Project acronym and title:
SECURe – Subsurface Evaluation of Carbon capture and storage and Unconventional risks

REPORT ON APPLICABILITY OF UAV TECHNOLOGY FOR MONITORING LARGE-SCALE SITES AND THE IMPACT OF REMOTE SENSING ON DECISIONS OF BASELINE CHARACTERISATIONS

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Public introduction

Subsurface Evaluation of CCS and Unconventional Risks (SECURe) is gathering unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The main outputs of SECURe comprise recommendations for best practice for unconventional hydrocarbon production and geological CO_2 storage. The project is funded from June 2018–May 2021.

The project is developing monitoring and mitigation strategies for the full geoenergy project lifecycle; by assessing plausible hazards and monitoring associated environmental risks. This is achieved through a program of experimental research and advanced technology development that includes demonstration at commercial and research facilities to formulate best practice. We will meet stakeholder needs; from the design of monitoring and mitigation strategies relevant to operators and regulators, to developing communication strategies to provide a greater level of understanding of the potential impacts.

The SECURe partnership comprises major research and commercial organisations from countries that host shale gas and CCS industries at different stages of operation (from permitted to closed). We are forming a durable international partnership with non-European groups; providing international access to study sites, creating links between projects and increasing our collective capability through exchange of scientific staff.

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Executive report summary

This deliverable comprises a report on the research undertaken within Subtask 4.1.1 of the SECURe consortium into the efficacy and development of Unmanned Aerial Vehicle (UAV) technology for large scale greenhouse gas monitoring of shale gas and CCS sites. In particular we address strategies to detect and monitor greenhouse gases (CO_2 and CH_4) directly with world-leading technology flown on rotary and fixed-wing small UAV platforms.

We also consider systems to monitor gas emissions indirectly from vegetation stress indices using hyperspectral sensors. The SECURe team did not have access to UAV hyperspectral sensors therefore ground based measurements using spectroradiometers were used as a proxy.

The report includes a summary review of the current state-of-the-art for large scale monitoring, followed by descriptions of prototype UAV gas sensing systems flown in the UK and the French Alps within the framework of the SECURe project.

Field tests of the BGS (fixed-wing) and TOTAL AUSEA (rotary) UAV gas sensor systems demonstrated that they are capable of monitoring and recording gas concentrations in flight. They record positional data and detect gas from surface emissions. Analysis of the UAV data results highlight that in-flight gas concentrations should be collected at the same time as ancillary data such as wind speed and 3D direction to enable modelling that can localise the source of emissions on the ground. As part of an integrated monitoring programme, the UAV data would help to focus ground investigations and aid monitoring efficiency.

The UAV datasets, produced within SECURe, contribute to the assessment of the advancement of the technology readiness level (TRL) for operational drone-based monitoring systems, moving the research from TRL 4 (i.e. technology validated in a laboratory) to TRL 5 (technology validated in a relevant environment). We conclude that with further operational testing, UAVs could be a practical additional tool for site monitoring, scaling up the ability to capture conventional / traditional ground-based measurements. UAVs can efficiently cover sites that would be time-consuming or even inaccessible for ground surveys.

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Contents

FIGURES

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TABLES

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1 Introduction

As noted in the Public Introduction section of this report, Subsurface Evaluation of CCS and Unconventional Risks (SECURe) is gathering unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The research within Subtask 4.1.1 focusses on large scale gas monitoring using UAVs (Unmanned Aerial Vehicles).

This deliverable comprises a report on the research undertaken into the efficacy and development of UAV technology for large scale greenhouse gas monitoring of shale gas and CCS sites. For the purposes of this research, we define the term 'large scale monitoring' to mean routine data collection at the scale of an operations site.

UAV data (and derived information such as orthophotographs, surface models and vegetation indices) are routinely collected and analysed for a range of geoscience applications. However, UAV data are not routinely used for monitoring gases as these systems are still at research or prototype stages of development.

In this research we address strategies to detect and monitor CO_2 and CH_4 directly with world-leading prototype technology flown on small UAV platforms. We utilised the British Geological Survey prototype fixed wing UAV system and the TOTAL AUSEA rotary UAV system; both carry CO_2 and CH_4 sensors.

The report includes a brief review of the current state-of-the-art for UAV large scale monitoring, followed by an overview of prototype UAV gas sensing systems flown in the French Alps (October 2019) and the UK (June and August 2019) in the framework of the SECURe project.

We also consider systems to monitor gas emissions indirectly by detecting vegetation stress using UAV-based hyperspectral sensors and correlating those with in-situ gas sources. Project partners have multispectral UAV systems that produce vegetation indices, but hyperspectral systems were not available. Therefore, we utilised ground-based sensors as a proxy for what can be achieved with hyperspectral instruments mounted on UAVs.

Gas monitoring can be undertaken at a variety of scales from the ground up using in-situ instruments, airborne sensors (on UAVs or conventional aircraft) and satellite-based methods. UAVs fill an important gap between what is possible with in-situ surveys and conventional aircraft. Conventional survey aircraft can carry full-scale thermal, photographic and hyperspectral instruments along with gas sensors (e.g. Cavity Ring-Down Spectroscopy analyser), but they are expensive to mobilise, and the raw data require significant processing time. In-situ (i.e. on the ground) surveys can be time-consuming and require full access to the field sites, which might not always be possible for a variety of reasons including health and safety (e.g. rough terrain) or accessibility (e.g. dense scrub). UAVs cannot cover the same area as conventional aircraft, and the sensors are miniaturised and are therefore often not as precise as their larger counterparts, however we review what they can achieve and how they can be used to direct/focus ground-based surveys as part of an integrated monitoring operation.

2 Review of large-scale monitoring with UAVs

2.1 WHAT ARE UAVS?

UAVs (commonly known as 'drones') are unmanned aircraft that are piloted remotely from the ground. UAVs come in a wide variety of types and masses, all of which are regulated nationally and internationally.

Types of UAV. The main types of UAV are (i) rotary, which are primarily multi-copter systems (ii) fixed-wing airplanes, (iii) balloons, where the lift is provided by gases such as helium, and (iv) kites. Each system has a range of advantages and disadvantages, as outlined in Table 1. Furthermore, UAVs can be tethered or untethered. Tethered systems sometimes have the option to provide power along with the tethering cable, which provides longer flying times but restricts the aerial coverage.

Mass of UAV. Across Europe, the Regulation (EU) 2018/1139 (the EASA Basic Regulation – BR) sets out the common rules for civil aviation and establishes the European Aviation Safety Agency (EASA). Across all of Europe, drone operators have to register themselves, except when they operate drones lighter than 250g and without a camera. Until recently the UK Civil Aviation Authority (CAA) had three classes of UAV (i) below 7 kg (ii) 7-20 kg and (iii) above 20 kg. Regulations changed in 2019 to two classes, those with an operating mass

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below 20 kg (termed small UAV, or sUAV), and those above that. UAVs above 20 kg are subject to the whole of the UK aviation regulations.

Table 1 Advantages and disadvantages of selected UAV types

UAV type	Advantages	Disadvantages	Example
Rotary	Vertical take-off and landing Minimal space required for take-off and landing Can hover in one location to increase sensor dwell time at a location of interest	Flight time can be limited (~18 minutes or more) Generally limited to wind conditions below 22 m/s Downdraft from rotors can affect gas concentrations	DJI Matrice 210 
Fixed-wing	Can cover large areas Can fly in higher winds than rotary Longer flight times that rotary UAVs	Take-off and landing can require significant areas They generally fly at ~35 kts so they require fast sensor acquisition times	Quest Q200 
Balloon	Unlimited time in the air	Can be affected by wind Gas needs to be transported to inflate the balloon Tethered, so limited acquisition area unless the balloon is 'walked' around the site	Weather balloon 
Kite	Can operate in stronger winds than rotary, balloon and fixed-wing Long time in the air – as long as there is sufficient wind	Tethered, so limited field of view unless the aircraft is 'walked' around the site Requires wind for flight	Kite with gimbal camera 

Flight permissions. Permission to fly UAVs varies across Europe and internationally, often depending on whether the flights are for research or commercial purposes. As an example, for commercial operations in the UK, pilots need to pass theory and practical flight tests, hold valid insurance, maintain an operations manual plus relevant flight logs, and register pilots, aircraft plus all paperwork with the Civil Aviation Authority. Unless special permissions are obtained, there are also operational flight restrictions to consider including (i) limitations on flights in congested (urban) areas and in close proximity to airfields, (ii) constrained to flights below 400 ft (120 m), (iii) flights must be within visual line of sight of the pilot, (iv) flights should take place during hours of daylight so that the aircraft can be kept in sight and manoeuvred away from hazards, if required. It is mandatory to have permission from the landowner to take off and land on their property; although this should not be an issue if surveying a site on behalf of the site owner or operator.

Regulations for flying UAVs across Europe can be found at https://www.easa.europa.eu/domains/civil-drones-rpas while UK regulations are found at https://www.caa.co.uk/consumers/unmanned-aircraft-and-drones/.

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2.2 GEOSCIENCE APPLICATIONS OF UAVS

UAVs are utilised across a broad range of geoscience research and operational fields. A review by Madjid et al. (2018), which includes authors of this report, demonstrates the wide range of the earth science applications including **archaeology** (De Reu et al., 2016), **natural hazards** (Jordan and Napier, 2016; Mateos et al., 2017; Serban et al., 2016; Tamminga et al., 2015), **ecology** (Anderson and Gaston, 2013; Faye et al., 2016; Flynn and Chapra, 2014; Ouedraogo et al., 2014; Ventura et al., 2016; Yang et al., 2014), **forestry** (Masek et al., 2015; Padua et al., 2017; Paneque-Galvez et al., 2014; Puliti et al., 2015; Sankey et al., 2017; Tang and Shao, 2015), **sedimentary geology** (Chesley et al., 2017; Nieminski and Graham, 2017), **glaciology** (Bhardwaj et al., 2016; De Michele et al., 2016; Westoby et al., 2015), **geothermal research** (Nishar et al., 2016), **atmospheric chemistry** (Caturegli et al., 2016; Schrod et al., 2017), **hydrology** (Bandini et al., 2017; Spence and Mengistu, 2016), **mining** (Jakob et al., 2017; Tong et al., 2015), **environmental science** (Hird et al., 2017; Mlambo et al., 2017; Sanders and Masri, 2016), **structural geology** (Bemis et al., 2014) and **carbonate geology** (Madjid et al. 2018).

2.3 GROUND SURFACE MAPPING AND MONITORING WITH UAVS

UAVs are routinely utilised by earth scientists to collect overlapping red, green, blue (RGB) photography that is used to produce true colour orthomosaics and 3D models in the form of terrain models (bare earth) or elevation models (including additional features such as tress) (Jordan & Napier, 2016). Products from UAV photogrammetry have become more pervasive with the advent of (i) consumer drones fitted with high resolution cameras, and (ii) software algorithms such as structure from motion (sfm). Examples of four key surface mapping outputs that were produced from data captured with a BGS rotary UAV are illustrated in Figure 1, consisting of orthophoto mosaics, textured point clouds, digital elevation models (DEMs) and digital terrain models (DTMs). An orthophoto mosaic is when overlapping photographs are processed so that they are stitched together into one image that has been geometrically corrected so that the scale is uniform like a map. This product can be opened in a Geographic Information System (GIS), allowing distances to be measured.

DTMs and DEMs can also be produced directly by Light Detection and Ranging (LiDAR) sensors. Until recently such systems were only available on >20kg UAVs and were priced above ~£200k. Miniaturisation of sensors has been a significant benefit for UAV monitoring. LiDAR sensors, appropriate for small UAVs can now be obtained for less than £50k. Thiel and Schmullius (2016) reported on a high match between the outputs from UAV LiDAR and photogrammetry over forested terrains.

2.4 GAS MONITORING WITH UAVS

There are two primary methods to detect and monitor gases using remote sensing platforms: (i) indirectly, by monitoring the effects on vegetation of locally elevated greenhouse gases either in the atmosphere or in soil gas with multispectral or hyperspectral sensors; and (ii) by directly measuring the gases via instruments including thermal (e.g. thermal conductivity detectors), mass methods (e.g. mass spectrometry), and spectroscopy (e.g. infrared spectroscopy).

