D.3.1

Report on the Sensing System Framework

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4.	20.06.2022	BeeoDiversity	Kim Nguyen, Laetitia Boels	Contribution to Chapter 5
5.	22.09.2022	POR; OPERATE	Tina Tement, Tadej Žurman; Gianluca Tapparini	Feedback from internal review process – document upgrade with subchapters 3.4.1.2.2.3.5 (Baseline Data Collection and Requirements) and 4.1.6 (SOIL CARBON SEQUESTRATION MEASURING), upgrade of subchapter 4.1.4.1.1 (Raising pH); upgrade of subchapter 3.4.1.2.2.3.2 (Choosing the provider)
6.	03.09.2023	POR	Tina Tement, Tadej Žurman, Mirko Šprinzer	Feedback from external review; document upgraded with modified executive summary, added Chapter 3 - How to use this framework as a tool to create tailor-made sensing systems, upgraded chapter 4.3.3.2 - In Field Co-Location, and chapter 4.4.2 - Quality assurance and quality control
7.	11.09.2023	UNI PASSAU	Janine Maier, Christina Haderer	Internal peer review process
8.	25.09.2023	POR	Tina Tement, Tadej Žurman, Mirko Šprinzer	Improvements based on the inter review, chapters 3, 3.2.1, 3.2.2, grammatical and stylistic improvements

ACRONYMS AND ABBREVIATIONS TABLE

Acronym / Abbreviation	Meaning
E-Institute	E-ZAVOD, ZAVOD ZA PROJEKTNO SVETOVANJE, RAZISKOVANJE IN RAZVOJ CELOVITIH RESITEV
UNIPASSAU	UNIVERSITAT PASSAU

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ICS	INSTITUTE OF COMMUNICATION STUDIESSKOPJE
LEITAT	ACONDICIONAMIENTO TARRASENSE ASSOCIACION
GCE	UNIVERSITEIT ANTWERPEN
PATRAS	DIMOS PATREON
POR	POR CONSULT DOO ZA POSLOVNO SAVJETOVANJE
PRATO	COMUNE DI PRATO
AITIIP	FUNDACION AITIIP
OC	OPENCONTENT SOCIETA COOPERATIVA
Belfast Council	Belfast City Council
BURST	BURST NONPROFIT KFT
ICLEI	ICLEI EUROPASEKRETARIAT GMBH
RRA-PODRAVJE	REGIONALNA RAZVOJNA AGENCIJA ZA PODRAVJE – MARIBOR
BOKU	UNIVERSITAET FUER BODENKULTUR WIEN
BP18	BUDAPEST FOVAROS XVIII. KERULET PESTSZENTLORINC-PESTSZENTIMRE ONKORMANYZATA
BREDA	GEMEENTE BREDA
BeeoDiv	BEEODIVERSITY
QUB	THE QUEEN'S UNIVERSITY OF BELFAST
OPERATE	FONDAZIONE OPERATE
UniLeeds	UNIVERSITY OF LEEDS
IETU	INSTYTUT EKOLOGII TERENOW UPRZEMYSLOWIONYCH
Katowice City	KATOWICE - MIASTO NA PRAWACH POWIATU
NBS	Nature Based Solutions
IoT	Internet of Things
AI	Artificial Intelligence
SC	Steering Committee
EC	European Commission
PC	Project Coordinator
PM	Project Manager

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KPIs	Key Performance Indicators

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1 EXECUTIVE SUMMARY

1.1 Purpose and Scope

To measure pollution from different sources and by different pollutants efficiently, UPSURGE will develop a multi-component pollution measuring approach as a reference holistic sensing and monitoring network comprised of several different sensing and monitoring parts targeting particular pollution-measuring and environmental-monitoring problems. Within D3.1, the sensing system Framework will define the types and scope of sensing technologies and approaches that can be implemented in the system. It will create a guideline for demonstration cities in order to concretize each demonstrated sensing system for optimal deployment.

1.2 Intended Readership/Users

This deliverable is intended to be used by entities aiming to establish a sensing system within a pre-defined area. This includes urban authorities, research organizations, NGOs, citizens' initiatives and others interested in air quality monitoring and potentially using said information for the improvement of their local environment. Since there are many particularities that have to be addressed when designing and implementing such a system, a plethora of knowledge and different expertise is needed, which is seldomly available within one organization, thus this deliverable aims to provide a comprehensive and detailed view of all necessary aspects to efficiently, representatively and legally establish such a system.

1.3 Contribution to Other WPs and Deliverables

D3.1 is comprehensively assessing all the aspects of establishing a multi-componential sensing system used for environmental verification of NBS effects by measuring physical inputs from the environment – parameters that can be measured by sensors. Thus, the deliverable serves as an input to Task 3.2 – Tailor-Made Plans for Operation of Sensing Systems at Demonstration Cities. Task 3.4 will assess the replicability potential of the system based on cost and implementability as observed in Task 3.3. Optimisation measures will be proposed in order to maximise the suitability and uptake of the sensing system for different cities wishing to replicate it. This final report will together with D3.1 be part of the knowledge base provided in the Urban Regenerative Clearinghouse (Task 7.2).

1.4 Summary of Key Findings and Recommendations

D3.1 is comprehensively assessing all the aspects of establishing a multi-componential sensing system to measure air pollution that will combine:

- stationary sensing stations, either already existing at or near the demonstration sites, or newly established within the project framework,
- mobile sensors that will be able to be mounted on non-fossil fuel transport modes and on unmanned aerial vehicles,
- participatory mobile sensors run via citizens' infrastructure.

The combination of said mobile sensing approaches and sensing data provided by other devices will offer the most accurate air pollution in any given moment and space, since pollutants are not uniformly distributed in space and time.

Moreover, the Framework is also presenting sensing possibilities for other parameters that were defined within the KPIs related to soil parameters (temperature, moisture, pH and nutrients), water parameters (precipitation, water levels, infiltration capacity), and urban heat islands by types. Automated weather stations that are coherently connected to sensing of other parameters, such as noise, wind etc. are also presented.

