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# AnthroAm Sentinel

Air pollution, such as fine particulate matter (PM2.5), is responsible for 659 000 deaths in Europe every year. Anthropogenic emission of ammonia from agriculture is a significant contributor to the European PM2.5 levels, and estimated to incur Europe of excess health expenses of more than € 9.7 billion annually. This project outlines how a European space initiative can mitigate ammonia emission by providing individual farmers with fertilizer management strategies tailored to their agricultural lands, by compiling information on the atmospheric spectral fingerprint and reflectance spectra from Earth Observation satellites in the ESA Copernicus Programme.

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# The AnthroAm Sentinel

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**Executive Summary**

Anthropogenic emission of ammonia is a significant contributor to European air pollution with fine particulate matter ($PM_{2.5}$). Studies have underpinned the role of $PM_{2.5}$ in lung carcinogenesis, cardiopulmonary disease, and more recently, in major depressive disorders. It has been estimated that about 659 000 deaths annually in EU alone, are caused by air pollution. In EU-28 92% of the anthropogenic emission of ammonia stems from agriculture, especially from the nitrogen content in organic and mineral fertilizers. Despite all efforts to mitigate emission, a recent briefing from the European Environment Agency states problems regarding limiting the agricultural emission to the targets set by the United Nations, and even by the EU member states themselves. This project proposes minimizing agricultural emissions by providing *individually tailored* decision support for farmers on fertilizer management strategies, by using ESA satellite imaging- and spectrometry to quantify field-level soil ammonia emission propensity. This project will enable farmers to increase nitrogen availability for crop uptake, reduce their economic burden from fertilizer oversupply, and reduce overall ammonia emission levels, entailing subsequent reductions in excess deaths and public health expenses. This project addresses UN Sustainable Development Goals 3, 12, 13, 14 and 15.

## Contents

# 1 Introduction

## 1.1 Anthropogenic ammonia emissions

Anthropogenic emission of ammonia ($NH_3$) is a **major environmental, societal and socio-economic challenge**. Detrimental effects on terrestrial and aquatic ecosystems, including eutrophication and ocean acidification, have been well documented (Grennfelt & Hultberg, 1986; Krupa, 2003), along with suggested impacts on biodiversity (Guthrie et al., 2018). In addition to the canonical view on ammonia emission and its impacts on Earth's ecosystems, it has been found that ammonia is a precursor to formation of atmospheric secondary inorganic aerosols, directly involved in air pollution with fine particulate matter, $PM_{2.5}$ (Lonati et al., 2008; Sharma et al., 2007). This is especially disturbing, as studies have underpinned or implicated the role of $PM_{2.5}$ across numerous diseases including cardiopulmonary diseases, lung cancer mortaility (Pope et al., 2002) and increased likelihood of a major depressive disorder given teenage exposure to $NO_2$ and $PM_{2.5}$ (Roberts et al., 2019). It has further been found that **particulate matter is likely capable of crossing the blood-brain barrier** through yet unknown mechanisms (Block & Calderón-Garcidueñas, 2009), with subsequent ability to induce the onset of neuroinflammatory responses. Indeed a recent epidemiological case-control study found evidence of **correlation between long-term exposure to air pollution and predisposition to Amyotrophic Lateral Sclerosis (ALS)** (Seelen et al., 2017).

In 2016 agriculture was responsible for 92% of the total **3.9 million metric tonnes of ammonia emitted in EU-28** according to the European Environment Agency (European Environment Agency, 2018), thus providing a significant contribution to the European $PM_{2.5}$ levels (Bauer et al., 2016). The emission primarily stems from the nitrogen (N) content in organic and mineral fertilizers, used for fertilizing fields for crop harvest. Through well documented mechanisms, ammoniacal nitrogen can be emitted to the atmosphere, thus reducing the pool of nitrogen that should otherwise have been available for crop uptake. Typically the atmospheric lifetime of $NH_3$ is short, generally re-deposited within tens to a hundred kilometers. However, atmospheric ammonia undergoing secondary inorganic aerosol formation is capable of traveling from hundreds to a thousand kilometers (Asman et al., 1998). Consequently, **anthropogenic $NH_3$ is not just a local or regional problem, but a continental problem**.