Both direct and indirect methods are currently possible using conventional and UAV aircraft, although they are not without their issues. Firstly, it is worth noting that conventional aircraft are more expensive and less flexible to operate than UAVs. Nevertheless, conventional aircraft can carry suites of full size sensors, but this does not guarantee success for environmental monitoring. A study by Bateson et al. (2008) evaluated the indirect method of remote sensing from conventional aircraft to monitor CO_2 storage sites by applying an integrated suite of multispectral instruments (ATM and CASI), a hyperspectral instrument (Eagle) and LiDAR (Light Detection and Ranging) over a site in Italy producing natural CO_2. The study located some vents that were previously unknown, but also failed to detect five known vents.

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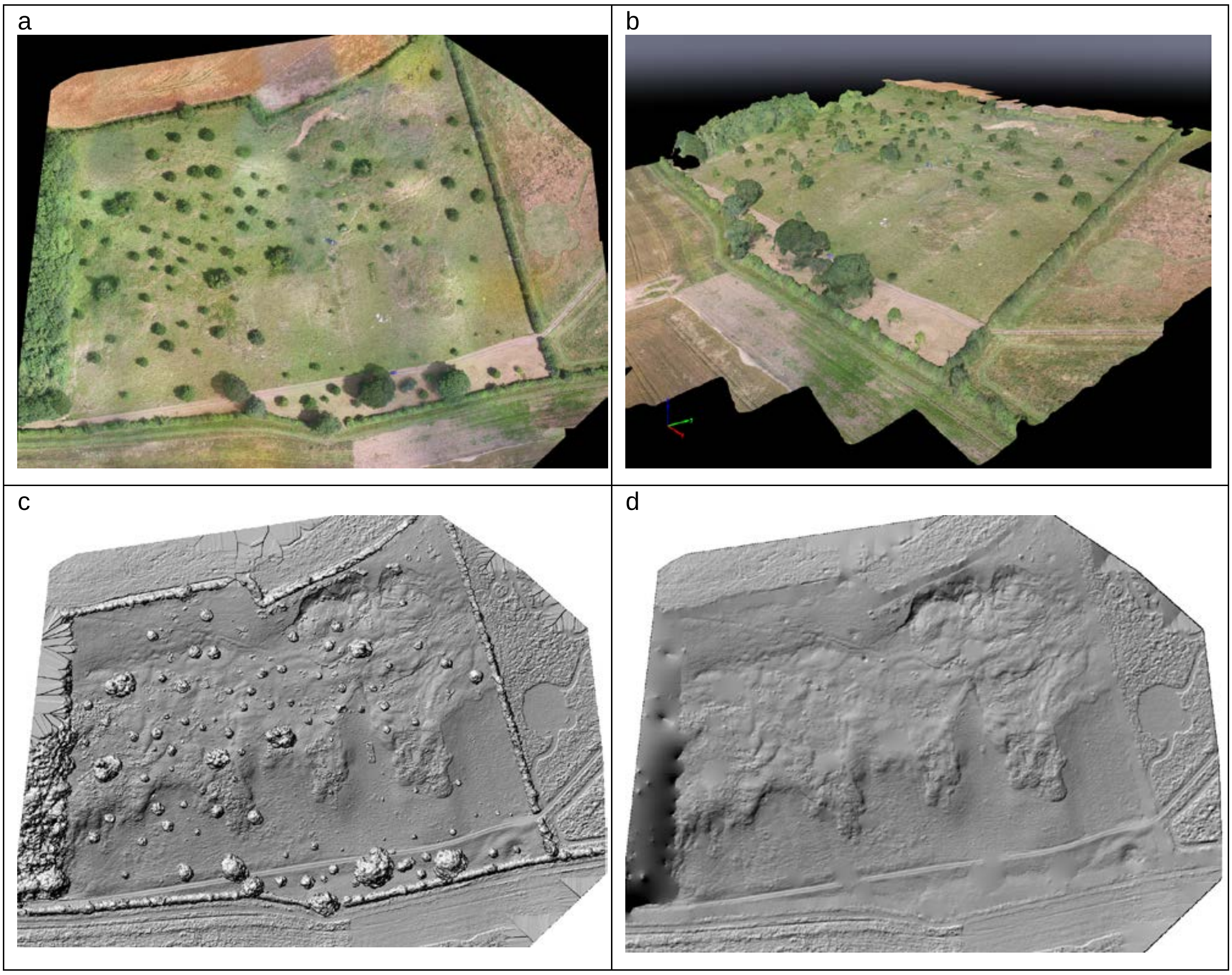

Figure 1 Examples of surface mapping with UAVs by the BGS at the Hollin Hill landslide observatory in UK (a) Orthophoto mosaic (b) textured point cloud (c) digital elevation model (d) digital terrain model. © BGS-UKRI. The field of view is approximately 450 m across.

Chen et al (2010) report on a study that achieved accuracy better than 0.05 ppm using cavity ring-down spectroscopy for CO_2 and CH_4 measurements by conventional aircraft over the Amazon rainforest. Similarly, Fix et al (2018) describe a mission with three conventional aircraft and a suite of twelve instruments to measure atmospheric CO_2 and CH_4.

The use of small UAVs restricts the payload to approximately < 2kg and therefore limits the sensor options. There is a very limited selection of hyperspectral sensors available for UAVs and none of the project partners has such a system due to their cost, their current unreliability and complexity of operation. For this reason, it was not possible to include UAV hyperspectral research in this study.

A literature review revealed research that is developing and utilising UAVs to monitor gases in volcanic terrains (e.g. McGonigle et al., 2008) where gas concentrations can be far higher than background levels. We are aware of some unpublished initiatives to develop UAV systems for monitoring greenhouse gases in the oil and gas industry and subsequently at CCS or shale gas sites. Both BGS and TOTAL have independently developed their own prototypes based on novel open path laser systems. Both systems were field tested and further developed within SECURe (see the following Section). TOTAL has its own roadmap for technology development independently from the SECURe programme, which was a valuable opportunity to test the TOTAL AUSEA sensor prototype at natural field sites along with other measurement approaches.

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2.5 VEGETATION MONITORING WITH UAVS

Production of Natural Difference Vegetation Indices (NDVIs) from UAVs is becoming commonplace using cameras such as the MicaSense RedEdge series along with image processing software such as Pix4D or AgiSoft Photoscan/Metasense. In basic terms, an NDVI is a measure of live / active vegetation in an area. Vegetation growth can be affected by CO_2 release, therefore monitoring active plant growth compared to areas of plant stress can provide an indirect indicator of the presence of greenhouse gases.

Bateson et al. (2008) did not have access to UAVs, but found that NDVIs produced from conventional aircraft were capable of identifying gas vents at a natural analogue site in Italy. They did note, however, that the use of NDVIs for gas detection is restricted to vegetated areas and would not work in arid or rocky terrains.

Currently, monitoring of vegetation by hyperspectral acquisition is a promising method to better characterize CO_2 or CH_4 leakage in vegetated areas (Noomen et al., 2008; Keith et al., 2009; Bellante et al., 2014). For SECURe, field acquisition of hyperspectral signatures of vegetation close to CH_4/CO_2 seeps was undertaken using a handheld spectroradiometer in the 350-2500 nm wavelength.

3 UAV research and data acquisition in SECURe

One of the primary field sites for the UAV research in SECURe is the Energy Research Accelerator GeoEnergy Test Bed (ERA-GTB) site at Sutton Bonington in the UK, where shallow subsurface injection (and subsequent migration) of CO_2 will be monitored using a range of subsurface, surface and airborne techniques. The injection had been planned for the summer of 2020, but had to be postponed until May 2021 for many reasons including the impact of COVID-19 on fieldwork. Therefore, the site could not be included in the UAV research flights to date so we undertook baseline flights elsewhere to trial the prototype equipment. In 2021 BGS plans to deploy gas sensing UAVs at ERA-GTB to monitor changes in atmospheric composition, while ground teams will simultaneously monitor soil gas flux.

Within this report, we outline results from test flights using the TOTAL prototype CO_2 and CH_4 rotary UAV at natural gas release sites in the French Alps (21-25 October 2019) along with baseline CH_4 and CO_2 sensor flights in the UK using the BGS fixed-wing system. We also include information on BGS modelling that determines the ground source of airborne concentrations that were acquired with the fixed-wing UAV system.

3.1 FIXED WING SENSOR RESEARCH

The BGS has a fleet of rotary and fixed-wing UAVs with a range of camera (RGB, radiometric thermal and multispectral) sensors. Prototype fixed-wing CO_2 and CH_4 UAV gas detection systems were developed by BGS via research co-funded by an InnovateUK grant and BGS National Capability research funds (https://www.bgs.ac.uk/geology-projects/geodesy/drone-research/#gas). The BGS UAV gas detection systems currently utilise a fixed-wing platform, enabling flights to take place in a wide range of wind conditions. Furthermore, the fixed-wing aircraft can stay airborne for longer than rotary devices allowing data to be acquired over a wide range of horizontal and vertical flight paths. The electric motors do not produce any gas emissions, while also minimising noise pollution during flights. The UAV platform is based on a QuestUAV Q200 aircraft that has been significantly remodelled by the manufacturers, who were partners on the InnovateUK research project. Given that the fixed-wing UAV flies at a ground speed of ~35 kts, this places specific response time requirements on the sensor (i.e. <1 second so that point data are obtained rather than an average over a considerable distance – e.g. a slow response time of 10 seconds at 35 kts =180m traversed).

BGS has two prototype fixed-wing UAVs and two gas sensors. The sensors contain diode laser modules that are specific to CO_2 and CH_4 gases along with a reference cell containing a precisely-known concentration of the gas of interest. They are specially made miniaturised versions of sensors that have been successfully used on off-road vehicles, quad bikes and walk-over surveys by BGS in CCS research projects (e.g. Jones *et al.*, 2014), and were produced by Boreal Laser Inc.

Due to a shortened planning schedule, it was not possible to mobilise the BGS UAVs for the SECURe fieldwork at the natural seeps in the French Alps in October 2019. Moreover, injection at the ERA GTB site has been postponed until 2021, therefore the BGS prototype systems have been tested on baseline flights at other sites in the UK.

The BGS CH_4 UAV system was first flown in February 2017 with a controlled gas release from canisters on the ground (Figure 2). Several methane release events were undertaken from a point source 6 m above ground level, with varying rates up to approximately 1.4 kg over 2 minutes. However, wind conditions were far from ideal, with a stiff onshore breeze rapidly dispersing the methane plume towards the west. The figure below illustrates the bungee launch of the UAV along with the spar on the top of the aircraft that houses the laser emitter and reflector. The sensor electronics are housed within the UAV pod, fully integrated with the electronic flight control and logging systems. Figure 2b shows a plot of the gas measurements (ppm) in GoogleEarth™. In this case the flight path was circular with altitude increasing throughout the flight. One circuit recorded higher levels of CH_4, illustrating when the gas was released into the atmosphere.

a b

Figure 2 BGS fixed-wing UAV CH_4 sensor prototype test flights, 2017. (a) bungee launch; (b) CH_4 results displayed as ppm. © BGS-UKRI

Prototype gas source determination modelling systems have been developed by BGS to locate the most likely ground sources of the gas release using information from the CH_4 flights as input data. The modelling system utilises the UAV gas results, wind direction data (ideally using a ground-based 3D sonic anemometer to record wind velocity, including vertical component, at a high temporal resolution) and a quantitative understanding of atmospheric boundary layer (ABL) dynamics. Example results from the ground source modelling (Figure 3) illustrate the potential for the software to determine the gas source - the yellow star denotes the actual ground source of the controlled gas release compared to the bottom left of the purple ellipse that denotes the modelled potential source of the plume.