Finally, the Framework is proposing an NBS-based pollutant monitoring “system” that will be able to sense heavy metals, PAHs, and pesticides. These pollutants have been previously airborne and have been deposited in different plants, wherefrom the bees have collected the pollen. Pollen from strategically placed beehives will be sampled and analyzed for said pollutants. BeeOmonitoring will enable us to track the pollutants’ origins with a reverse-engineering process.

Generally, the Framework could be considered to be divided into two main categories: air quality sensing and other environmental sensing. Whereas the latter is presented more as a concise “bill of fare” of technologies, the air quality sensing part demonstrates an in-depth study of all complementary influencing factors related to it, such as ensuring data integrity (collocation, calibration etc.), legal consideration especially in participatory sensing approaches (GDPR) etc. and should be carefully revised by the end-users of the Framework before deploying such a sensing system.

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2 INTRODUCTION

2.1 Purpose

Deliverable D.3.1 – Report on the Sensing System Framework defines, based on the KPIs defined in Task 2.2, the types and scope of sensing technologies and approaches that can be implemented in the system. It is an implementation guideline for demonstration cities in order to concretise each demonstrated sensing system in *Task 3.2* for optimal deployment in *Task 3.3*. The document is intended to provide useful information on available sensing technologies and approaches to (based on KPIs of interest) guide the (optimal) selection and implementation of sensing technologies to evaluate the performance and impact of NBS of interest in concrete monitoring studies. In *Task 3.4* a comprehensive holistic final evaluation will be performed, which will determine the overall success of particular sensing solutions and the sensing system itself. This task will also assess the replicability potential of the system based on cost and implementability as observed in *Task 3.3*. Optimisation measures will be proposed in order to maximise the suitability and uptake of the sensing system for different cities wishing to replicate it. This final report will together with D3.1 be part of the knowledge base provided in the Urban Regenerative Clearinghouse *(Task 7.2)*.

2.2 Structure of the Document

This document is organized as follows:

- Chapter 2: INTRODUCTION. Aims to introduce the document, its purpose and structure.
- Chapter 3: AIR POLLUTION MONITORING. Provides short background information about air quality (summarizes typical air pollutants, sources, health effects and concentrations); Introduces factors affecting air quality (such as type of pollutant, weather and data collection location), discusses how these factors relate to each other and explains how they may influence the way the sensors are used; Discusses uses for air quality data and of “low-cost sensors”(LCS) and describes LCS performance characteristics to consider; Discusses steps involved in the process of deploying (low cost) sensor technology to measure air pollutants (incl. requirements for the quality of data produced and with data quality objectives associated sensor performance characteristics as basis (besides the selection of a target pollutant) for selection of air sensors of Upsurge’s air quality sensing system network, establishment of data management system and data processing for the project Upsurge, practical aspects of deployment in field (determining sensor location, GDPR privacy implications for wearable mobile deployments, rules and procedures for the operation of unmanned aerial vehicles (UAV), sensor maintenance) and elements that need to be considered when interpreting and communicating LCS (and LCS network) data).
- Chapter 4: SENSING OF OTHER ENVIRONMENTAL PARAMETERS. This chapter includes several other environmental parameters that can be determined by sensing technologies and have been defined in the KPIs.
    - Soil sensing that facilitates the measurement and monitoring of soil's physical and biochemical attributes (e.g. nutrients, water).
    - Water-related sensing parameters that are inherently connected to the implementation of NBS.
    - Urban heat island effect sensing defining different types and sensing techniques and technologies to measure them.
    - Automated weather stations that include a short list of 11 additional sensing parameters usually integrated in the AWS.
- Chapter 5: BEEOMONITORING – NATURE-BASED SENSING SOLUTION. BeeOmonitoring is a tool for measuring biodiversity and pollution through the analysis of pollen

collected by bees, which act as natural drones and bioindicators. It is the only tool that allows the collection of qualitative and quantitative data on:

  - the number and type of plant species present and their deficiency and impact on the whole ecosystem (biodiversity measurement tool);
  - the type, concentration and impact of industrial and agricultural pollution (pollution measurement tool);
  - over large areas, at low cost and on a continuous basis.

- Chapter 6: REFERENCES. Structures the references.

2.3 Contribution of Partners

POR led the preparation of D.3.1 – Report on the Sensing System Framework. Inputs from BURST formed the basis for discussion and development of the structure of the document. OPERATE was responsible for subchapter *3.4.1.2.2.3 (Data Management System and Data Processing)* and contributed to subchapter *3.4.1.2.2 (Sensor Characterization for Upsurge's Sensing System Network)* – responsible for preparation of Table 4: Recommended LCS performance characteristics. BeeOdiversity was responsible for Chapter 5.

OPERATE, BURST, ICLEI, GCE and BP18 reviewed and commented on the deliverable in the Level II of deliverable preparation process according to *Upsurge Quality Assurance Plan (D1.2)*.

2.4 Process of Work and Relation to other Tasks and WPs

The WP 3 objective is to develop a reference holistic sensing network comprised of several complementary approaches that will be implemented in 5 demonstration cities. The environmental verification of different NBS effects researched *(Task 2.1, 2.2)*, proposed *(Task 2.3)*, and laboratory tested *(Task 2.4)*, and implemented *(WP 5)* will be performed using different methods (standard sensing, NBS-based sensing, using drones, mobile sensors combined with innovative modelling approaches in *Tasks 6.2 and 6.3*) and for different environmental aspects (air pollution, heavy metal pollution, pesticide presence, carbon sequestration, water retention, nutrient leaching). D3.1 is comprehensively assessing all the aspects of establishing a multi-componential sensing system used for environmental verification of NBS effects by measuring physical inputs from the environment – parameters that can be measured by sensors. Thus, the deliverable serves as an input to *Task 3.2 – Tailor-Made Plans for Operation of Sensing Systems at Demonstration Cities*. *Task 3.4* will assess the replicability potential of the system based on cost and implementability as observed in *Task 3.3*. Optimisation measures will be proposed in order to maximise the suitability and uptake of the sensing system for different cities wishing to replicate it. This final report will together with D3.1 be part of the knowledge base provided in the Urban Regenerative Clearinghouse *(Task 7.2)*.