It is conceivable that anthropogenic emission of ammonia and subsequent involvement in air pollution in the form of $PM_{2.5}$ will drive socio-economic imbalance, especially owing to the related health effects of long-term exposure to $PM_{2.5}$. It has been estimated that air pollution, including $PM_{2.5}$, **is responsible for approximately 659000 deaths in EU-28 annually** (Lelieveld et al., 2019). The associated excess health expenses are difficult to quantify, but a current best estimate is that excess health expenses incurred from ammonia emission is about €2.7 per kilogram of $NH_3$ emitted (Guthrie et al., 2018). Given the total $NH_3$-emission in 2016, **excess health expenses incurred were more than €9.7 billion in EU-28 alone that year**. Consequently, there are both environmental, societal and economic incentives to promote emission reduction strategies and sustainable fertilizer management.

## 1.2 Regulatory aspects of ammonia emission

Given the long-range transboundary pollution potential of ammonia-derived fine particulate matter (see Section 1.1), the emission has been incorporated in regulatory procedures. Briefly, in 1979 the United Nations Economic Commission for Europe (UNECE) included $NH_3$ in the Convention on Long-range Transboundary Air Pollution (CLRTAP; UNECE (2012)), to regulate the emission of $NH_3$. Reduction targets have been revised since the late 1970's to ensure a continuous strive towards limiting the emission of potent pollutants, among which anthropogenic ammonia is one. In the European Union emission reduction targets are set by the National Emission Ceilings Directive (NEC Directive; European Parliament (2001)), which are either equivalent or more ambitious than the UN-regulated emission targets. Unfortunately, despite regulatory action against emission of ammonia, there are still a number of problems that needs to be addressed.

### 1.3 Problem overview

Emission of ammonia from field-applied fertilizer is to a great extend governed by the characteristics of the fertilizer, including dry matter content and pH, fertilizer application method, soil characteristics, such as clay content and soil pH, as well as weather. In turn, the emission is highly variable, making it difficult for farmers to manage fertilization such that emission is minimized and the nitrogen content remains available for plant uptake. To date, **this variability makes emission prediction modeling highly non-trivial**. Owing to the lack of available tools for fertilization decision support, farmers may choose to oversupply the nitrogen content to ensure sufficient N-availability for crop uptake. However, not only does this **further drive emission losses, but it also constitutes an excess economic burden for the farmer** (Hansen et al., 2007), that in most cases are already under economic pressure. Research initiatives have resulted in the development of new technical means for emission mitigation. For instance, it has been found that by changing the application method from broadcast to open slot injection of animal manure, emission can be reduced by 70% (Hafner et al., 2018). **Unfortunately, technical means of mitigation will frequently require economic investment in new equipment, which may be down-prioritized given the already high economic burden**.