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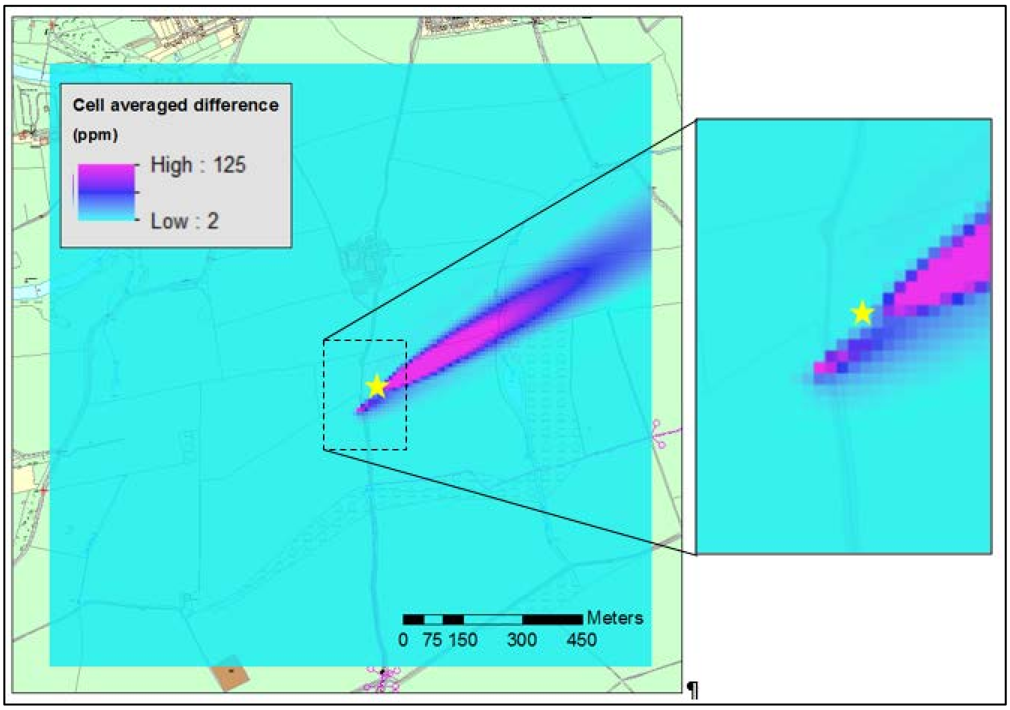

Figure 3 Example of outputs from BGS point source modelling. The star highlights the location of the controlled gas release point; the bottom left of the purple ellipse denotes the modelled source of the plume. © BGS-UKRI

We suggest that an expected detection / monitoring strategy would be to use the UAV to determine the estimated location of potential gas release, and then to mobilise ground instruments at that location to fix its location accurately and determine flux measurements. The UAV measurements would therefore provide large-scale monitoring capacity, and the ground-based systems would be focussed on points of interest. This procedure would form a combined approach to gas monitoring to produce a multi-layered flexible portfolio of survey/monitoring techniques.

BGS undertook baseline test flights and surveys with the CO_2 fixed-wing UAV prototype in July & August 2018, and June & August 2019. The June and August (2019) flights were part of the SECURe project, and the primary aim was to test the UAV and sensor in a field / operational environment. The survey determined baseline levels of CO_2 at the site; there was no controlled gas release. Unfortunately, follow-up tests with controlled gas releases were not possible in SECURe due to COVID travel restrictions, therefore it has not been possible to quantify precisely what level of gas emissions can be detected from what altitude, given various weather conditions including rainfall and wind speed/type.

Figure 4 illustrates the results of the June 2019 CO_2 sensor flights. The high values recorded while the aircraft was on the ground (denoted as red dots in Figure 4) are due to the sensor detecting the CO_2 exhaled in the breath of the UAV operators. Much of the data recorded in the air are in the 461-500 ppm range (when the background concentration in the atmosphere is normally approximately 400 ppm). We believe that the concentrations measured in flight are most likely due to:

- the local environment (plants or industry) that give a high local background; or
- (possibly more likely) these are ‘raw’ sensor data that have not been given a secondary correction in addition to the primary laboratory-derived calibrations set by the manufacturer.

Nevertheless, the relative pattern of gas concentrations would not change, just the absolute values. Significantly, the data are sufficient to show that the technique works. The successful demonstrations of recording and processing gas emissions data from a UAV are an important advancement of the TRL for drone-based monitoring systems. It indicates that miniaturised monitoring systems can be successfully deployed on fixed-wing UAVs, representing an early major achievement in the SECURe project.

BGS is currently modifying the fixed-wing CH_4 and CO_2 sensor systems to operate on our rotary drones.

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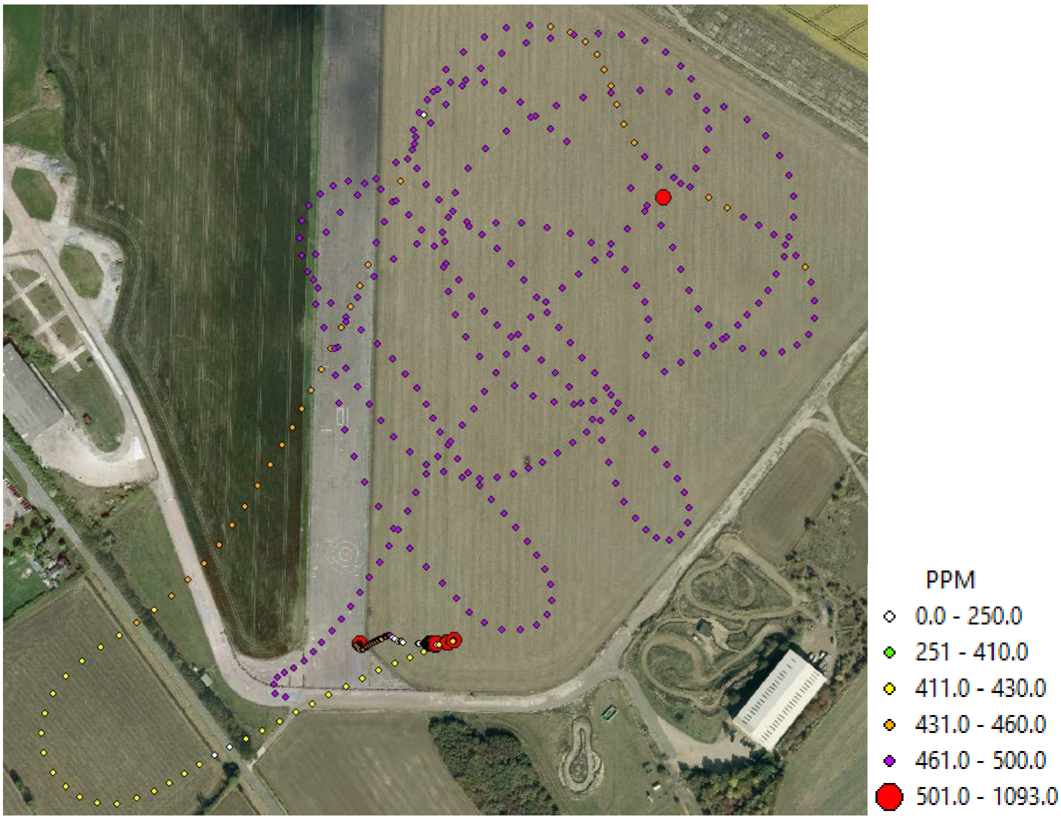

Figure 4 Results of the BGS fixed-wing UAV CH_4 sensor prototype test flights at an airfield (June 2019)

3.2 ROTARY SENSOR RESEARCH

Project partner, TOTAL has developed its own UAV sensor technology (AUSEA) in collaboration with CNRS (patent pending). It is a miniaturised diode laser-based sensor recording both CO_2 and CH_4 at high frequency and mounted on a DJI Matrice 200 rotary UAV.

The TOTAL AUSEA technology performance (detection and quantification of emission rates) has been evaluated during controlled rate releases carried out at an in-house facility dedicated to support the development and promote the knowledge of available technologies to quantify GHG emissions at industrial sites. Field scale evaluation of the TOTAL AUSEA sensor by flying the UAV over natural areas showing small and dispersed sources is a specific use case that was evaluated during SECURe fieldwork.

Fieldwork (comprising staff from BGS, BRGM and TOTAL) to assess and evaluate the system took place from 20th to 25th October 2019 at Jonchiers and Molières-Glandaz (Figure 5). The natural gas seeps in the area are well characterized by BRGM, TOTAL and others (Gal et al., 2017, 2019). The prototype TOTAL AUSEA gas sensor system was utilised alongside BRGM in-situ flux measurements (closed chamber system with external recirculation). The flux data collected at ground level were used to confirm the location and intensity of gas release detected by the UAV.

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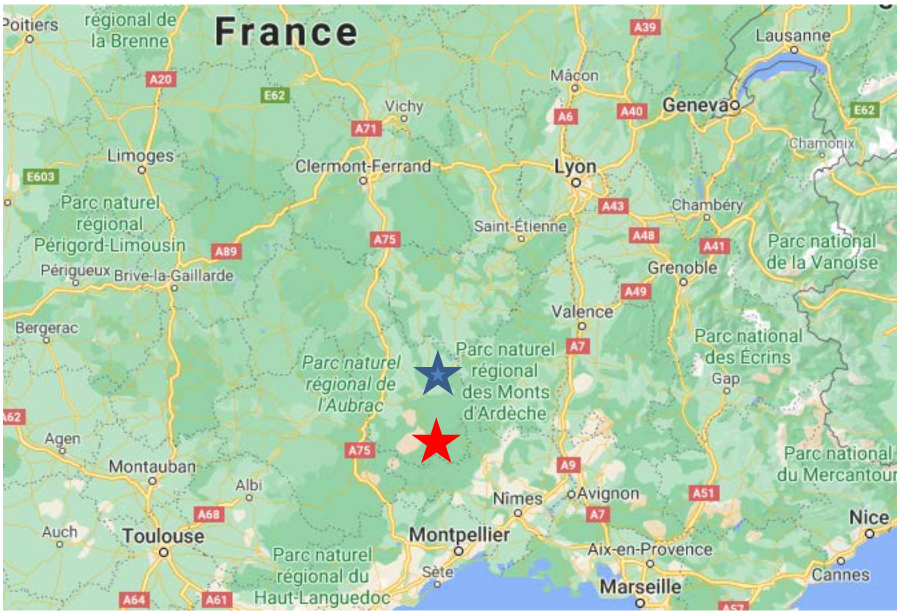

Figure 5 General location of Jonchiers (red star) and Molières-Glandaz (blue star) sites. Map from GoogleMaps.

Investigations performed at the Jonchiers site were first oriented close to the small seepage area rediscovered in 2017 on the basis of ancient documents (Figure 6 and Figure 7). This area has never been characterized previously. Albeit meteorological conditions were not ideal (muddy conditions), CH_4 emission at this location was recorded between 6 and 36 g/m²/h, with high frequency fluctuations of emission rate in time, probably linked to bubble bursting. Interestingly, a CO_2 flux was associated with the CH_4 emission. The emission occurred over a very small area (some hundreds of cm²).

The TOTAL AUSEA gas sensor, operated by hand on the ground near the emission point (Figure 8), picked up the CH_4 emissions with up to 200 ppm CH_4 directly above the source point. The sensor was then used to perform a walk-over investigation in the neighbouring thalwegs; increases up to 50 ppm CH_4 were measured. CO_2 concentration measurements during walk-over survey were mostly impacted by breathing of the operator holding the sensor so it could not be used to detect any CO_2 source point at ground level.

Such elevations of CH_4 concentration in the air are not 'normal', consequently detailed investigations were performed using the flux chamber system. This led to the discovery of a new point of emission (Figure 7, Figure 8) where gas bubbling was noticed from a small pool in the riverbed. The combined CH_4 and CO_2 gas emission was again largely variable in time. The highest values were recorded when a bubble burst, close to 200 g/m²/h for CH_4 and 36 g/m²/h for CO_2. Unexpectedly, new acquisitions performed the day after the discovery only yielded low values of the CH_4 emission (max. 0.1 g/m²/h), thus suggesting a strong relationship with the environmental parameters (rainfall, atmospheric pressure) which need to be investigated in more detail.