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3 HOW TO USE THIS FRAMEWORK AS A TOOL TO CREATE TAILOR-MADE SENSING SYSTEMS

Before considering the establishment or expansion of an air quality sensing system, it is essential to examine the objectives carefully if the appropriate data is to be collected with a minimum of effort and cost. Although it may be tempting to design a system that could serve a multitude of different objectives and associated data needs, in practice it appears that only certain combinations of objectives are realizable with a given network.For example, it is generally not possible to use a network designed to monitor long-term trends of air pollution levels to investigate a specific complaint. Of course, it is possible to modify a network designed primarily for one purpose so that it will serve another as well[1].

Air monitoring using sensors can be complicated and requires advance planning to be successful. This planning is a critical component of quality assurance and is necessary to produce useful and high-quality data. The planning steps and activities outlined in this section enable users to collect quality data, build trust in the data, and allow others to use the data, as applicable.

Figure 1: Representation in phases of how to use this Framework as a process creation and guiding tool.

3.1 PHASE I: DEFINING THE PURPOSE, OBJECTIVES AND BACKGROUND

It is essential for air sensor users to ask questions and to provide a clear monitoring goal before beginning data collection. Asking what data may already exist and why new air quality data are needed is important before purchasing an air sensor.

As you consider your monitoring purpose, you should also consider what you will do with the information collected. Are there specific people, groups, organizations, or companies with whom you will share your findings? Are there actions that you hope to inform and inspire in yourself or others? What are some of those potential actions? These intentions may shape your question, help you recruit team members, and inform your data quality needs.

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There are many purposes for monitoring with air sensors, including, but not limited to, general interest in air quality, education, and participatory science engagement; identifying an air pollutant of concern (e.g., hotspot identification); supplementing reference instruments; and conducting research.

Defining questions to be answered will help identify the pollutant of interest, the field conditions likely to be encountered, the data collection period, the type of measurements needed (e.g., short-term vs. long-term, stationary measurements), and the desired quality of these measurements. All these data collection characteristics will determine the air sensor(s) best suited for your purpose.

The following questions could be considered when determining a purpose for a tailor-made sensing system: what is the air quality concern or suspicion; what data/knowledge is already available about the air quality concern; what is not known about the situation that needs to be clarified; what are the desired outcomes for monitoring; where are the nearest reference instruments and what pollutants do those instruments measure; do the pollutants measured by nearest reference instruments reflect the sources that are of concern etc.

The selection of pollutants is commonly done in one of two ways. The first method recognizes that the most common air pollutants are present in varying amounts in almost all urban areas (e.g. CO_2, PMs, NO_x, SO_2, VOCs et.al.). The second way to define the target pollutant(s) to be measured by the sensor will depend on the question asked and the purpose for monitoring. It is important to keep in mind that a sensor's cost may depend on the types and number of pollutants selected. For each target pollutant, consider other factors (e.g., detection limit, measurement range, accuracy) to determine if a sensor will meet your monitoring needs.

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3.2 PHASE II: INITIAL ASSESSMENT OF LOCAL CONDITIONS

3.2.1 EXISTING SOURCES OF POLLUTION

One of the first steps in the design of a sensing system is to gather information concerning the sources and emissions of air pollution in the area to assemble an emission inventory. The main sources in a city usually include industries, motor vehicles, power plants, incinerators and heating. Information should be collected about their number, type, size and location related to the sensing area. In some cases, there may be publications that give local, regional and national totals. (national environmental agencies' databases are most common source of such data).

When considering the distribution of sources, it is important to make a distinction between large sources, which often emit through high stacks, and small sources, which emit at a relatively low height. Thus, smaller sources may have proportionately a much greater impact on ground level concentrations in the surrounding area than the large industrial sources.

3.2.2 METEOROLOGICAL INFORMATION

Meteorological data are generally assembled for purposes other than air pollution monitoring, e.g., weather forecasting, air traffic assistance, and agriculture and hydrological services. The local meteorological services usually have general information about climatic conditions in the area. Wind direction, wind speed and temperature variations with the time of day and year are some of the more common parameters measured. Other measurements that are often available are precipitation data, hours of sunshine, relative and absolute humidity and the potential for fog formation. Temperature gradient observations and data on the height of inversion base are very useful but are not always readily available (national official meteorological services would be the most appropriate data source) .

3.2.3 TOPOGRAPHICAL INFORMATION

Topography plays an important role in the selection of monitoring sites because of its effect on local wind and stability conditions. Many industrial areas have developed in river valleys, where there is an increased tendency for temperature inversions to develop and to trap the air pollution. In cities built on hilly ground there are substantial variations in concentrations within the urban area. In general, the more complex the terrain, the more samplers will be needed to determine the distribution of pollution. Other topographic features that affect the dispersion of pollutants include mountains, lakes and oceans.

3.2.4 EXISTING AIR QUALITY INFORMATION

Even if a continuous monitoring programme has not yet been established, there is often some information on air quality that has been collected in a sporadic manner, for example, special studies done by health and meteorological services, university and scientific researchers or even students preparing their graduation theses. All this information should be collected and if possible, tabulated. Sometimes a first estimate of the magnitude of the problem can be obtained in this way. Caution should be exercised in the use of these data since a variety of sampling and analytical procedures may have been used.