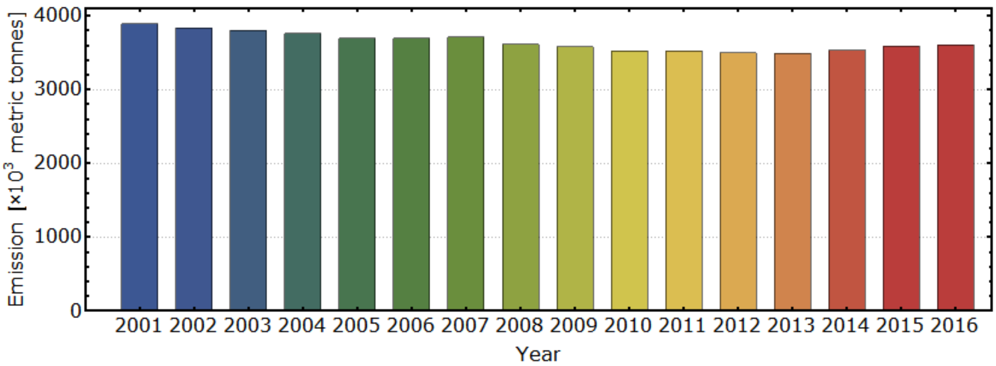


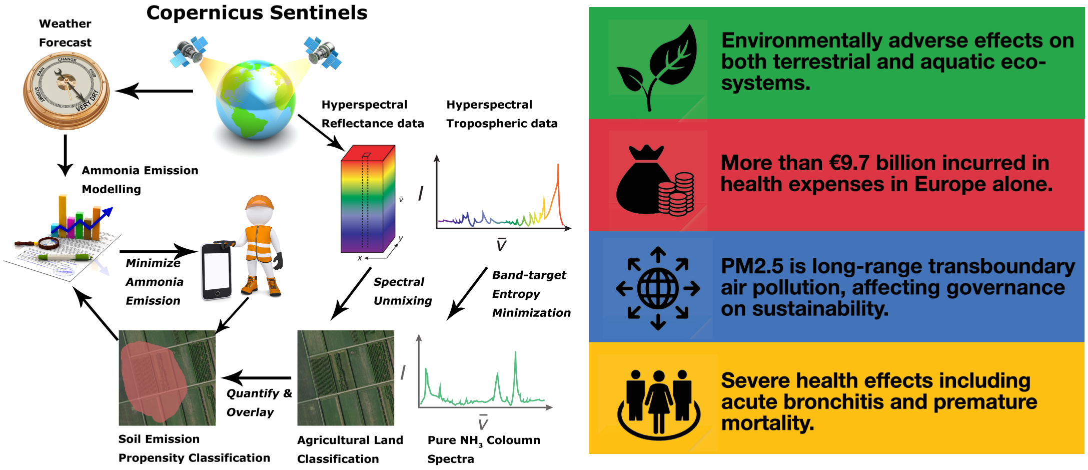

**Figure 1:** Emission of ammonia ($\times 10^3$ million metric tonne) from EU-28 agriculture between 2001 to 2016. Emission has increased by approximately 113000 metric tonnes since 2013. Numbers are from European Environment Agency (2018).

Given the amount of research and regulatory efforts, it may be surprising that ammonia emission from agriculture in EU-28 has been increasing since 2013 and not since 2008 has the emission been higher (Figure 1, European Environment Agency (2018)). It would thus seem **there is a *raison d'être* for freely accessible decision support on emission mitigation strategies, tailored to the individual farmer at field-level**.

## 2 The AnthroAm Sentinel project

### 2.1 Project description and methodology

The proposed project, the *AnthroAm Sentinel*, is **a unique attempt to provide freely accessible decision support to farmers, based on their individual lands**. As mentioned in Section 1.3, degree of N-emission is dependent on soil characteristics such as pH, sand- and clay content and cation exchange capacity of the soil. However, these parameters can vary greatly, even locally. Consequently, providing decision support on fertilizer management strategies is non-trivial, given that most emission prediction models are developed based on experimental data from relatively few research fields scattered across Europe. The project proposes combining established satellite Earth Observation techniques *with new data handling processes and emission prediction models*,




(a) (b)

**Figure 2:** Overview of (a) the *AnthroAm Sentinel* project idea, and (b) effects of anthropogenic ammonia emission on the four pillars of sustainability.

to develop a novel platform for ammonia emission **prediction** (for discussion on value-added compared to prior art, please see Section 2.3). **Hence, the project idea is established within a well known context and of timely applicability, as reviewed in the Section *Problem Overview***. The mission statement of the *AnthroAm Sentinel* project is:

**To freely and openly provide precise ammonia emission predictions tailored to *the individual farmer* at field-level, by using satellite imagery and spectrometry to enable decision support on fertilization strategies that minimize emission, and increase pool of nitrogen available for crop uptake**

An outline of the *AnthroAm Sentinel* project idea is found in Figure 2a. The system operates as follows:

1. Multi-/hyperspectral data is collected by Sentinel-2 (A and B) MSI and Sentinel-3 OLCI. The spectral datacubes are classified based on endmember spectra using simplex maximization algorithms (Winter, 1999). The satellite scenes are mapped into agricultural lands of which a farmer can request ownership.
2. The farmer enters her/his current fertilization strategy into the *AnthroAm Sentinel* online web platform.
3. Infrared (short-wave IR or far infrared) spectral information is acquired by one or more designated satellites, for instance ESA Sentinel-5P TROPOMI or CNES IASI (or CNES IASI-NG from 2022 and onward).
4. It is proposed for Sentinel-5P to extract $NH_3$ bands in the short-wave IR range around 4300 $cm^{-1}$ (just covered by TROPOMI). For IASI, analysis is easier, as absorption bands near 800-1000 $cm^{-1}$ can be targeted instead.
5. Using information from step 2), calculate a *soil emission propensity factor* that combined describes the farmer's soils' tendency to emit ammonia, accounting for weather patterns at the time of fertilizer application.
6. Use the soil emission propensity factor to ***predict future*** ammonia emission. Use emission models with weather forecasts to determine a favorable point in time to fertilize, such that N-emission is minimized.

