processes

Eva Brusselman

Laura Peeters

Technician





KING'S College LONDON

Observations of biosphere-atmosphere interactions, Operation of remote sensing instruments (on-ground and airborne), Field campaigns

Martin Wooster

Postdoctoral Researcher

BEAM - Innovations

BEAM will provide:

1. The first dataset of NH_3 from a geostationary satellite over Europe at unprecedented spatial (~6 km) and temporal (every 30 min) resolution

2. The first survey flights over enclosed livestock housings and industrial sources in Belgium

3. A unique set of NH_3 vertical profiles measured in Europe

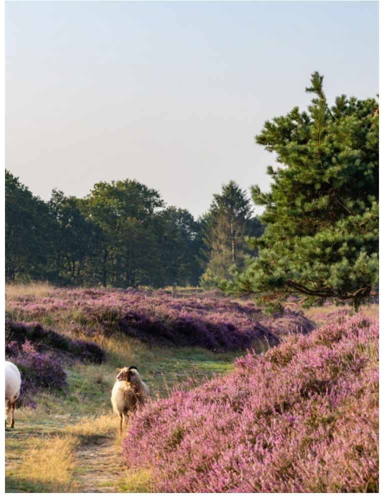
4. A multi-sensor analysis of nitrogen fluxes (emission, transport and deposition) over protected ecosystems in Flanders at hyperfine spatial and temporal resolution

5. A publicly available high-resolution top-down emission inventory

6. New tools to reinforce the Belgian capacity to model NH_3 and to make the most of currently planned (IRS, IASI-NG) and potential future (Nitrosat) European satellite mission

7. Support to policy making processes aiming at reducing environmental impacts of agriculture and nitrogen pollution



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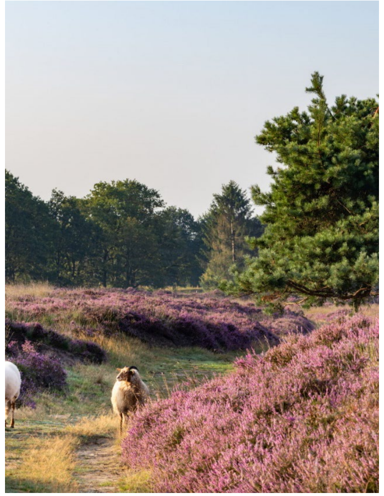