3.3 PHASE III: SELECTING AN AIR SENSOR

For in-depth analysis and explanation of the following sub-chapters *see chapter **4.3 - Sensor characterization** and chapter **4.4 - Deployment of air sensor systems.***

3.3.1 MEASUREMENT RANGE AND DETECTION LIMIT

Air pollutants can often be present at very low or very high concentrations in the ambient air. The measurement range refers to the lowest and highest pollutant concentrations that a device can measure. A sensor will be most useful when it measures a target pollutant over the full range of concentrations commonly found in the atmosphere. Depending on proximity to a pollution source, the sensor’s ability to measure either very low or very high concentrations is essential. The detection limit is the lowest concentration of a pollutant that a device can routinely detect. It is important to consult the manufacturer’s specifications for the detection limit to ensure that the air sensor can measure lower concentrations.

3.3.2 SENSOR ACCURACY

Accuracy describes the agreement between the sensor's pollutant concentration measurement and the concentration measured by the reference instrument. The accuracy of a sensor is determined by two components: precision and bias. Precision refers to how well a set of sensors reproduces the measurement of a pollutant under identical conditions (e.g., same concentration and temperature). Bias refers to measurement error. For example, a sensor may always measure a little higher or lower than the true concentration. Before purchasing a sensor, buyers should evaluate the air sensor’s precision and bias using the manufacturer’s specifications, evaluation reports, and published literature. Also, users should conduct checks of the precision and bias to qualify the air sensor’s accuracy. Users should be aware that a sensor’s accuracy, precision, and bias can change over time.

3.3.3 CALIBRATION OR COLLOCATION AND DATA CORRECTION

Calibration is a procedure that checks and adjusts an instrument’s settings so that the measurements produced are comparable to a certified standard. Collocation is the process of checking the performance of an air sensor by installing and operating a sensor in close proximity to a reference instrument(s). Data

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correction involves adjusting the air sensor data to increase its accuracy relative to a known reference value.

Before purchasing a sensor, users should determine whether the manufacturer has calibrated or corrected the sensor. In addition, users should fully understand when and how collocation should be performed and how to correct the air sensor's measurements. Talk to the sensor manufacturer about the method, frequency, and any additional costs for the calibration or collocation and correction services. The methods, periodicity and responsibility for calibration, collocation and data collection should already be included in the sensing system framework.

It is advisable to select a collocation strategy before actual deployment. *See* ***Chapter 4.3.3 - In Field Co-Location*** *and* ***Figure 2****.*

3.3.4 RESPONSE TIME

A sensor may be quick or slow to detect changing pollutant concentrations in the air. A sensor that responds quickly (i.e., high time resolution) may be useful for mobile monitoring and observing very rapid (e.g., seconds to minutes) changes in pollutant concentrations at fixed sites (such as near roadways with heavy traffic). A sensor that responds slowly (i.e., low time resolution) may be more suited to stationary monitoring where pollutant concentrations often change more gradually (e.g., minutes to hours). Specific data collection goals and purposes will determine which type of sensor is best.

3.3.5 GENERAL FEATURES OF THE SENSOR

3.3.5.1 Durability

Sensors vary in size, shape, durability, and quality of construction. Durability refers to an air sensor's ability to be shipped, moved, and to endure wear and tear and continue to perform. Sensors that are worn by the user or are deployed for mobile monitoring on vehicles might be shaken, hit against other objects, or dropped and must be designed to handle these impacts. All sensors measuring outdoor air quality are likely to be exposed to variable weather conditions such as wind, heat, cold, moisture, and dust and should be built to handle this exposure. A user manual or manufacturer's specification sheet should provide details on the general durability of the sensor.

3.3.5.2 Enclosure.

An enclosure is a case or structure that contains the sensor and its components and protects the components from water, light, temperature variations (e.g., by adding heaters or cooling fans), and electromagnetic noise. The sensor enclosure must allow air to reach the sensing components while shielding the components from weather effects. The materials, design of the enclosure, and sensor orientation (e.g., air inlet location, air flow path) may affect measured pollutant concentration levels and response time. Sensors that are exposed to ambient conditions for an extended period may experience a build-up of dust, dirt, ice/snow, and other debris near the sensor inlet. This may alter the accuracy and bias of the sensor, and users should ensure that a sensor's inlet remains clear of obstruction.

3.3.5.3 Ease-of-use

A wide variety of people with different levels of experience may use an air sensor and it is important to understand how easy or difficult it is to operate a sensor. Everyone, especially less experienced users, appreciate sensors that are easier to use. Determine whether any special expertise (e.g., technician, programmer) or tools (e.g., ladders, computers with specific software, special screwdrivers) are needed to operate or maintain the sensor both in the short term and long term.

3.3.5.4 Power

Power requirements vary for sensors and include plug-in, battery, or solar power. The choice of power options will depend on the user's application. Some sensors may alter their sampling frequency depending on the type of power supply used. This may result in some sensors logging data at intervals spaced longer apart when configured for battery or solar-powered operation. Plug-in devices are best suited for stationary monitoring applications with access to a wall power outlet; however, users need to ensure that power is available and easily accessible at the installation site. Battery-powered devices are often suitable for mobile applications or short-term data collection activities, although users should be aware of how long the battery lasts after charging and at what point the charge is too low to fully operate the sensor. For solar-powered devices, users should consult the manufacturer to ensure proper sizing of the solar components for the device and the available sunlight at the monitoring location (e.g., latitude, longitude, season) and information about proper placement, orientation, and maintenance.

3.3.5.5 Display

Some sensors do not include a data display and require users to visit a website or use an app to view data instead. Others feature a screen or display allowing users to view sensor information, real-time data, and/or view historical data. Some sensors include lights which indicate power or may change color depending on pollutant concentration and these lights may be paired with a data screen or be the only form of display. Consider whether a display is necessary for your project.