It is noteworthy, that although the system is designed for the farmers, the *AnthroAm Sentinel* would also constitute a significant scientific contribution to the field, as it would provide agronomists and environmental researchers with a new tool to research emission dynamics globally, across soil characteristics, fertilizer management strategies and climate. Another benefit is that the *AnthroAm Sentinel* would **provide a standardized European measurement method of ammonia emission**, enabling *fair* comparison of N-emission among EU member states and thus **facilitating political decision-making on emission targets**. Furthermore, in addition to the European interest in standardizing emission measurements, it is in EU interest to ensure that emission mitigation strategies are not down-prioritized owing to the economy, for instance by supporting freely available decision support tools to all farmers.

*Space* and *sustainability* are two central terms in the *AnthroAm Sentinel* project idea. The proposed project deploys several streams of space spectrometry information and satellite imagery (required for weather reports, plant land cover classification, and quantification of ammonia emission flux). Hence, space plays a pivotal role for the success of the project. By addressing anthropogenic emission of ammonia in Europe, the *AnthroAm Sentinel* targets all four pillars of sustainability (Figure 2b, *not* listed in order of priority), and furthermore addresses UN Sustainable Development Goals 3, 12, 13, 14, and 15.

### 2.2 The AnthroAm Sentinel online platform

A key concept of the *AnthroAm Sentinel* project is the access to tailored decision support on minimizing N-loss to the atmosphere given fertilizer management strategies **at field-level, for the individual farmer**. To this end, especially two factors will play a pivotal role on the success of the *AnthroAm Sentinel*.

- Easy access to a user interface that through appealing design enables easy decision-making on fertilization strategy. Optimum strategy is proposed by the *AnthroAm Sentinel* system to limit N-emissions to the atmosphere.
- **Involving the farmer** in the mitigation process, by providing metrics such as 'to date'-mitigated emission.

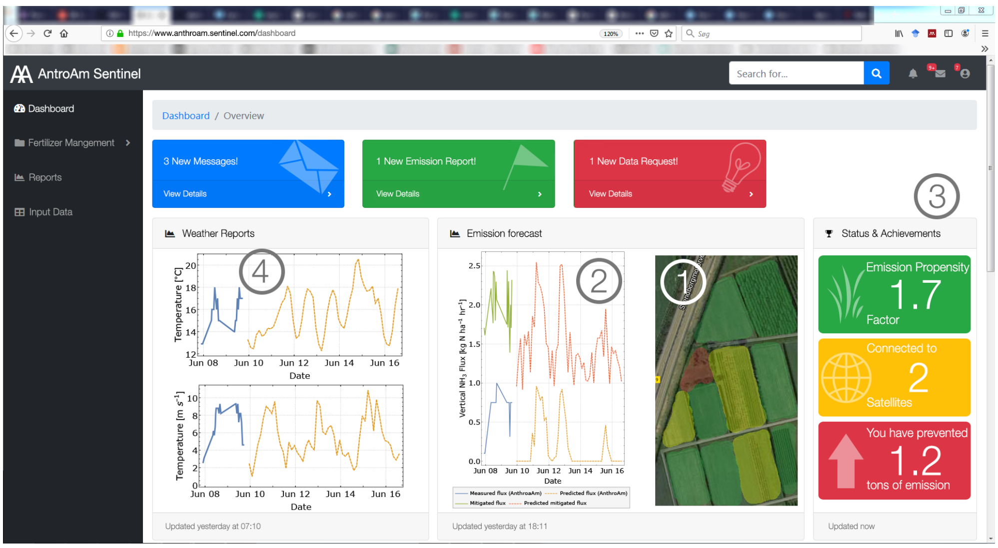



**Figure 3:** Mock-up dashboard of the *AnthroAm Sentinel* online web-platform, freely accessible for farmers to manage their individual field fertilization strategies. For a description of the user interface numbering, please refer to the in-text presentation of the platform in this section. Weather reports labeled **(4)** were obtained through Wolfram Alpha LLC at midnight on the $10^{th}$ June 2019.