After the preliminary investigation at ground level, a series of flights were carried out with TOTAL AUSEA UAV. Wind measurement data were not collected during this campaign as usual with 3D sonic anemometer because of equipment non-availability. Advanced data processing like emission rate derivation from TOTAL AUSEA plume concentration was therefore not possible from this campaign. However, the wind conditions (easterly gusts blowing down into the thalweg towards south) and the rough terrain would have made these wind data poorly representative of the actual wind at measuring points. The UAV was flown manually by the pilots according to the following real-time parameters:

- CH_4 concentration enhancement above background (here +1ppm to +4ppm CH_4)
- CO_2 concentration enhancement above background (here not significantly)
- perception of the very local winds to catch plumes downwind from expected sources
- drone safety distance to obstacles (trees, rough terrain etc.).

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Figure 6 In-situ gas flux measurements by BRGM (top left). TOTAL AUSEA UAV sensor combining CO_2 and CH_4 drone-based sensor deployed by TOTAL at Jonchiers (top right). Plot of a selection of flight paths (while lines) with prevailing wind direction (red arrows) and take-off spot (H) (bottom).

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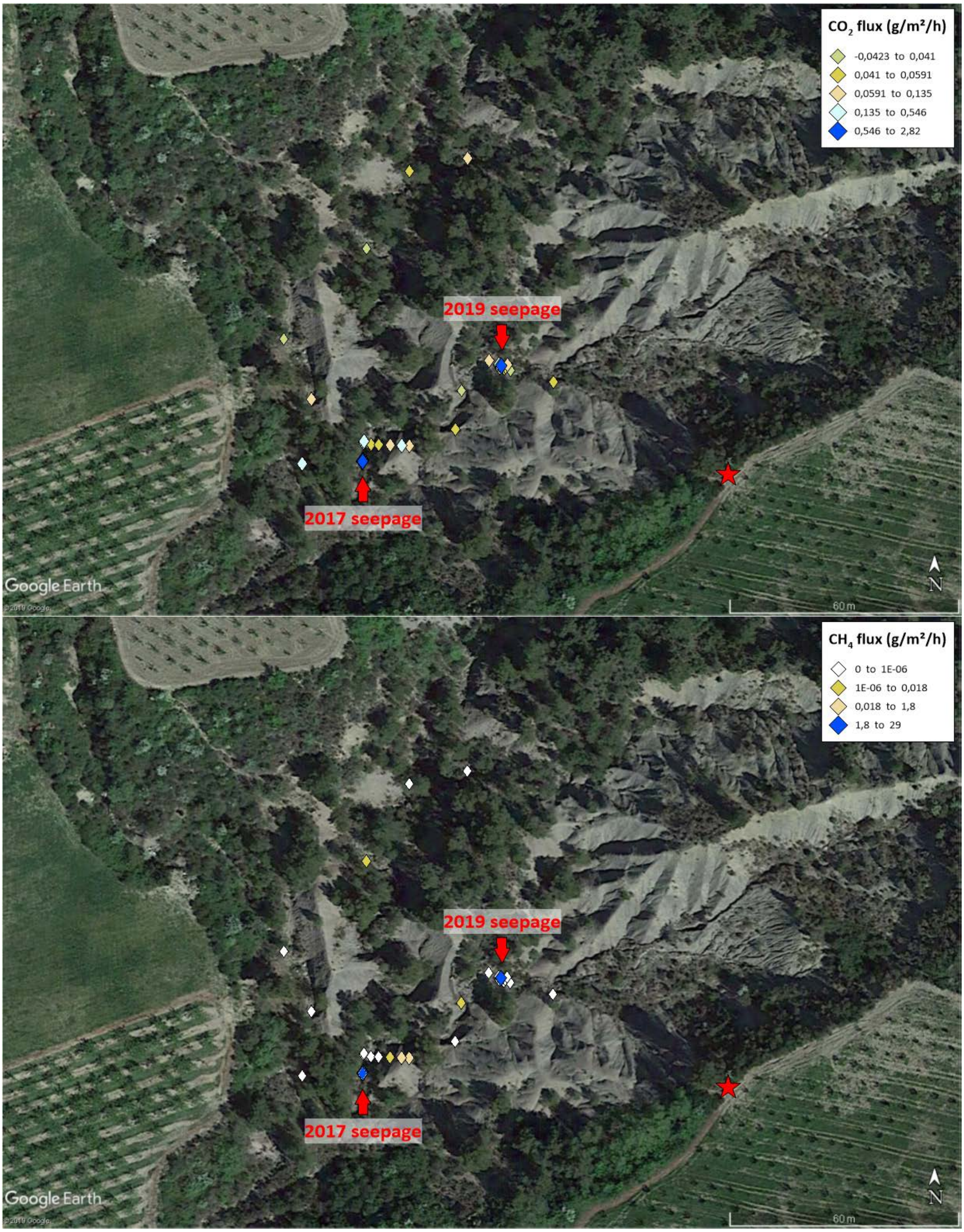

Figure 7 Results of soil flux survey: CO_2 (top) and CH_4 (bottom). The red star indicates a second location from where the drone was operated (take-off and landing).

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Figure 8 AUSEA sensor in operation at Jonchiers (left). View of the CH_4 emission point discovered in 2019 (right).

CO_2 concentration dataset: The CO_2 dataset was split into 5 ppm ranges using the natural breaks (Jenks) method for ease of visualisation. There was no clear plume revealed in the 3D dataset, with significant CO_2 concentration enhancements above environmental background. However, the lower concentration range of 388-393 ppm does appear to be located more to the SW of the area investigated (Figure 9a). Nevertheless, these data were recorded over flatter topography and the flight paths here were at a lower altitude, so it is not clear if this ‘apparent’ distribution is a function of altitude, topography/vegetation, wind direction, or the CO_2 concentrations to the north and east (above the vent areas) are genuinely higher. This uncertainty could likely be resolved with further testing. At the other end of the concentration range, there are a number of data points with values > 400 ppm. Several appear to be associated with take-off/landing, and are thus probably artefactual. A further 16-18 appear randomly distributed through the 3D data cloud, and appear to show no significant distribution. They thus likely represent the upper bound of ‘signal noise’. Such noise is to be expected in any dataset (both TOTAL and BGS), especially when utilising novel techniques, though it would be useful to develop semi-automated techniques to strip out noise and identify what could be small ‘real’ anomalies amongst a raw dataset of varying values. One way to approach this for the utilised infrared laser sensors with a relatively high sampling frequency (operating at approximately 1 Hz), would be to look for an anomaly picked up by several neighbouring data points.

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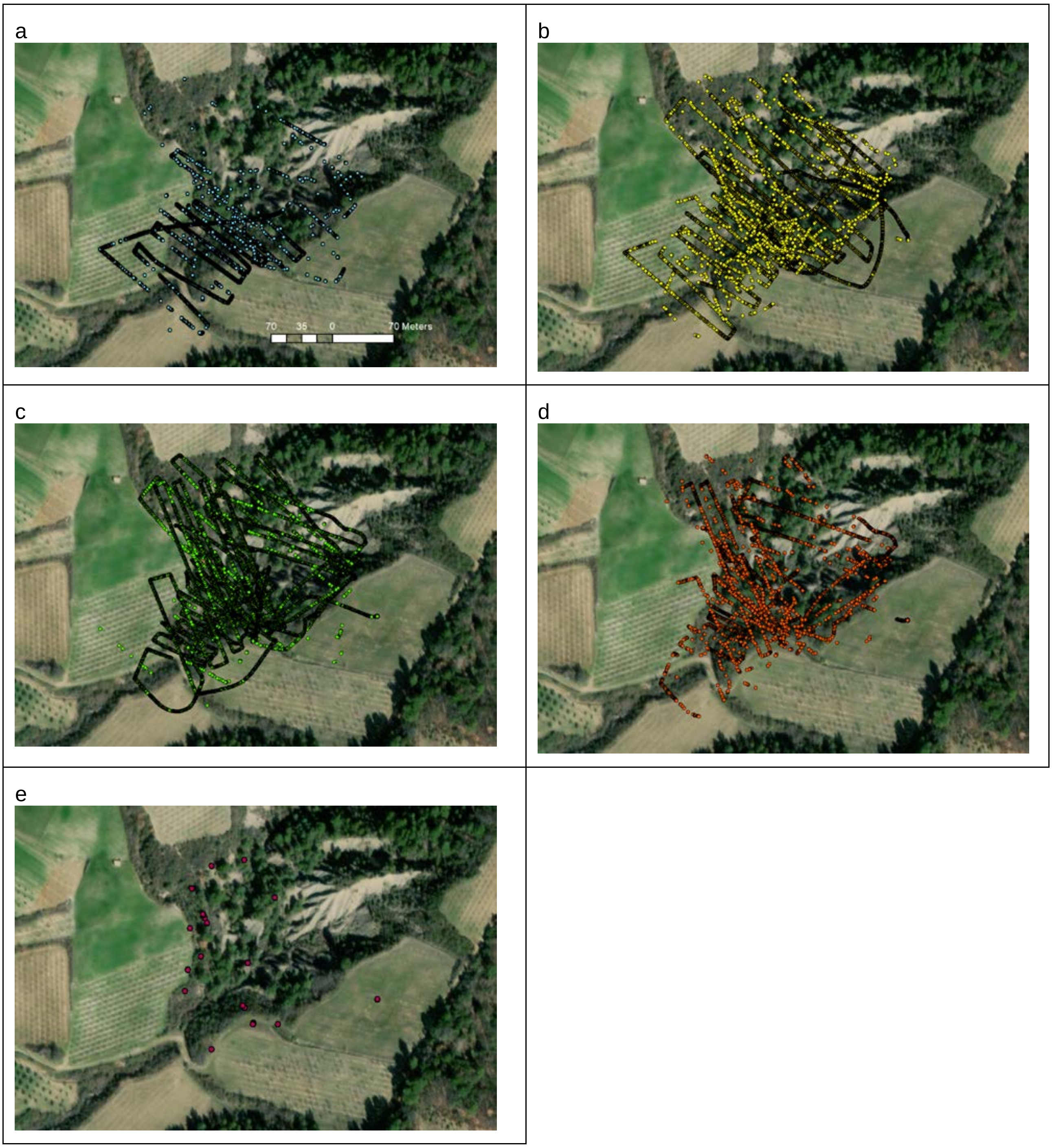

Figure 9 TOTAL AUSEA CO_2 data recorded in flight at Jonchiers, 22 October 2019. a) 388-393 b) 394-395.4 c) 395.5-396.4 d) 396.5 – 400 and e) > 400 ppm.

CH_4 concentration dataset: CH_4 local background was determined at 1.9 ppm. CH_4 concentration enhancements of 1 ppm to 2.4 ppm above environmental CH_4 background were measured during flights. These concentrations were located at the lowest heights above ground (few meters) and downwind from the ground source points. Compared to the emission rates measured at ground level these results demonstrated the feasibility to detect low emission rates with TOTAL AUSEA UAV sensor. Measurement at higher altitudes did not showed any CH_4 anomalies for the most part.