3.3.5.6 Data transmission.

There are several options available for data transmission. Options vary from sensor to sensor and include, but are not limited to, cellular, WiFi, Bluetooth, satellite, and low-power wide-area network (LoRa). Some sensors store data on the unit itself (e.g., local on-board storage, memory card) and data must be transferred manually. When selecting sensors, users should consider their application and whether the sensor's data transmission methods will suit their needs, cost constraints (e.g., subscription costs associated with cellular services), and will work in their desired monitoring location.

3.3.5.7 Data access.

There are a variety of data storage options available that may influence data access options. Sensors with on-board data storage require physical data download. Other sensors communicate data to central servers and data can be accessed by remote download or call from an Application Programming Interface (API). Users should consider how the data can be accessed, who has permission to access, who has data ownership rights, and how long the data will be available. Once data can be accessed, users will need to fully understand the data format, data analysis, and visualization options. For devices that share information with the public, carefully consider what information is shown as there may be privacy concerns (e.g., sharing a specific address).

3.3.5.8 Data handling

Conversion of information from the raw sensor signal to the final reported pollutant concentration happens in a variety of ways but often involves some kind of mathematical equation or model. These methods may depend only on data collected onboard the sensor or may include other data (e.g., nearby weather station). Users should ask manufacturers to describe how data is processed and any of these other data dependencies to understand whether that data will be available in their study area. Sensor manufacturers may choose to make their data handling methods public or keep them proprietary.

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3.3.5.9 Cost

A sensor's cost may vary greatly depending on the pollutant measured and degree of accuracy and sensitivity needed. Even for sensors measuring the same pollutant, the costs can vary depending on the device's features. Some sensor manufacturers offer different purchasing options, including buy, lease, or rent. Users should be aware that there are upfront costs (e.g., purchasing the sensor and sensor components) and long-term costs that can include, but are not limited to, repair or replacement of the sensor and their components, calibration services, data transmission charges (e.g., cellular service), or data hosting and storage fees (e.g., cloud storage on a manufacturer server or other server). Additionally, other potential costs (or time) could include data analysis, interpretation, and communication of air sensor data. Of course, costs increase if more sensors are needed (e.g., sensor networks).

3.4 PHASE IV: SETUP - LOCATING SITES FOR AIR SENSORS

Finding locations to set up air sensors, whether a single air sensor or a network of sensors (and other instruments), is a critical task. Finding suitable sites enables air sensors to collect useful data representing the surrounding conditions, ensures the sensor has power (and internet access, if needed), provides security for the sensor, allows easy access for maintenance, and adds credibility to the data.

3.4.1. INSTALLATION OF SENSORS

Users should carefully place a sensor or instrument in a location where it can reliably and safely measure the ambient air or source of interest with minimal interference from the location’s surroundings. A well-placed sensor yields data that is representative of the air quality in the area being monitored.

3.4.1.1 Location

Air pollution concentrations can be affected considerably by local sources (e.g., fire pit, grill), buildings, and structures, among other factors. These factors may vary based on the target pollutant or monitoring goal and users should consider the potential effects of these factors when choosing a monitoring location. The data will be most useful if the sensor can measure the pollutant of interest with little impact from other sources at the site.

Before setting up a sensor, it is useful to consider your monitoring goals since they can impact your ideal location selection. For example, a sensor that will be used to monitor emissions from idling buses may be set up in a different location than one used to estimate the local ambient air quality index (AQI).

3.4.1.2 Access

Although easy to use, air sensors are generally not something you can “set up and forget.” You will want to access your site to install and periodically check on the sensor. If you do not control the site, you will want to determine permissions, access requirements, and any limitations on access frequency or timing during the planning stage. Some users have found formal access agreements helpful in explicitly defining these conditions.

3.4.1.3 Power

Air sensors may need to be plugged in, may have solar panels, or may offer both options. Some sensors that offer power options may operate differently depending on which option is used (e.g., the data reporting frequency may change). Be sure to consult the sensor manufacturer to understand the implications. It can be expensive and time consuming to deliver power to a location that does not have the existing infrastructure. Available outlets should be tested rather than assuming they work. Consider using a surge protected power strip so that others can also use the outlet without unplugging your sensor. Extension cords may be needed for optimal sensor placement safety (e.g., trip hazard, fire risk). Water and electricity don't mix so be sure to consider electrical safety and water proofing for all connections. Solar panels may not be adequate if your location does not get enough sun and they will need periodic maintenance to remove dust. Areas that experience public safety power shutoffs may benefit from solar power to prevent monitoring interruptions.

3.4.1.4 Communications

Sensors may communicate data to a cloud-based interface using a variety of technologies (e.g., cellular, WiFi, LoRa). Some sensors may offer just one option, while other sensors may provide multiple options. Be sure to consult the manufacturer to understand specific requirements such as network limitations (e.g., 2G, 5G), carrier limitations, area coverage, and signal strength needs. If supplying your own mobile hotspot, you may also want to know the typical data use to properly estimate costs and if the sensor settings can be adjusted to reduce data use.

3.4.1.5 Security

Sensors and their peripheral equipment (such as solar panels) are subject to tampering and theft. A small sign describing your project and the device may help. Users will want to consider placing sensors in secure locations. Ideas include mounting a sensor overhead out of arms reach, in an inconspicuous location, or behind a locked gate or fence. When considering secure locations, keep in mind that sensors need a free flow of air, and consider your physical safety when visiting the area or even while climbing a ladder or stepstool for installation or maintenance.

3.4.1.6 Placement

It is ideal to place sensors near the typical breathing zone height (3-6 feet). Sensors should be placed away from pollutant sources (e.g., fire pit, grill) or pollution sinks (e.g., trees, shrub barrier) to get a more representative measure of air quality within the local area. Sensors should also be located to allow for free air flow to the sensor. Avoid placing sensors near high voltage power lines, which may create electronic interferences. Consider what hardware might be needed to mount the sensor (e.g., tripods, poles). Note that some locations (e.g., on top of buildings) may have specific engineering requirements to withstand wind, etc.