Given the aforementioned, and confer the project description in Section 2.1, it is envisioned that the *AnthroAm Sentinel* should provide **easy access to an online web-platform**, freely available to farmers using the system. A first iteration of the web-platform dashboard is presented in Figure 3. Briefly, the dashboard is divided into three main views, pertaining to different aspects of the *AnthroAm Sentinel* system, and specifically comprised by **(1):** satellite imagery of the field(s) managed by a given farmer, overlaid with soil ammonia emission propensity factor contour plot estimated given the ouline in Section 2.1. Yellow-marked fields indicate higher emission propensity compared to green-marked fields. Higher emission propensity could, for instance, be caused by unfavourable soil pH, or generally higher windspeeds owing to lack of planted shelterbelts along the field; **(2):** ammonia emission forecasting presenting the 'business-as-usual' emission flux (top), and the possible *AnthroAm Sentinel* mitigated flux (bottom); **(3):** status and achievements panel presenting a) the overall emission propensity factor of the farmers' field(s), b) number of satellites currently connected to the *AnthroAm Sentinel* system, and c) the total 'to-date' count of mitigated ammonia emission compared to the predicted 'business-as-usual' emission; **(4):** current whether reports for the geographical location of the managed fields. The weather reports are used for the ammonia emission prediction models.

### 2.3 Project benefits compared to prior art

The novelty of the proposed project is not satellite scenery classification using simplex maximization approaches, nor the concept of determining total column of $NH_3$ from infrared spectrometry. Simplex maximization algorithms, such as N-FINDR, were originally demonstrated for satellite imagery (Winter, 1999), and ammonia columns have previously been mapped using spectral data from CNES IASI through the pivotal work of, among others, Clarisse et al. (2009, 2010) and Van Damme et al. (2015). However, to the knowledge of this author, never has satellite imagery and spectrometry been combined and applied to **predict future ammonia emission**, and designed as a decision support tool. Other significant contributions of the *AnthroAm Sentinel* project are outlined in Table 1.

| Category | AnthroAm Sentinel | Value-added AnthroAm Sentinel |
|---|---|---|
| Ammonia measurement | Based on spectral entropy minimization | • Enables resolving 'pure' spectra, even in regions with spectral overlap from interfering species.<br>• Enables quantification of ammonia over an entire spectrum rather than at discrete wavenumbers.<br>• May facilitate quantification even during unfavorable weather conditions and thermal contrasts.<br>• Enables retro-fitting and joining of spectral information from several satellites even if not originally designed for the purpose |
| Emission modeling | Calculates soil emission propensity | • The AnthroAm Sentinel can in this way include soil effects on emission modeling, which otherwise only would be available from research fields.<br>• Enables the farmer to adopt the best fertilization strategy at field-level, to minimize emission and increase N-availability for crop uptake. |