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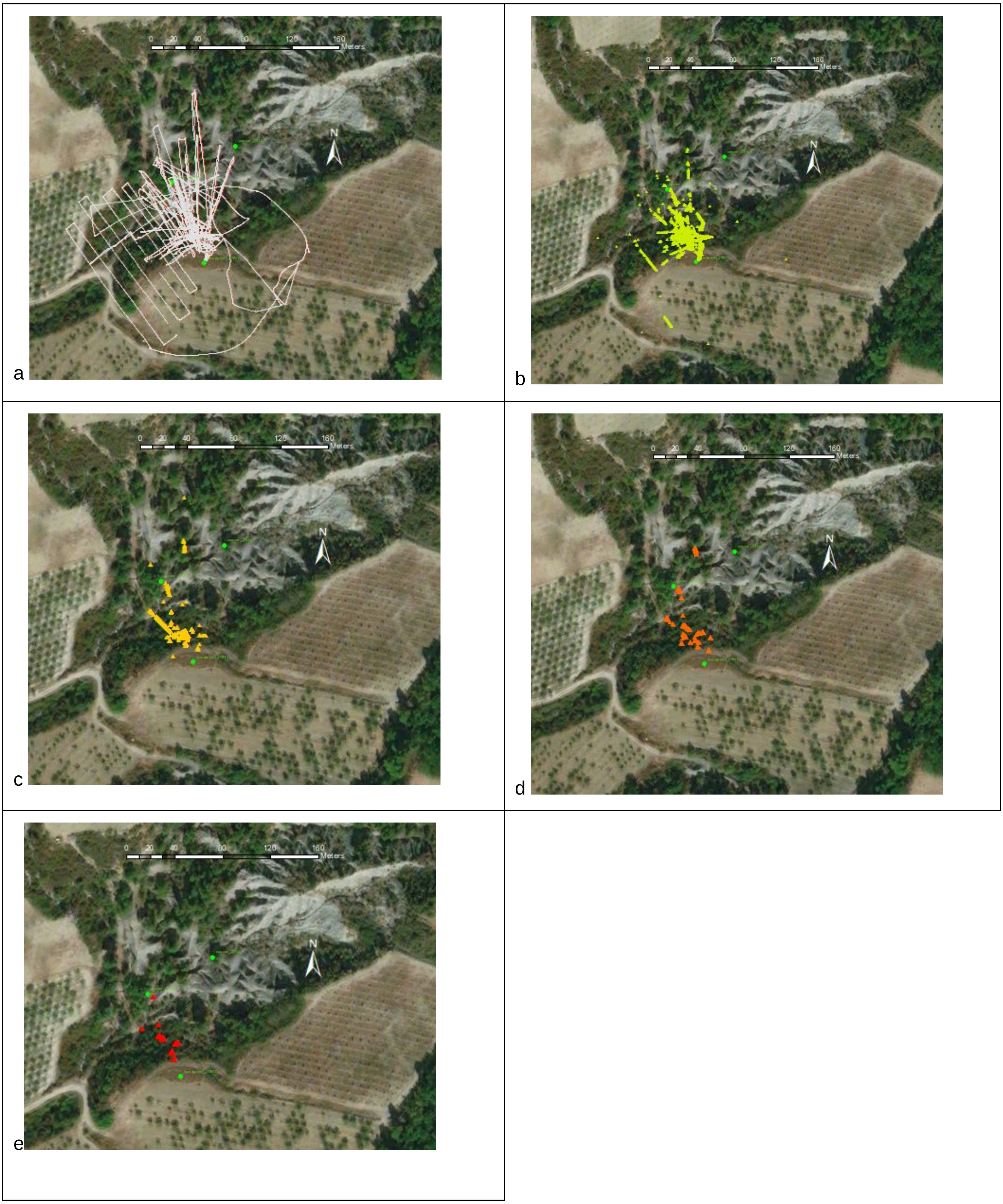

Figure 10 : TOTAL AUSEA CH_4 concentration recorded in flight at Jonchiers, 23 October 2019. a) 1,7 – 2,0ppm b) 2,0 - 2,5ppm c) 2,5 - 3,0ppm d) 3,5 - 3,5ppm and e) 3,5 – 4,5ppm.

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The dispersion plume was also affected by the wind behaviour within the topography of the thalweg. This is most likely why the position just in front of the UAV home point at the edge of the thalweg concentrated the most CH_4 plume detections (CH_4 plume being channelled and uplifted along the slope).

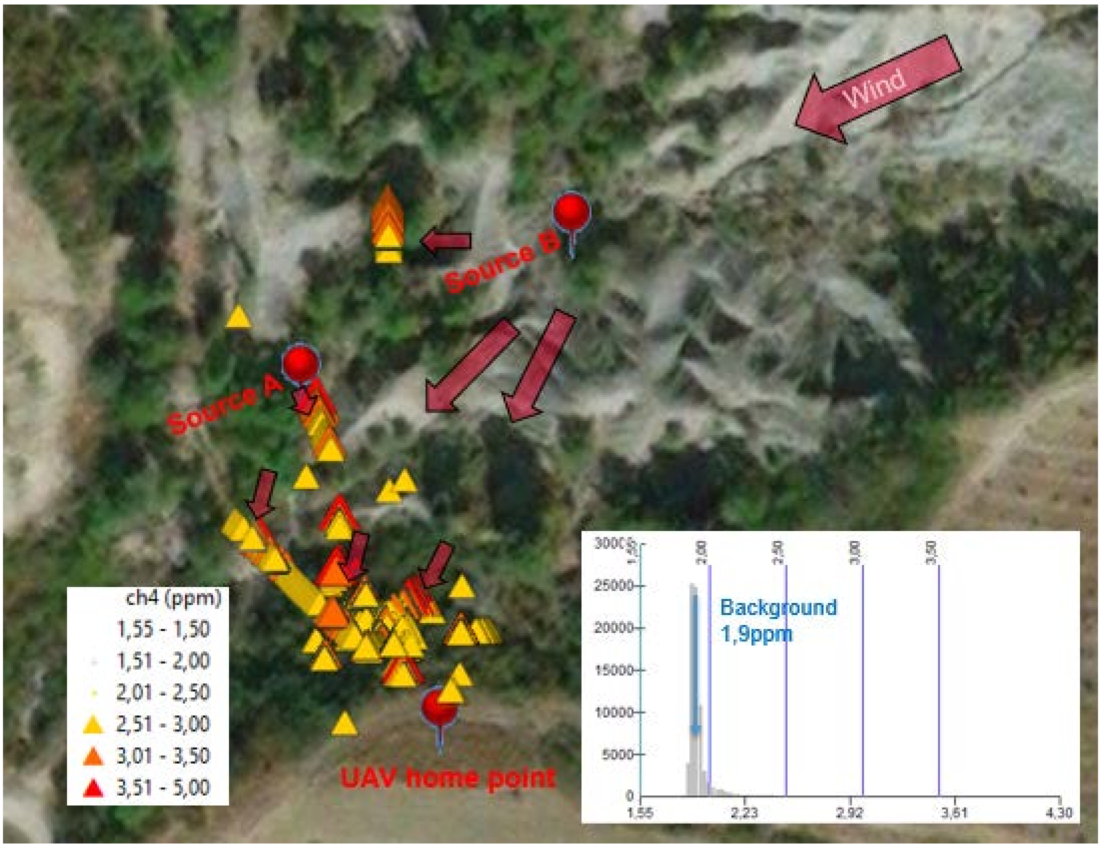

Figure 11 : CH_4 concentration above local environmental background measured at 1.9 ppm. Red arrows indicated supposed ground level ground producing CH_4 plumes being detected.

There is a relationship between sensitivity of the detector, dispersion of gas in the atmosphere, and distance of the sensor from the gas release point. Whilst UAV-based measurements thus do have limitations, it is important to quantify them so that they can be used to best effect during monitoring studies. This case study illustrates how limitations can vary from one situation to another depending on the local concentration background, dispersion conditions according to wind and topography, and reachable measurement distance to the source point or ground surface.

At Molières-Glandaz a second set of combined investigations were performed. If the Jonchiers site was appropriate for drone flying manually within line of sight, albeit the altitude of flight was quite high, the Molières-Glandaz site was not adapted to such manual flights, because of high relief, the presence of mature forest cover and thus the absence of any viable take-off/landing location nearby (Figure 12). Without authorization to carry out beyond visual line of sight (BVLOS) flights it was decided to cancel TOTAL AUSEA UAV measurements at Molieres Glandaz. The UAV team chose another flight site close to Sallieres to test various flight configurations and patterns rather than trying to detect unknown gas sources.

Ground level flux measurements:

Gas bubbling in the riverbed was occurring at a high rate (Figure 13). Flux measurements performed on the 2 m x 6 m perimeter (Figure 14) gave values as high as 790 g/m²/h for the CH_4 gas phase, more than 3 times the highest values measured some years ago (Gal et al., 2019). If flights could have been done in vicinity of the seepage area at Moliere Glandaz, we expect that the TOTAL AUSEA sensor would have monitored deviations of the CH_4 concentration in the atmosphere. Again, a relationship with the atmospheric conditions has to be investigated more in detail.

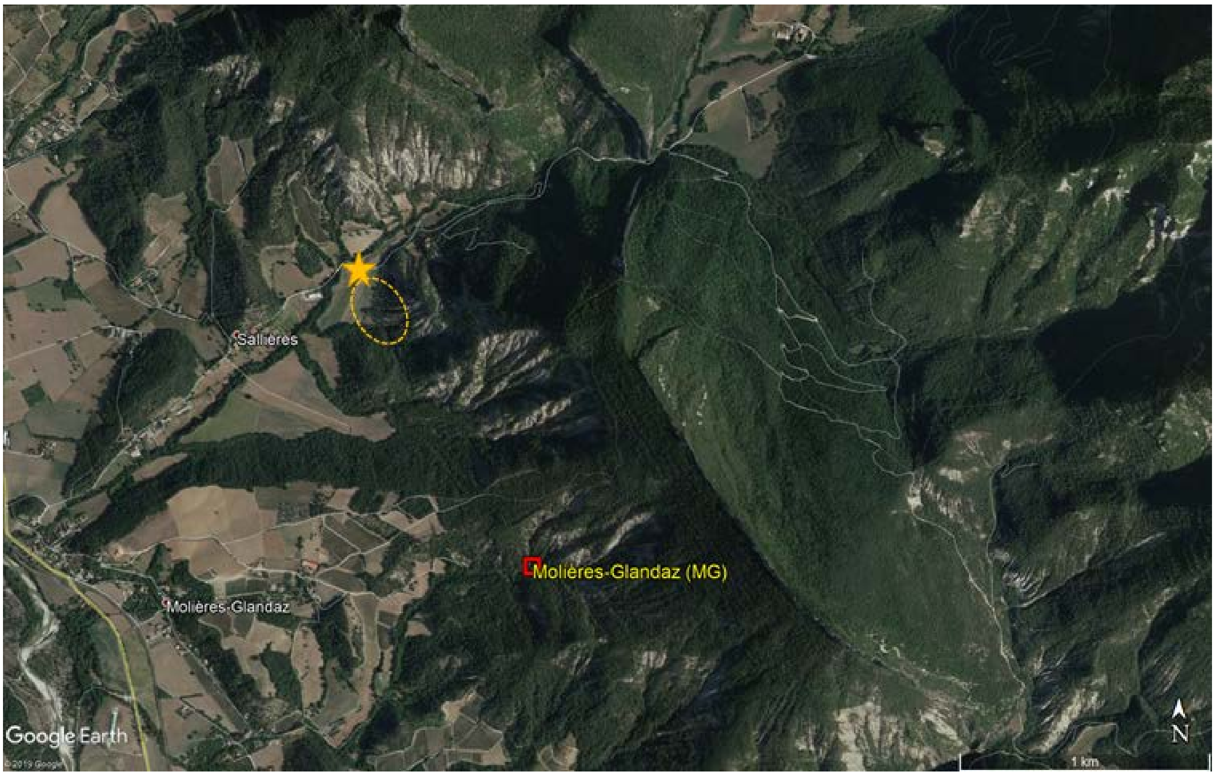

Figure 12 Location of the Molières-Glandaz gas seep (red square) and of the AUSEA drone flight perimeter (ellipse in orange); the orange star indicates the location of take-off and landing of the UAV.

Figure 13 Overview of the Molières-Glandaz gas seep; details show gas bubbles in small pools.