N Cycle Perturbations & Consequences of Excess Nr

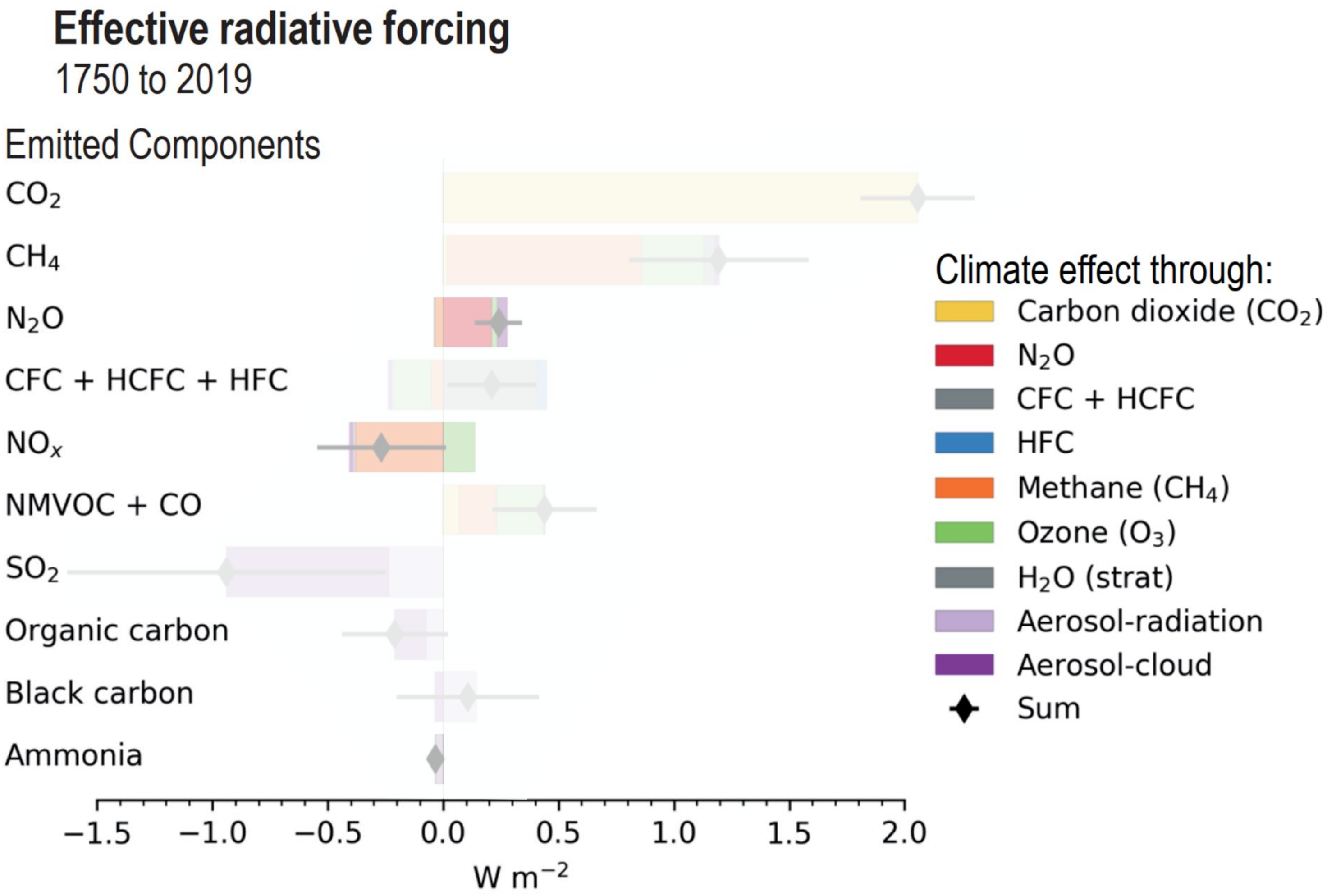
Climate

Direct positive forcing via N_2O

Indirect effects via:

- Tropospheric O_3
- NO_x changes CH_4 lifetime
- Aerosols

Indirect effect via Nr impacts on carbon cycling (largely uncertain)