**Table 1:** Value-added of the *AnthroAm Sentinel* project compared to prior art.

## 3 Feasibility and implementation

### 3.1 Technical demonstration of feasibility

With a view to demonstrating a proof-of-concept of entropy minimization with spectral data, **a laboratory experiment was designed specifically for this *AnthroAm Sentinel* project proposal**. Two components, microcrystalline cellulose and stearic acid, were mixed in various ratios. The two materials have several overlapping spectral features, especially in the lower wavenumber region, but also contain few spectrally distinct features. Spectra of the mixtures were acquired using Fourier transform infrared spectroscopy (FTIR) using a Cary 630 FTIR (Agilent Technologies Inc., Santa Clara, CA, USA) at a resolution of $4\,\mathrm{cm}^{-1}$ after Happ-Genzel apodization. A total of 52 mixture spectra were acquired (see Figure 4a) for the analysis. Subsequently, the measured mixture spectra in Figure 4a were decomposed using a linear algebra technique termed singular value decomposition (SVD). The decomposition yields a matrix containing vectors termed right-singular vectors. The first three right-singular vectors were chosen as the basis of reconstruction. Next, spectral band targets were selected for the reconstruction, 3200-3400 $\mathrm{cm}^{-1}$ for cellulose and 1600-1800 $\mathrm{cm}^{-1}$ for stearic acid. The information entropy was then minimized around band-targets using simmulated annealing (entropy minimization is described by Widjaja et al. (2003)). Last, the entire spectrum of each component was reconstructed using the selected right-singular vectors. Both the cellulose (Figure 4b) and stearic acid (Figure 4c) reconstructions (red), compare well with the pure reference spectra (green) in terms of peak characteristics and location in the spectrum.

In both cases is the coefficients of determination $> 0.93$. The spectra were reconstructed **without *a priori information*** about the spectral characteristics of the pure material spectra.

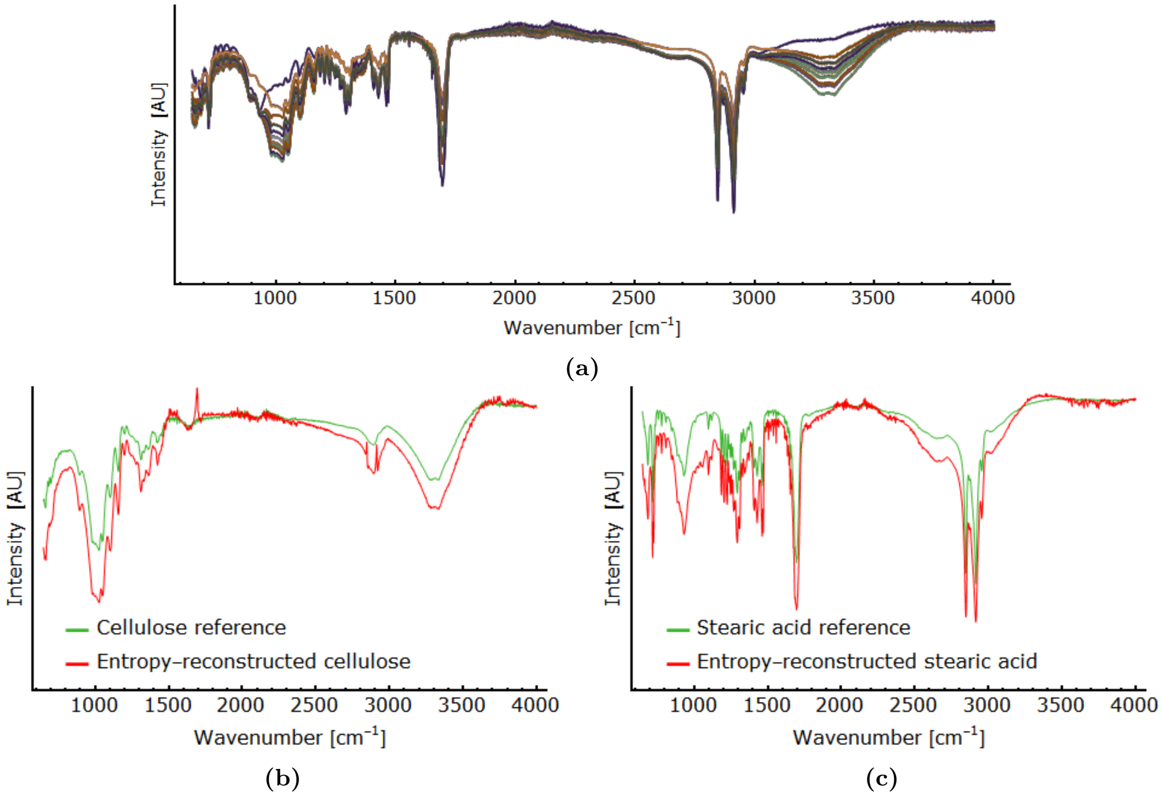



**Figure 4:** Proof-of-concept application of entropy minimization to mixture FTIR spectra. (a) acquired FTIR mixture spectra of samples containing cellulose and stearic acid, (b-c) reconstructed 'pure' spectral estimates of the mixture spectra constituents (red) and pure reference spectra of the constituents (green).