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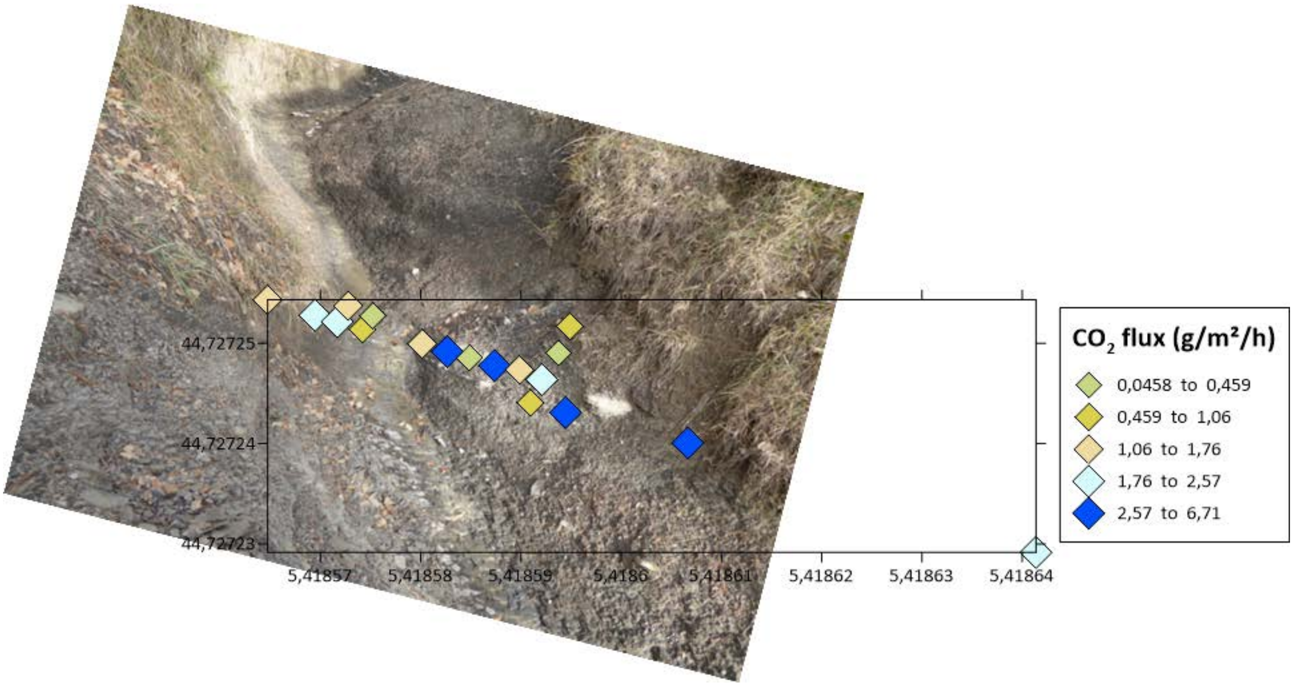

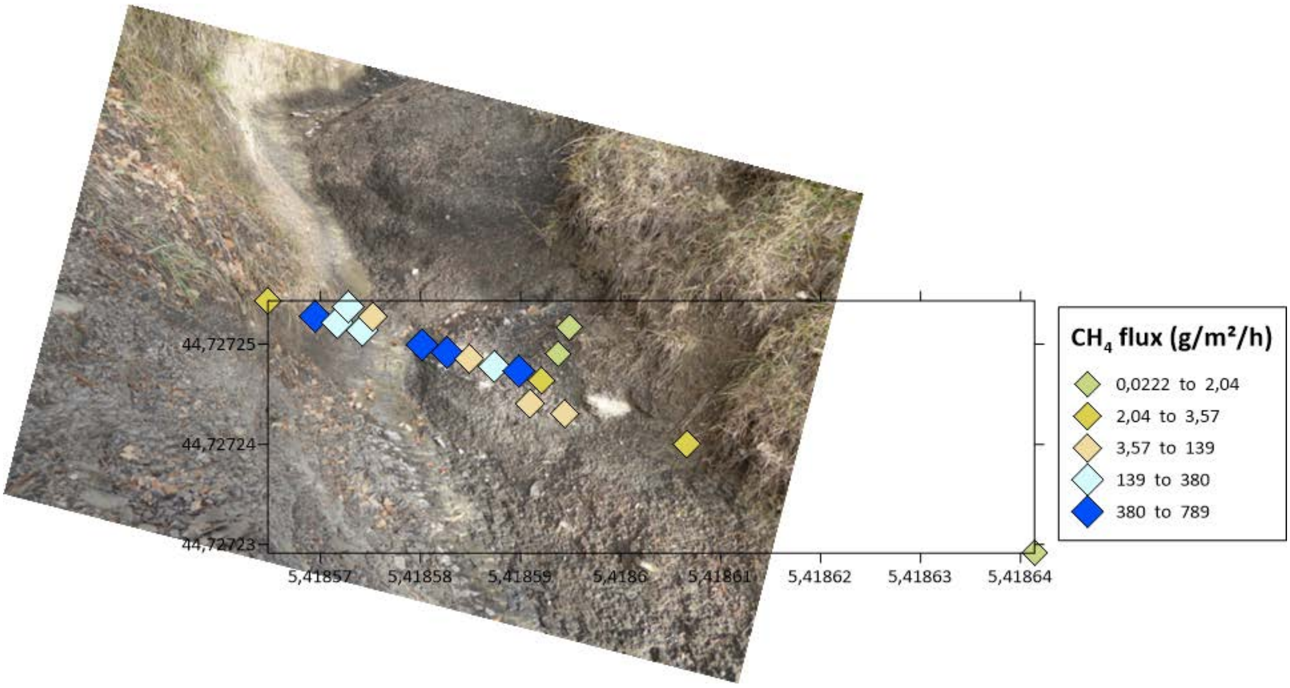

Figure 14 Molières-Glandaz gas seep: CO_2 (top) and CH_4 (bottom) gas flux measurements. Background photograph oriented to the North.

Preliminary results indicate that the drone with the TOTAL AUSEA CO_2/CH_4 dual sensor successfully recorded gas emissions. This is an important contribution to the SECRUe TRL assessment for overall UAV-based monitoring systems, indicating that miniaturised UAV monitoring systems can be successfully deployed even for the detection of small and dispersed ground emissions as low as tens of g/m²/h.

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3.3 HYPERSPECTRAL ACQUISITION ON VEGETATED AREAS

Hyperspectral sensors can be used to detect gas emissions indirectly, if the gases affect vegetation growth patterns e.g. by causing vegetation stress. For example, Bateson et al. (2008) completed tests at an analogue site at Latera, Italy, using hyperspectral data from conventional aircraft. The study located some vents that were previously unknown, however it failed to detect five known vents.

Hyperspectral data from a UAV were not tested in SECURe because no partner had access to a UAV system equipped with a hyperspectral sensor. Therefore, the SECURe team concentrated on methods to measure gases on the ground with hyperspectral sensors such as the Panalytical ASD spectroradiometer, and to use those data as a proxy for data acquired from drones.

3.3.1 Introduction

In the framework of Work Packages 3 (Baseline) and 4 (Monitoring) of SECURe, TOTAL R&D undertook a field campaign in the vicinity of the Vercors Region in the south of Grenoble, at Fontaine Ardente (Figure 15). This field campaign was organized by BRGM (leader: Wolfram Kloppmann) with BGS (UK), GFZ (Germany) and TNO (Netherlands). Gas seepages occur at Fontaine Ardente (FA), an historical area of natural CH_4 emission which was anthropized for centuries. CO_2 emissions are also documented by previous researchers in the area.

The main objective of the SECURe field campaign was to deploy several tools and methods of characterization and monitoring of direct and indirect effects of CH_4/CO_2 natural seepages. TOTAL R&D (Air Quality Lab – LQA) did a first campaign in June 2019 with the AUSEA rotary drone equipped with CH_4 and CO_2 sensors. In October 2019, three types of measurements/analyses were performed by the team:

(i) soil/atmosphere gas fluxes (CH_4, CO_2, VOC, H_2S),
(ii) hyperspectral signatures of black shales and vegetation surrounding gas emissions,
(iii) pigment analyses on vegetation surrounding gas emissions.

Figure 15 Fontaine Ardente site burning, site description and location map (from GoogleMaps)

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3.3.2 Study Area

The area of inspection was located on the FA hot spot of CH_4/CO_2 emission and 100-m radius of prospection around (Figure 16, Figure 17).

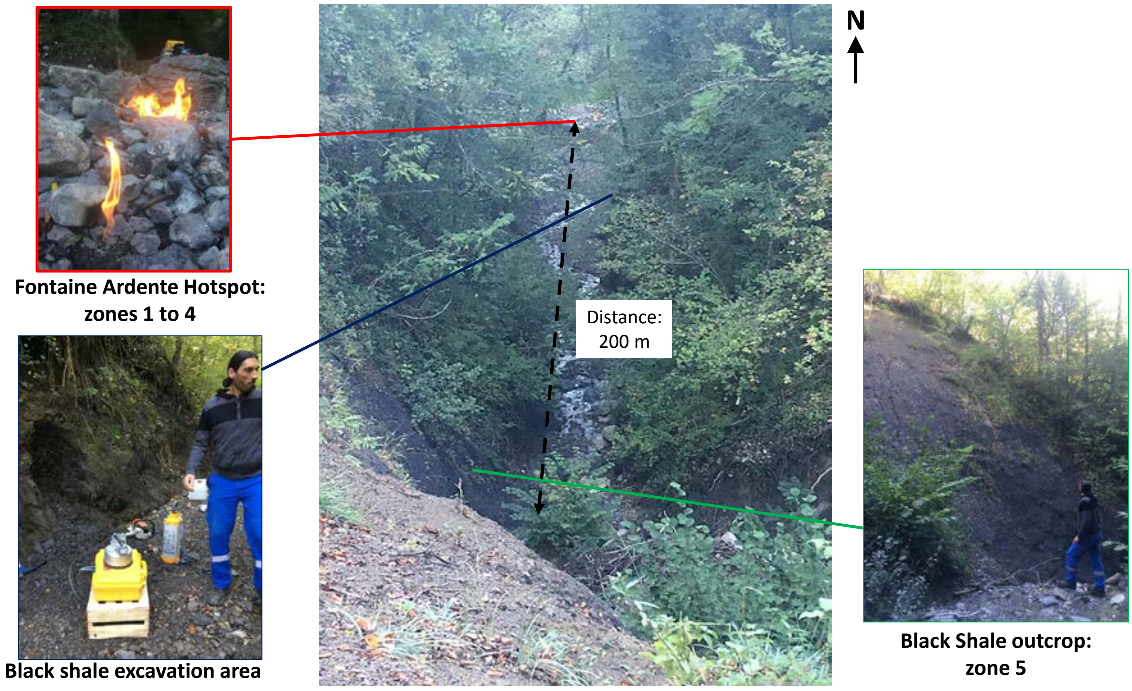

Figure 16 Main locations of sampling, measurements and analyses at Fontaine Ardente

Figure 17 Zones 1 to 4 at Fontaine Ardente and references of sampling locations and hot spots

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3.3.3 Characterization tools

Three types of equipment were deployed at FA:

(i) **Portable diffuse flux meter for CH_4, CO_2, VOC and H_2S (**Figure 18**):** West Systems with WS-CH4-TLD-1605 methane detector, LICOR LI830 Carbon dioxide detector, WS-VOC-PID-1804 volatile organic compounds detector and WS-TOX-H2S-1808 Hydrogen sulphide detector;

Figure 18 Accumulation chamber West Systems for CH_4, CO_2, VOC and H_2S fluxes measurement onsite at soil/atmosphere interface (source: westsystems.com)

(ii) **Spectroradiometer** ASD Panalytical (Malvern) FieldSpec 4 High Res (Figure 19) with two sensors for VNIR (3 nm resolution) and SWIR (8 nm resolution) measurements (350 to 2500 µm) with contact probe and leafclip devices.

Figure 19 Spectroradiometer ASD Panalytical for hyperspectral signature acquisition onsite (source: nerc.ac.uk)

(iii) **Force A Dualex** scientific device (Figure 20) to measure Nitrogen Balance Index (NBI), Chlorophyll (Chl), Flavonols (Flav) and Anthocyans (Anth).

Figure 20 Contact probe Force-A Dualex for pigment analyses onsite (source: force-a.com)

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3.3.4 Results of gas flux measurements

CH_4, CO_2, VOC and H_2S fluxes were measured onsite at the soil/atmosphere interface in the 5 zones previously documented (Figure 16 and Figure 17) at 19 locations (Table 2). 6 hot spots showed high fluxes for CH_4 and CO_2 mainly and VOC positive anomalies in zones 1, 2 and 4 (F59, F61, F76, F24, F11, F7). Maximum fluxes reached 13 $mol.m^{-2}.day^{-1}$ for CH_4, 1,8 $mol.m^{-2}.day^{-1}$ for CO_2 and $4,4.10^{-4}$ $mol.m^{-2}.day^{-1}$ for VOC at F76 and 8,4 $mol.m^{-2}.day^{-1}$ for CH_4, 2,8 $mol.m^{-2}.day^{-1}$ for CO_2 and $3,0.10^{-4}$ $mol.m^{-2}.day^{-1}$ for VOC at F11 (Figure 21). One H_2S flux anomaly has been observed at the south of the river (zone 5) on the black shale with a value of $5,8.10^{-5}$ $mol.m^{-2}.day^{-1}$ whereas CH_4 and CO_2 fluxes values were $1,2.10^{-2}$ and $2,4.10^{-2}$ $mol.m^{-2}.day^{-1}$ respectively.