Intergovernmental Panel on Climate Change (2021)

Better quantify and understand the sources and processes driving atmospheric NH_3 agricultural and industrial emissions and subsequent deposition in Belgium

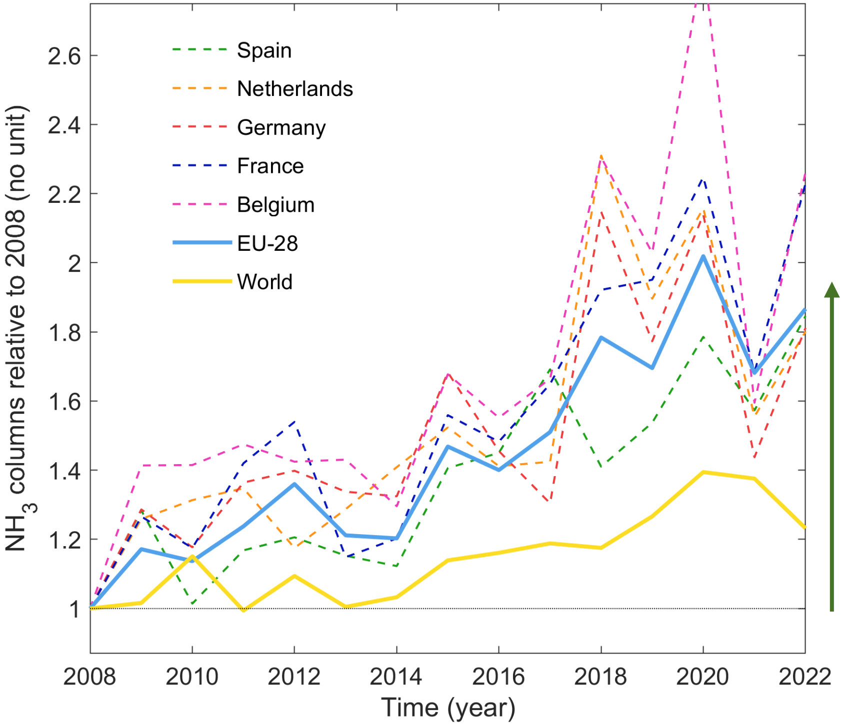
Scientific Questions:

1. What are the limitations of the current observational and modelling means to monitor NH_3?
2. How can we best exploit geostationary satellite observations for quantifying NH_3?
3. What are the emission and deposition fluxes of NH_3 over the target domain, and how do these vary in time and space?
4. To what extent do agricultural and industrial NH_3 emissions affect sensitive ecosystems?
5. How are trends in the NH_3 satellite measurements impacted by abatement strategies and climate change?
6. Are the models able to assimilate satellite observations at high spatial and temporal resolution (e.g., IRS, Nitrosat)?

BEAM - Scientific Objective 8

Establish the NH_3 trends (2008-present), assess their causes and estimate their consequences for air quality and NH_x deposition over Belgium and the Netherlands

- Trends re-assessment from IASI data record (2008-present)
- Evaluation against WRF-chem dedicated model runs for 2008, 2013, 2018 and 2023
- Investigation of the impact of global warming and NO_x and SO_2 emission control on NH_3 levels



(updated from Van Damme *et al.*, 2021)

BEAM - Scientific Objective 9

Quantify the contributions of NH_3 and NO_x emissions to nitrogen deposition over Belgium and the Netherlands

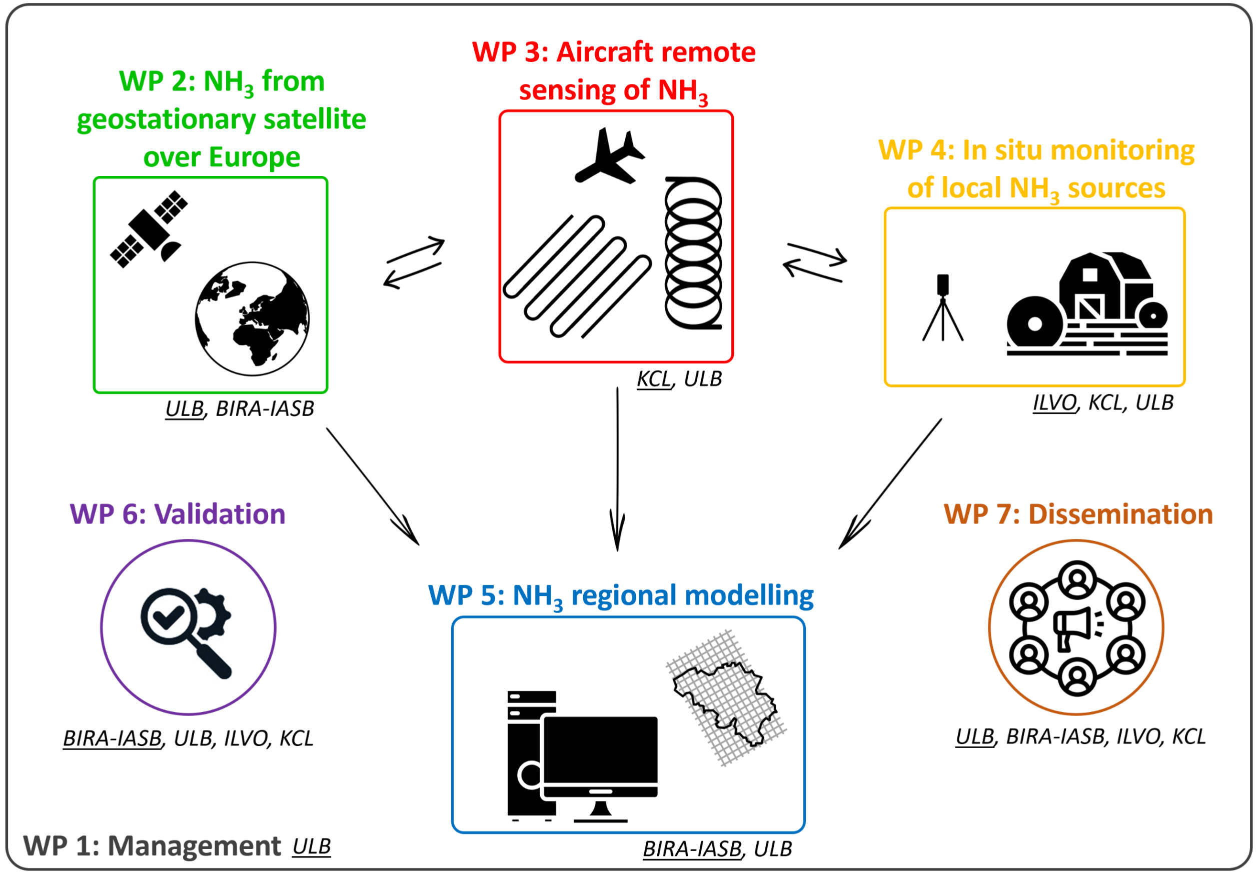
- Dry and wet deposition maps of NH_x and total nitrates (HNO_3+NO_3^-) will be produced with WRF-Chem
- Impact on ecosystems will be assessed via critical load for N deposition exceedance