### 3.2 The central role of Sentinel-5P

TROPOMI, aboard the Sentinel-5P, was not originally designed for the measurement of total ammonia columns. It operates in the UV-VIS regime, but extends into the short-wave IR region of the electromagnetic spectrum, including around $4300\,\mathrm{cm}^{-1}$ where ammonia **does** have absorption bands. One of the value-added key-points of the *AnthroAm Sentinel* project compared to prior art, and critical for the success of the proposed project, is that spectral entropy minimization could possibly enable the joining of satellite spectral information across satellites, even if not covering the most intense spectral bands associated with ammonia. To this end, Sentinel-5P TROPOMI plays a central role, as it initially can be joined with spectral information from IASI (not originally developed for ammonia emission sensing either), and IASI-NG from 2022 and onward (optimized for measuring ammonia columns). In turn, the use of multiple satellites for emission measurements **maximizes the reliability of the measurements, and minimizes the impact of unfavorable meteorological conditions**.

### 3.3 Expected results and potential risks

The proof-of-concept in Section 3.1 **succesfully demonstrated the prospects of using spectral entropy minimization techniques with FTIR data to recover pure constituent spectra**. It is thus expected that total ammonia columns can be quantified using this technique. In addition to the proof-of-concept in Section 3.1, internal and external factors capable of affecting the development and implementation of the *AnthroAm Sentinel* system have been outlined in the SWOT analysis in Figure 5.


**Figure 5:** SWOT analysis of the *AnthroAm Sentinel* project, outlining the effect of internal and external factors on the successful development and implementation of the system.

In addition to the outlined opportunities, future versions of the *AnthroAm Sentinel* may utilize the next-generation IASI and machine learning, to further retrofit satellites, and to re-validate emission measurements made using TROPOMI. It follows that existing satellite data, including reflectance spectra and spectrometry data, can advantageously be coupled with established cross-continent ammonia emission databases such as ALFAM 1 and 2 (Hafner et al., 2018), to compare average satellite emission measurements with field-trial measurements of ammonia emission. One of the threats to the development and implementation of the *AnthroAm Sentinel* is the lack of funding. While a proof-of-concept has already been demonstrated herein, funding is still required to **(1)** develop pipeline for feeding satellite spectrometry measurements and calculated soil emission propensity factors to a predictive emission model. Existing models can be used (such as the ALFAM 2 model), but would still have to be adapted to the extra input and validated against experimental measurements, and **(2)** develop the *AnthroAm Sentinel* online web-platform. Inaccurate fertilization data entered into the system is only a minor threat, as it only affects that specific farmer, and not the entire system.

## 4 Conclusion

Unseen since 2008, the anthropogenic emission of ammonia from agriculture has risen with about 113000 metric tonnes, despite intense research and regulatory efforts. As a new tool for mitigation of anthropogenic ammonia emission, the *AnthroAm Sentinel* project proposes using ESA satellites and satellites in ESA partner programmes, to quantify **highly local** *soil ammonia emission propensity factors*. The emission propensity factors are subsequently used in **predictive modeling** by the *AnthroAm Sentinel* system, to enable farmers in decision-making on fertilization strategy. This is done by joining local weather forecasts with the emission propensity factor of the farmers' lands, to calculate the most favorable time of field fertilization, such that emission is minimized and the pool of available nitrogen for crop uptake is increased. By doing so, the farmer avoids having to oversupply fertilizer and thereby drives the mitigation of ammonia emission. In the spirit of open data, and for relieving farmers of additional economic burden, the project involves giving farmers **free access** to an online user interface, from which they can manage their fertilization management strategies.

The *AnthroAm Sentinel* project proposes a novel approach to joining spectral information between satellites and **to circumvent spectrally overlapping interfering compounds through entropy minimization of ammonia band targets**. To the knowledge of this author, has entropy minimization not hitherto been used to recover reconstructed ammonia spectra from satellite spectral data. In conclusion, the *AnthroAm Sentinel* project addresses the four pillars of sustainability, powered by space spectrometry, to drive mitigation of European air pollution and associated health effects.

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