3.4.1.7 Additional Documentation

A deployment log can assist you in recording notes about sensor placement (e.g., location, height, date of installation) and maintenance (e.g., cleaning, component replacement). It's easiest to track or tag this information by assigning each sensor an ID (e.g., serial number, user given name). You may also want to capture more information about how the area is used. Also consider that temporary activities (e.g., road work, construction activities, cleaning, cooking) may impact the area and confuse data interpretation, so keep notes while the sensor is in use.

3.4.2 Specifics for Designing a Network of Air Sensors

An air sensor network is made up of two or more sensors placed at several different locations in an area to gain more information about variations in pollutant concentrations. Examples of a network include deploying air sensors throughout a neighborhood to gather general knowledge of air pollution levels or designing a monitoring network to locate the potential source of pollution impacting a location.

Initially, identify the general locations on a map to place air sensors. Consider the following:

- Spread out the deployment locations to get good spatial coverage.
- Avoid hyperlocal sources (e.g., smoking stations, grills) and locations where winds can channel and trap pollutants unless that is your specific research question.
- If there is an area of concern (e.g., pollutant source, area of suspected higher concentrations), locate sensors near/inside the area of concern upwind and downwind of the area so that meaningful comparisons can be made.
- Account for factors that affect safety when installing and maintaining the sensors that include access to facility, security, signage, weather conditions (e.g., lightning), etc.

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- Locate a reference instrument for future collocation activities. Seek input from your local air quality agency, a university professor, environmental consultant, or other experts who are useful resources to help design effective sensor networks.
- Contact your local, state, or local air quality agency.
- Contact professors in academic institutions with expertise in air quality such as environmental studies, engineering, atmospheric science, or other sciences.

3.5 PHASE V: Collect - Data Collection, Quality Assurance/Quality Control, and Data Management

With a question well-posed, a plan created, and sensors properly set up after collocation, it is time to collect data. There are many activities involved in data collection beyond simply turning on the sensor and collecting measurements. Users will need additional preparation before and during data collection activities to ensure that useful data is collected.

3.5.1 Data Collection Activities

Collecting good quality, complete, and ultimately useable data will require attention to several oversight tasks after the air sensors begin operating. These tasks include:

3.5.1.1 Frequent data review

Reviewing data frequently (e.g., daily, weekly) lets you detect problems early, notice trends in the data, ensure that maintenance activities are completed, and become familiar with recurring patterns. For instance, plotting the data, whether in a time series (i.e., a plot with the pollutant concentrations on the y-axis and the date and time on the x-axis) or another form can be a good place to start. You might see typical patterns, such as low concentrations during the morning hours or identify when high pollution episodes occur. These data reviews help you develop a general sense of air quality in an area under different conditions. When typical conditions are known, it becomes easier to identify times when sensor readings are atypical and why these atypical readings are occurring (e.g., Is an air sensor malfunctioning? Is wildfire smoke present? Is the weather pattern responsible for higher levels?).

3.5.1.2 Maintenance and Troubleshooting

Like most other forms of technology, air sensors require preventive maintenance to ensure proper functionality and reliable data collection. Maintenance activities are necessary for both short- and long-term operations. Air sensor maintenance can include regularly scheduled cleaning of surfaces or inlets to prevent the buildup of bugs or dust, replacing filters, or replacing sensor detector components as they age. Maintenance can also include examining site conditions for any changes (e.g., vandalism, overgrown trees). By properly maintaining an air sensor device, you can reduce errors in data collection, extend the device's operating life, and save money that would otherwise be spent on replacement parts and repair services.

Problems with air sensors (e.g., failing to report data) will likely occur and may require troubleshooting to resolve the problem and to continue collecting data. Troubleshooting might include visiting the sensor, contacting the manufacturer, seeking guidance from other air sensor users, or other activities. User manuals may also provide tips on troubleshooting.

3.5.1.3 Quality control (QC) checks.

It is important to frequently review the data for problems such as outliers (e.g., data that are significantly different from other data values), drift, etc. Some sensor manufacturers may offer a software package or online user interface that offers some automated checks of the data to assist in this process. Note that automated checks may not catch subtle problems (e.g., a gas sensor slowly degrading and losing its response) or may flag a real-life event or very high concentrations (e.g., high PM2.5 concentrations from wildfire smoke) as bad data. Do not solely rely on automatic QC checks to identify issues with the data—always review the data frequently.

3.5.1.4 Periodic collocation.

Collocation can help quantify the accuracy of a sensor while periodic checks can help ensure that accuracy is not changing over time or in different conditions. Users should develop a collocation approach or use the manufacturer's recommendation to conduct a periodic collocation to check the quality of the air sensor's measurements.

Sections 3.3.3 and 4.3.3 provide extensive additional information on the process of collocation and how to correct data to make it more accurate.

3.5.2 CHECKS TO ENSURE QUALITY ASSURANCE AND QUALITY CONTROL

Quality assurance (QA) and quality control (QC) are essential components of a project that will ensure that credible and useful data are collected. QA consists of planned steps to manage the project and collect, assess, and review the data. An example of QA is developing a plan for air monitoring to ensure identification of all tasks or steps to review air sensor data and confirm the sensor is operating properly. QC includes steps taken to reduce error from the instruments or measurements during a project. QC procedures are activities that include collocation, correction of data, maintenance, automatic data checks, and data review. Essentially, QA is the planning and QC is the action taken to produce high-quality data.

QA/QC are important components of a project that will help ensure that credible and useful data is collected. Regardless of whether the user presents the results as a written report, oral presentation, or in conversation, users should clearly describe the approach, the measurements obtained, the QA/QC checks in place, and the interpretation of the data. If any of these components are missing or not well executed, your data's credibility will diminish.

For more in-depth information *see* ***Chapter 4.4.2 - Quality assurance and quality control*** *and* ***Table 5 - a list of common quality control checks***.