BEAM - Scientific Objective 10

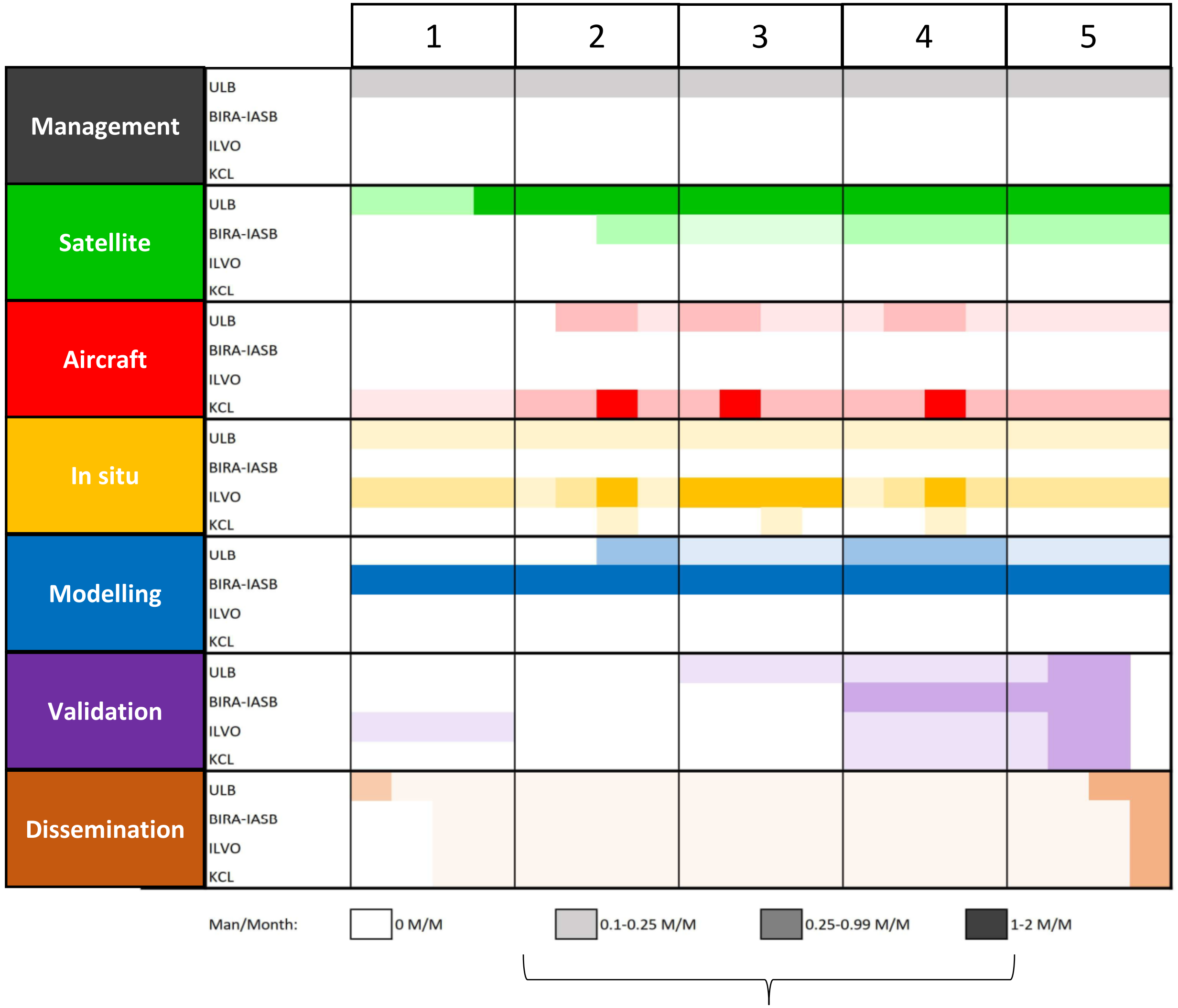
Validation of BEAM datasets and main findings