The highest fluxes have been previously measured in the center of FA location by BRGM with 100 % CH_4 reaching 130 $L.min^{-1}$.

Table 2 CH_4, CO_2, VOC and H_2S gas fluxes (in $mol.m^{-2}.day^{-1}$) at Fontaine Ardente measured on-field and retreated

Reference point	Time	Zone	CH_4	CO_2	VOC	H_2S	CH_4	CO_2	VOC	H_2S
			Gas flux observed [$mol.m^{-2}.d^{-1}$]				Gas flux measured [$mol.m^{-2}.d^{-1}$]			
F63	10h44	1	6,00E-03	3,00E-02	<DL	<DL	6,21E-03	2,49E-02	0,00E+00	0,00E+00
F59	11h01	1	4,60E-01	1,20E-01	<DL	<DL	4,47E-01	1,23E-01	0,00E+00	0,00E+00
F61	11h07	1	1,1	4,10E-01	<DL	<DL	1,03E+00	3,77E-01	0,00E+00	0,00E+00
F64	11h15	1	<DL	4,50E-01	<DL	<DL	0,00E+00	4,33E-01	0,00E+00	0,00E+00
F62	11h22	1	2,90E-02	6,80E-02	<DL	<DL	2,82E-02	6,62E-02	0,00E+00	0,00E+00
F58	11h29	1	3,30E-02	2,60E-01	<DL	<DL	3,17E-02	2,50E-01	0,00E+00	0,00E+00
F76	12h06	2	13	1,80E+00	4,50E-04	<DL	1,31E+01	1,80E+00	4,39E-04	0,00E+00
F24	12h13	2	1	2,00E-01	1,00E-04	<DL	9,75E-01	1,91E-01	8,92E-05	0,00E+00
F55	12h18	2	1,50E-02	7,00E-02	1,00E-05	<DL	1,54E-02	6,78E-02	1,03E-05	0,00E+00
F54	12h24	2	8,00E-03	3,00E-02	<DL	<DL	7,76E-03	2,72E-02	1,91E-06	0,00E+00
F39	11h39	3	<DL	1,60E-02	<DL	<DL	0,00E+00	1,62E-02	0,00E+00	0,00E+00
F37	11h50	3	<DL	4,80E-02	<DL	<DL	0,00E+00	4,67E-02	0,00E+00	0,00E+00
F32	11h57	3	<DL	2,60E-02	<DL	<DL	-6,66E-04	2,53E-02	0,00E+00	0,00E+00
F11	12h33	4	9,00E+00	3,00E+00	<DL	<DL	8,43E+00	2,82E+00	3,03E-04	0,00E+00
F7	12h45	4	8,00E-01	5,20E-01	2,60E-05	<DL	7,69E-01	5,02E-01	2,51E-05	1,87E-07
F9	12h56	4	3,70E-03	3,40E-02	<DL	<DL	3,59E-03	3,36E-02	4,05E-06	0,00E+00
Forage BRGM 1	13h03	5	1,40E-03	1,60E-01	<DL	<DL	1,41E-03	1,62E-01	1,88E-02	0,00E+00
Forage BRGM 2	13h08	5	8,80E-04	3,00E-02	<DL	<DL	8,51E-04	2,99E-02	2,85E-06	0,00E+00
Sud Torrent	13h15	5	1,00E-02	2,50E-02	<DL	<DL	1,23E-02	2,40E-02	1,33E-03	5,75E-05

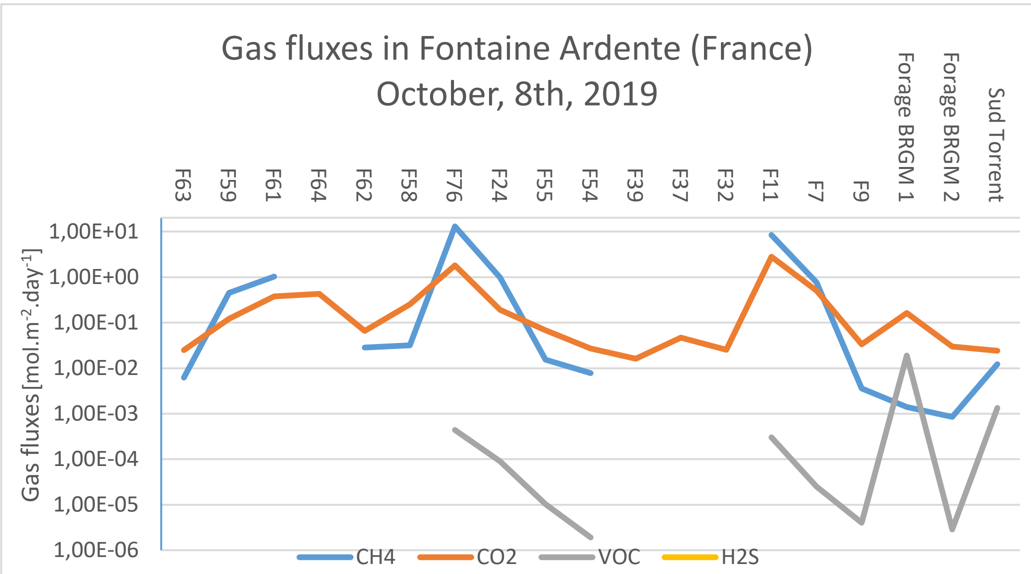

Figure 21 CH_4, CO_2, VOC and H_2S gas fluxes (in $mol.m^{-2}.day^{-1}$) at several reference points

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All the reference points have been previously documented by BRGM in published studies with TOTAL R&D co-authorship (Gal et al., 2017).

3.3.5 Hyperspectral signatures of vegetation

Three (zones 1, 3, 5) of the total five zones of the FA field have been studied with an additional zone 0 at the center of CH_4 emission where a horn beam surrounds the FA location. Some leaves were collected on the shrub vegetation and trees growing on emitting locations (Figure 22). Tree species that have been found locally are: hazel (Corylus avellana), bramble (Rubus fruticosus), Horn beams (Carpinus), dogwood (Cornus).

Figure 22 Observation of leaves from the 4 zones of vegetation sampling in Fontaine Ardente

Hyperspectral acquisitions were performed on each leaf sampled on trees and shrubs utilising the leaf clip device directly connected to the spectroradiometer. Incident radiomagnetic flux was measured due to the internal spectralon ("perfect white screen") that gives the highest reflectance in the range 350 to 2500 µm. Average reflectance signatures of the vegetation (fraction of incident electromagnetic power that is reflected of the leaves) have been obtained for each zone to better represent a potential remote acquisition from UAVs. The 4 zones studied presented typical spectra of vegetation from VNIR to SWIR with no evidence of impacts from CH_4/CO_2 emissions: no evidence of water stress nor toxicity at this stage of development (Figure 23).

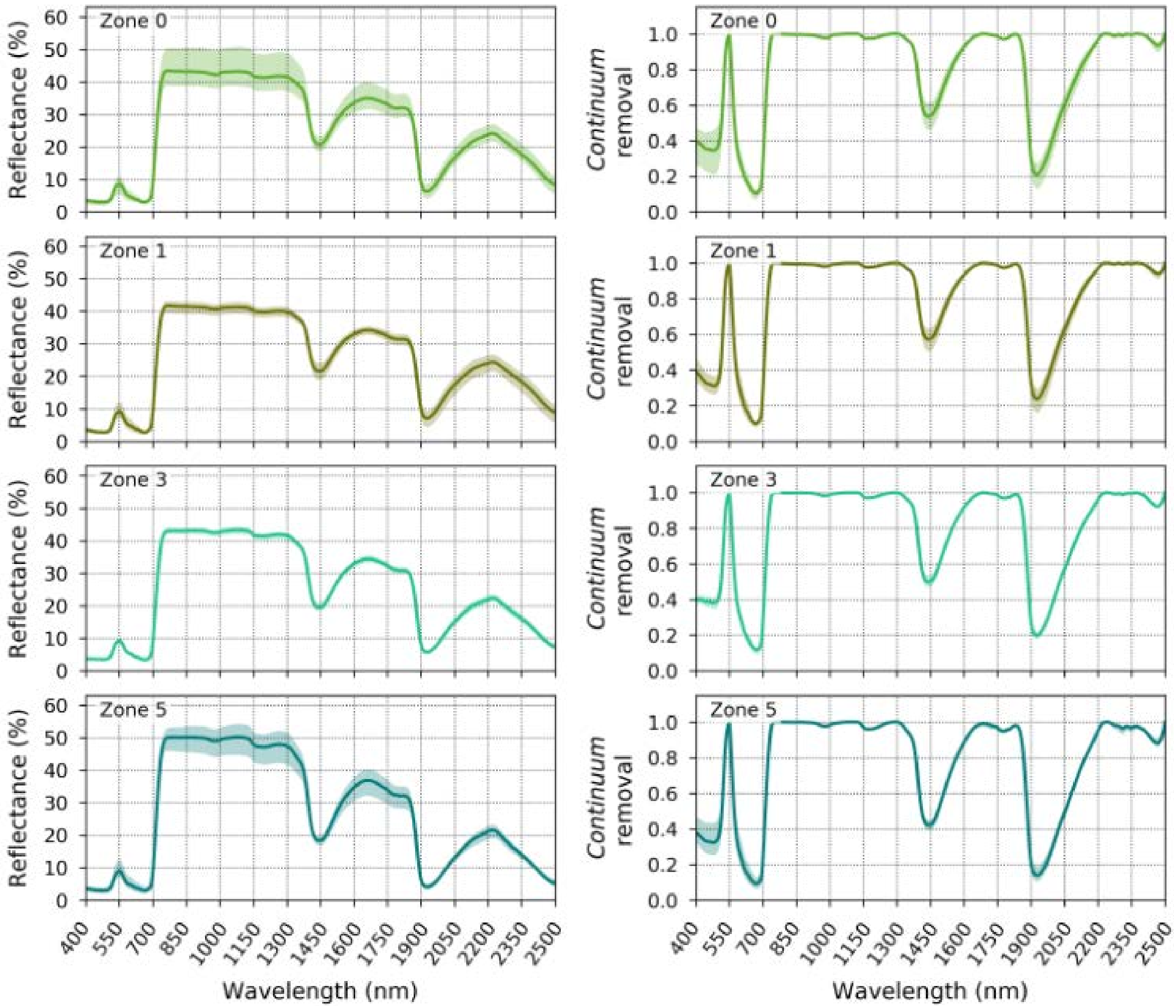

Figure 23 Hyperspectral signatures averaged for the 4 zones of vegetation studied in Fontaine Ardente.

Continuum removal representation (on the right of Figure 23) helps at better contrast anomalies in the individual absorption peaks normalizing the global signature from 400 to 2500 nm. Normalization is performed by dividing the reflectance value at a wavelength by the value of the general convex hull of the signature at the same wavelength. Some variabilities could be observed in the visible range, blue to green wavelengths (400 to 500 µm), and for water absorption at 1450 and 1900 µm, but are not so significant.

3.3.6 Pigment onsite analyses

Pigments analyses have been performed onsite for two species, hazel and bramble and on 4 parameters: Nitrogen Balance Index (NBI), Chlorophylls, Flavonols and Anthocyans (table 2). NBI and Chlorophylls are usually well correlated to nitrogen contains of the plants. Chlorophyll parameter has been calibrated by Force-A to get values in a range of 5 to 80 µg.cm^{-2}. Flavonols are synthetised after sunlight exposure and represent good indicators of plant-light interaction. Flavonols and anthocyans values represent relative absorbance units and are in the range of 0 to 3 and 0 to 1,5 respectively.