3.5.3 DATA MANAGEMENT SYSTEM

Air sensors produce a large amount of data that must be routinely tracked and managed to access, review, and use the data effectively. A data management system (DMS) is a collection of procedures and software needed to acquire, process, and distribute data. A DMS helps streamline data processing, provides QC and review tools, maintains digital records and backups of the data, and displays, reviews, and facilitates sharing the data. These features make it easier to use air sensor data and to identify instrument errors or other problems early.

A DMS also makes it easier to operate and manage a network of multiple sensors simultaneously. Note that a DMS may be bundled with a sensor (e.g., manufacturer offered cloud data portal), purchased as a third-party system, or be available as open-source software.

For more in-depth information *see* ***Chapter 4.4.1.2.2.3 - Data Management System and Data Processing***.

3.6 PHASE VI: Evaluate - Analyzing, Interpreting, Communicating

Understanding air sensor data is as important as selecting and operating an air sensor. You should plan early for how to process, analyze, and interpret the data and how you will share and communicate the results. Do not wait until data have been collected to determine how you will use the data. There are many methods to analyze, evaluate, and share results, but the choice of which approach to use depends on the questions you are seeking to answer. Some analysis and interpretation can be relatively simple, while others that involve complex evaluations and in-depth interpretation can be a challenge to communicate. For example, a PM2.5 air sensor outside a home can measure local concentrations and

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help users determine the times of day when PM2.5 levels are lowest. However, deploying an air sensor network consisting of many sensors to detect areas of higher or lower concentrations will require much more detailed data analyzes and interpretation. Again, users should plan how they will analyze, evaluate, and communicate their results in advance. The remainder of this section provides guidance on methods and techniques for accomplishing these tasks and resources for getting started.

Data analysis is generally comprised of processing, then visualizing the data. Processing the data typically includes the following steps:

1. Data cleaning to prepare the data for analysis. Cleaning includes: a) QC checks and validation of the data to remove problems (e.g., large negative values, high values caused by sensor failure) and outliers, and b) checking timestamps and units.
2. Documenting any adjustments or changes to the data.
3. Acquiring data from other sources needed for the analysis. These data could include corresponding meteorological data, traffic data, emissions information, and/or other sources.
4. Averaging data to evaluate the "big picture" signals in the data.
5. Grouping data to summarize the data, or group or filter data to explore more details. Some examples include grouping data by time of day, day of week, location, and/or meteorological conditions.
6. Correlating data to begin evaluating the relationships between the air sensor data and other data values. For example, correlating PM2.5 concentrations and wind speed can show how different weather conditions are related to PM2.5 concentrations.
7. Comparing data to evaluate the air sensor data against different air quality standards and indices like the AQI.

For further reading *see* ***Chapter 4.5 - Interpreting and communicating air quality data*** and the deliverable under ***Task 3.4 – Final Assessment and Optimization of the Sensing System.***

4 AIR POLLUTION MONITORING

4.1 AIR QUALITY

Air quality is a major concern worldwide, particularly in urban areas, due to its direct consequences on human health, plants, animals, infrastructure and historical buildings (among others). World Health Organization (WHO) estimates show that around 7 million deaths, mainly from noncommunicable diseases, are attributable to the joint effects of ambient and household air pollution (*WHO, 2018*). Similar global assessments of ambient air pollution alone suggest between 4 million and 9 million deaths annually and hundreds of millions of lost years of healthy life, with the greatest attributable disease burden seen in low- and middle-income countries (*Burnett et al.., 2018; GBD 2019 Risk Factors Collaborators, 2020; Vohra et al.., 2021; WHO, 2018*).

To date, strong evidence shows causal relationships between PM2.5 air pollution exposure and all-cause mortality, as well as acute lower respiratory infections, chronic obstructive pulmonary disease (COPD), ischaemic heart disease (IHD), lung cancer and stroke (*Cohen et al.., 2017; WHO, 2018*). A growing body of evidence also suggests causal relationships for type II diabetes and impacts on neonatal mortality from low birth weight and short gestation (*GBD 2019 Risk Factors Collaborators, 2020*). Air pollution exposure may increase the incidence of and mortality from a larger number of diseases than those currently considered, such as Alzheimer's and other neurological diseases (*Peters et al.., 2019*). The burden of disease attributable to air pollution is now estimated to be competing with other major global health risks such as unhealthy diet and tobacco smoking and was in the top five out of 87 risk factors in the global assessment (*GBD 2019 Risk Factors Collaborators, 2020*). These global burden estimates are limited to PM2.5 and ozone. Other common pollutants such as nitrogen dioxide and sulfur dioxide are not yet included and, therefore, these figures based on exposure to PM2.5 and ozone are likely to underestimate the full health toll from ambient air pollution (*WHO, 2021*). The European Environment Agency (EEA) estimates that, in 2019, approximately 307,000 premature deaths were attributable to PM2.5 in the 27 EU Member States. Nitrogen dioxide (NO2) was linked to 40,400 premature deaths, and ground-level ozone was linked to 16,800 premature deaths[1].

In 2021, the WHO published new air quality guidelines to protect human health, updating the 2005 air quality guidelines based on a systematic review of the latest scientific evidence of how air pollution damages human health. The European Union (EU) has also developed an extensive body of legislation which establishes health-based standards and objectives[2] for a number of pollutants present in the air, which apply over differing periods of time because the observed health impacts associated with the various pollutants occur over different exposure times.