- Cross-evaluation of BEAM ground-based, airborne and satellite data
- Comparison with independent data (e.g., in situ networks, CrIS)
- Evaluation of emission and deposition fluxes against available datasets and measurements

BEAM – Work Structure

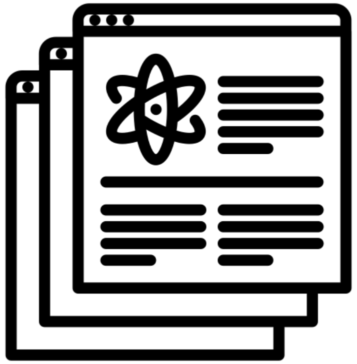


5-year project

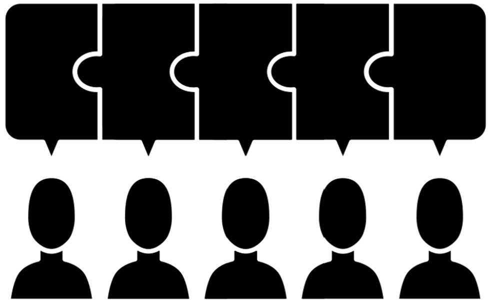


Campaigns take place year 2, 3 & 4

BEAM – Valorisation and Dissemination



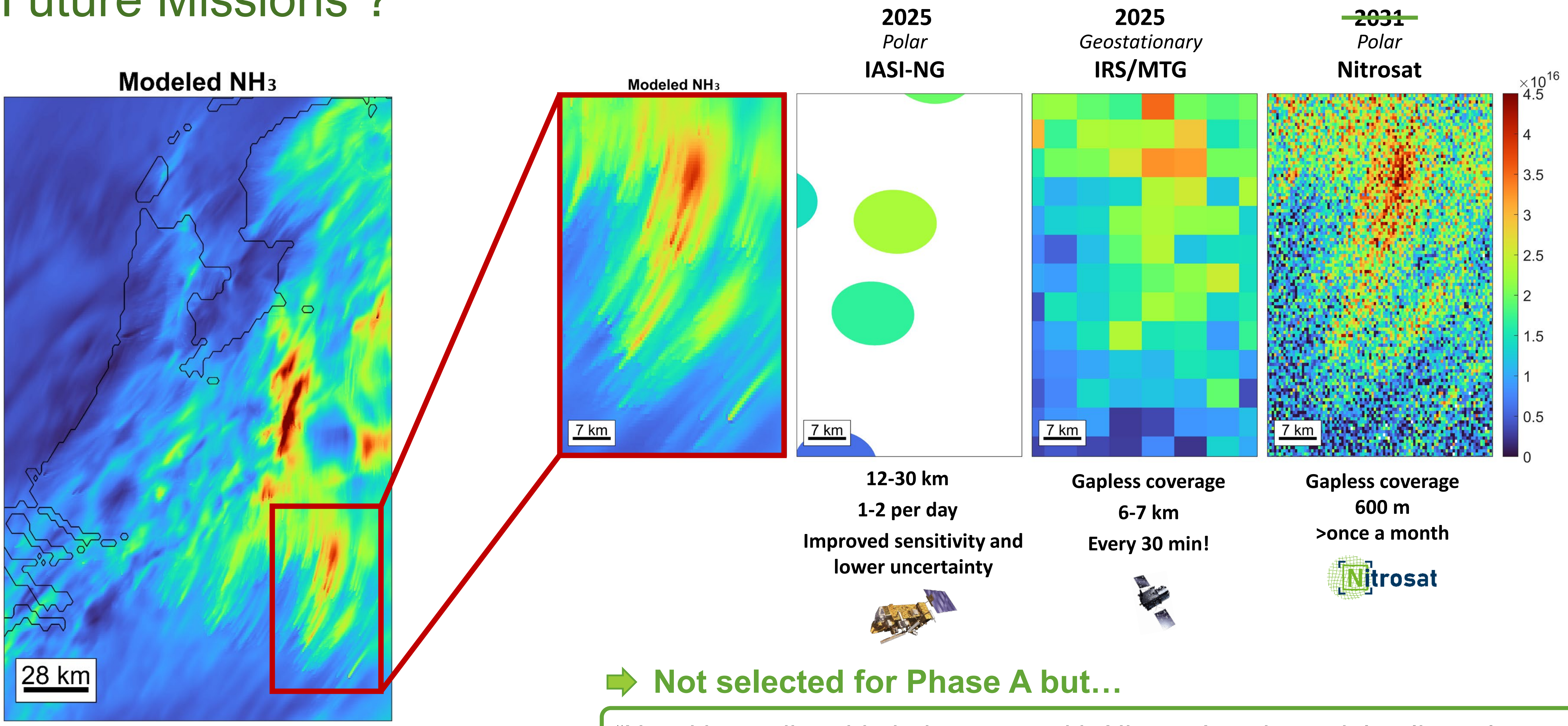
www.beam-stereo4.be



- Publications in (open-access) peer-reviewed international journals
- Presentations in international conferences
- Dedicated web site to promote BEAM and its main achievements and outcomes
- Involvement of master students in campaign activities and data analysis
- Results will be presented and used for course given at ULB ("Télédétection des variables climatiques et environnementales")
- Main results will be advertised via communications tools from the partners (e.g., Facebook, Twitter, Instagram, etc.)
- 2-day workshop at the end of the project involving potential stakeholders and experts from various scientific communities

\+ Appealing web stories, attendance to open-doors of involved institutes, foster interactions with international programs

Future Missions ?



15.06.2018
0.4×0.7 km²
1pm

12-30 km
1-2 per day
Improved sensitivity and lower uncertainty

Gapless coverage
6-7 km
Every 30 min!

Gapless coverage
600 m
>once a month

Nitrosat

➡ Not selected for Phase A but…

"Notwithstanding this judgement, with Nitrosat's substantial policy relevance and potential societal benefits, ACEO encourages ESA to consider means for developing the mission within an alternative programmatic framework."