Table 3 NBI, Chlorophylls, Flavonols and Anthocyanins acquisitions for leaves of two species

Zone	Species	NBI		Chlorophylls		Flavonols		Anthocyanins	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Zone 0	Hazel	27,13	2,14	29,43	1,70	1,09	0,09	0,22	0,02
Zone 1	Hazel	20,57	5,78	24,83	10,86	1,16	0,25	0,28	0,07
Zone 5	Hazel	32,10	5,89	44,50	2,88	1,40	0,17	0,15	0,01
Zone 0	Bramble	42,73	5,72	37,53	8,49	0,87	0,10	0,16	0,03
Zone 1	Bramble	37,87	6,39	32,47	2,87	0,87	0,14	0,19	0,01
Zone 3	Bramble	26,60	2,91	39,90	2,95	1,52	0,27	0,18	0,00
Zone 5	Bramble	28,87	1,48	39,17	3,07	1,36	0,17	0,16	0,01

For hazel, no clear tendency could be observed in spite of a negative anomaly in zone 1, that is not confirmed by bramble. Further sampling (multi-temporal) would be necessary to confirm any continuous effect of CH_4/CO_2 on vegetation.

For bramble, a positive anomaly is observed with higher NBI (correlated to nitrogen content) and Chlorophylls content in Zone 0 (center of the FA hot spot). This clear tendency can be explained by a preferential exposition the sunlight in this deforested area rather than a positive effect of methane of carbon dioxide on bramble growth.

3.3.7 Conclusion

During the 2-day baseline campaign on Fontaine Ardente (French Alps), high seepages of CH_4 and CO_2 were confirmed at the soil/atmosphere interface (> 10 mol.m^{-2}.day^{-1}). These seepages occur on hot spots referenced previously and lower fluxes in the surrounding area have been referenced by BRGM and TOTAL teams. This area suffered anthropogenic transformation removing vegetation in the last decades. Some measurements were taken with the spectroradiometer and Dualex for hyperspectral and pigments acquisitions respectively on vegetation, mainly bramble and hazel, surrounding the hot spots of CH_4/CO_2 emissions. However, the specificities and recent history of the site avoid concluding any clear effects of methane and carbon dioxide on the vegetation at this stage of the study.

The main objective of this campaign was a merging of several tools and methods for direct and indirect baseline and monitoring. Hyperspectral imaging represents a powerful tool for further study on potentially impacted soil and vegetation but would need a larger area of prospection and multi-temporal acquisitions to determine clear baselines and potential anomalies of CO_2/CH_4 emissions at the soil/atmosphere interface.

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4 Discussion

The primary task addressed in this component of the SECURe project was to consider approaches and efficacy of utilising UAVs for large-scale remotely-sensed monitoring strategies of shale gas and CCS sites. The research was led by BGS alongside BRGM and TOTAL. Both BGS and TOTAL deployed, tested and further evaluated their prototype UAV-based gas sensors in SECURe, while BRGM collected gas data on the ground during the UAV field tests in the French Alps.

A key factor to consider for this research is the scale of monitoring. In this case we focussed on large scale (i.e. site scale) monitoring of CCS and shale gas sites. We also sought to focus on monitoring gas emissions (in particular CH_4 and CO_2).

Hyperspectral sensors can be used to detect gas emissions indirectly, if the gases affect vegetation growth patterns. For example, Bateson et al. (2008) completed tests at an analogue site in Italy using hyperspectral data from conventional aircraft. Hyperspectral data acquired from UAVs were not tested in SECURe because no partner had access to a UAV equipped with a hyperspectral sensor. As an alternative, we collected hyperspectral data on the ground using spectroradiometers and used these as a proxy for UAV data. The SECURe team concentrated on methods to measure gases directly with sensors mounted on fixed-wing and rotary UAVs.

Our literature review noted various products that are routinely derived from camera-equipped UAVs including point clouds, DEMs, DTMs and orthophotographs. These products, in their own right, are useful for CCS and shale gas site monitoring, but they do not contribute directly to gas detection and monitoring.

Within SECURe, TOTAL deployed their prototype TOTAL AUSEA rotary drone system that detects both CH_4 and CO_2 simultaneously. The BGS research utilised their prototype fixed-wing UAV system mounted with CH_4 and CO_2 sensors. BGS has also been converting their system to operate on rotary drones, although the rotary system could not be tested prior to publication of this report due to COVID travel restrictions. In fact, COVID-19 impacted the work schedules of all partners in this work package in several ways including:

(i) travel restrictions meant that we were unable to undertake field testing from March 2020 onwards. For example, we had expected to fly the BGS gas sensing UAVs at the ERA GTB site where CO_2 injection was planned for 2020. Injection has been delayed until March 2021 when the BGS UAV gas sensor will be deployed.

(ii) due to office closures, TOTAL were unable to access hyperspectral data from the October 2019 flights until May 2020, leaving less time for processing and analysis than originally planned.

(iii) due to schedule re-prioritisation at TOTAL, the October Alps UAV data could not be processed before October 2020 leaving less time for in depth processing and analysis.

Field tests of the BGS and TOTAL AUSEA UAV gas sensor systems demonstrated that they are capable of monitoring and recording gas concentrations in flight. They record positional data and detect gas from surface emissions (albeit with caveats, see below). The datasets produced within SECURe contribute to the assessment of the advancement of the technology readiness level (TRL) for operational drone-based monitoring systems, moving the research from TRL 4 (i.e. technology validated in a laboratory) to TRL 5 (technology validated in a relevant environment) (Figure 24). SECURe thus provided a research opportunity to demonstrate in the field that miniaturised monitoring systems can be successfully deployed by drone to detect emissions from ground level and at low emission rates.

Data processing of UAV-based datasets could not be addressed in depth during this work package due to COVID-19 limitations. Nevertheless, BGS has demonstrated some advances on identification of gas sources on the ground by modelling UAV in-flight data. Independently from SECURe, TOTAL has developed quantification proprietary algorithms along with its AUSEA technology development framework. This has already been assessed even at low emission rates against others and at controlled release site simulating industrial environment. Though applying these methods to natural rough terrain exhibiting dispersed small intermittent sources is very challenging. This would be a necessary milestone to reach if environmental baselines are to be produced with UAV based systems.

Further study of hyperspectral acquisition by drone is a promising way of detecting CO_2/CH_4 leakage in vegetated areas through the detection and quantification of vegetation exposure.

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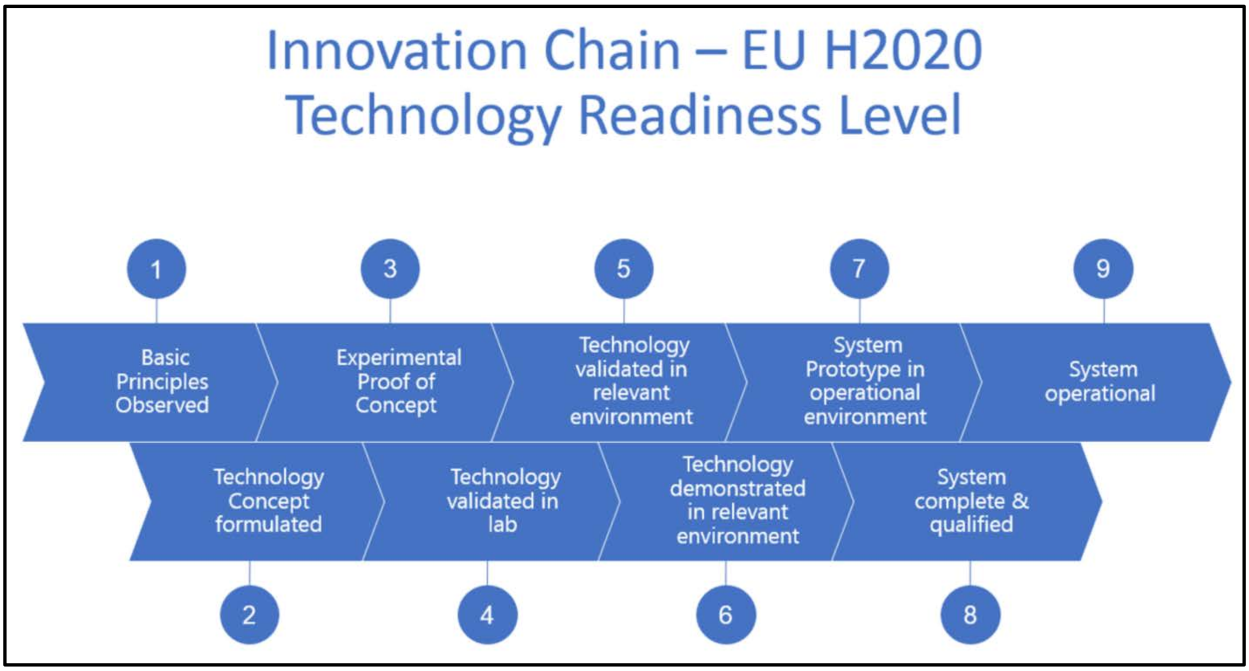

Figure 24 Technology Readiness Levels

Analysis of the UAV results highlight that in-flight gas concentrations should be acquired at the same time as ancillary data including wind speed and 3D direction. We have shown that, with these ancillary data, modelling can be undertaken to localise the source of the emissions on the ground. This modelling would help to focus ground investigations to pinpoint the gas source and help to determine the flux. This is an important demonstration, as it highlights the potential for a tiered monitoring programme. For example:

1) UAVs deployed initially to cover large or poorly-accessible areas, to highlight key areas of interest (or at the very least, rule out the vast majority of land);
2) Follow-up ground surveys directed by UAV-based data, to pinpoint individual vents or vent clusters (e.g. if aligned along a fault/fracture);
3) Gas sampling at individual vents for specialised gas analysis (e.g. for tracers or noble gases), and/or deployment of automated equipment at fixed sites/vents to gather time-series data (e.g. to quantify how gas fluxes change under different meteorological conditions or seasonally).

Unfortunately, follow-up tests with controlled gas releases were not possible in SECURe due to COVID travel restrictions, therefore it has not been possible to quantify precisely what level of gas emissions can be detected from what altitude, given various weather conditions including rainfall and wind speed/type. This is an important area that needs further study. In controlled gas releases it is possible to know precisely how much gas has entered the air mass, and for how long. It is therefore possible to draw a clear link with what is detected at altitude. Natural gas releases are very much harder to characterise accurately, and significant effort is required to define a reliable overall release rate. As a consequence, we still need to demonstrate a quantitative link between UAV-based gas monitoring data over natural sites and monitoring with ground instruments at the same sites. Key to defining this will be well-characterised and instrumented sites (i.e. 'natural laboratories'), at a range of scales, that can be used to test various gas monitoring technologies. This could include tower-based eddy-covariance monitoring (not applied during this study) that can indicate summarised emission rates over a large area, and thus a closer link to UAV-based measurements.

Optimal flight patterns for gas monitoring were also qualitatively reviewed in this task. If the requirement of the drone survey is simply to determine if there are gas concentrations in the air that differ from the background / baseline, then a flight that traverses the area in a grid pattern at a single altitude is sufficient. Conducting automated flights at a constant altitude above ground or obstacles is this thus a critical requirement for UAV systems. However, these data would not be appropriate to determine if high values originated from the site or were dispersed from further afield, or if the size and shape of a plume of gas were required. The ideal flight pattern traverses the area at a range of altitudes and with good coverage at 90° to the wind direction. It is also

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important to have simultaneous data on both wind speed and its direction in 3D (the vertical component being especially important).

We have demonstrated that the partner UAV-based gas sensor systems (rotary and fixed-wing) can collect acceptable CH_4 and CO_2 measurements. With further operational testing they could be a practical additional tool for site monitoring, scaling up the ability to capture conventional / traditional ground-based measurements. UAVs can efficiently cover sites that would be time-consuming or even inaccessible for ground surveys. The in-flight gas measurements should be collected alongside ancillary data such as wind speed and direction to help locate ground sources of gas emissions. Furthermore we recommend that the UAV data are collected in conjunction with ground measurements for calibration and validation of these novel and cutting edge systems.

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5 Glossary

CAA	Civil Aviation Authority
EO	Earth Observation
ERA-GTB	Energy Research Accelerator GeoEnergy Test Bed
DEM	Digital Elevation Model
DTM	Digital Terrain Model
GIS	Geographic Information System
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle

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