Table 1: Summary list of ambient air quality pollutants and limit concentrations

Pollutant	Units	Limit concentration	Averaging period
PM2.5	µg/m3	20 µg/m	1 year
PM10	µg/m3	50 µg/m	24 hours
PM10	µg/m3	40 µg/m	1 year
NO2	µg/m3	200 µg/m	1 hour

[1] European Environment Agency, https://www.eea.europa.eu/themes/air/health-impacts-of-air-pollution, accessed 10 February 2022.
[2] European Commission, https://ec.europa.eu/environment/air/quality/standards.htm, accessed 10 February 2022

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NO2	µg/m3	40 µg/m	1 year
SO2	µg/m3	350 µg/m	1 hour
SO2	µg/m3	125 µg/m	24 hours
CO	µg/m3	10 mg/m3	Maximum daily 8-hour mean
O3	µg/m3	120 µg/m	Maximum daily 8-hour mean
PAHs	ng BaP/m3	1 ng/m3	1 year

As part of the European Green Deal, the EU is revising these standards, to align them more closely with the more demanding new WHO air quality guidelines.

With the increasing urban population in most of the European countries and worldwide, air quality in cities, where air pollution can reach high levels, becomes a priority. EU legislation has led to improvements in air quality, with the percentage of urban citizens exposed to pollutant levels above standards set to protect human health falling between 2000 and 2019. However, poor air quality remains a problem: in 2019, 21 % of citizens were exposed to O3 and 10 % to PM10 levels above EU standards[3].

Although the first concern of air quality in the urban environment relates to human, the impact on urban ecosystems and biodiversity including either vegetation and animals, should not be neglected. Background information on pollutants and their effects on health can be found in the Air Quality Guidelines of the WHO and information on other air pollution effects and data can be obtained from the European Environment Agency[4].

4.1.1 ATMOSPHERIC POLLUTANTS AND THEIR SOURCES

Air pollution consists of a complex mixture of different chemical compounds in the form of solid particles (in a range of sizes), liquid droplets, and gases. Some of these pollutants are short-lived in the atmosphere (i.e. hours to days), while others are long-lived (i.e. years). The amount of time that a particular pollutant remains in the atmosphere depends on its reactivity with other substances and its tendency to deposit on a surface; these factors are governed by the pollutant form (i.e., chemical compound) and weather conditions including temperature, sunlight, precipitation, and wind speed (*Williams et al., 2014*).

Significant cuts in emissions are essential to improve air quality, as air pollutant emissions are the principal drivers behind air pollution. At the same time, reductions in emissions do not always automatically result in similar falls in concentrations. There are complex links between air pollutant emissions and air quality. These include emission heights, chemical transformations, reactions to sunlight, additional natural and hemispheric contributions and the impact of weather and topography[5].

4.1.1.1 Atmospheric pollutants

Short-lived pollutants that react quickly after they have been emitted may be highly variable in space and time, whilst long-lived pollutants typically show less variation over distances or time. **Detecting a**

[3] European Environment Agency, https://www.eea.europa.eu/ims/exceedance-of-air-quality-standards, accessed 10 February 2022
[4]https://www.eea.europa.eu/themes/air
[5] European Environment Agency, https://www.eea.europa.eu/themes/air/air-pollution-sources-1, accessed 10 March 2022

short-lived pollutant therefore requires a sensor that responds quickly. A slower sensor response may be used for detecting long-lived pollutants, especially if the sensor is not moving.

Air pollutants may also be categorised as primary or secondary. Primary pollutants are directly emitted to the atmosphere by a source, whereas secondary pollutants are formed in the atmosphere from precursor gases through chemical reactions and microphysical processes. Primary pollutants that contribute to the formation of secondary pollutants are also called precursors. Air pollutants may have a natural, anthropogenic or mixed origin, depending on their sources or the sources of their precursors.

Key primary air pollutants include particulate matter (PM), black carbon (BC), sulphur oxides (SO2), nitrogen oxides (NOX) (including nitrogen monoxide and nitrogen dioxide, NO2), ammonia (NH3), carbon monoxide (CO), methane (CH4), non-methane volatile organic compounds (NMVOCs), including benzene, and certain metals and polycyclic aromatic hydrocarbons, including benzo[a]pyrene (BaP).

Key secondary air pollutants are PM, ozone (O3), NO2 and several oxidised volatile organic compounds (VOCs). Key precursor gases for secondary PM are sulphur dioxide (SO2), NOX, NH3 and VOCs.

4.1.1.2 Pollutant sources and their formation

Key secondary air pollutants and their precursor gases can be of both natural and anthropogenic origin including: burning of fossil fuels in electricity generation, transport, industry and households; industrial processes and solvent use, for example in the chemical and mining industries; agriculture; waste treatment; natural sources, including volcanic eruptions, windblown dust, sea-salt spray and emissions of volatile organic compounds from plants.

Ground-level (tropospheric) ozone is not directly emitted into the atmosphere. Instead, it forms in the atmosphere from a chain of chemical reactions (triggered by sunlight) following emissions of certain precursor gases: NOX, carbon monoxide (CO) and NMVOCs and methane (CH4), including those by transport, natural gas extraction, landfills and household chemicals.

Nitrogen oxides are emitted during fuel combustion from industrial facilities and the road transport sector. NOX is a group of gases comprising nitrogen monoxide (NO) and nitrogen dioxide (NO2). NO makes up the majority of NOX emissions. NOX contributes to the formation of ozone and particulate matter.

Particulate matter is a mixture of aerosol particles (solid and liquid) covering a wide range of sizes and chemical compositions. PM is either directly emitted as primary particles or it forms in the atmosphere from emissions of certain precursor pollutants such as SO2, NOX, NH3 and NMVOCs. PM is emitted from many anthropogenic sources, including both combustion and non-combustion sources. Natural emissions of PM also occur, including from sea salt and windblown Saharan dust.

Sulphur dioxide is formed and emitted by combustion of fossil fuels (mainly coal and oil) for heating, power generation and transport. The highest concentrations of SO2 have been recorded in the vicinity of large industrial facilities. SO2 emissions are an important environmental issue because they are a major precursor to ambient PM2.5 concentrations.

Benzo(a)pyrene is a polycyclic aromatic hydrocarbon (PAH) found in fine PM. Its origin is the incomplete combustion of various fuels. The main sources of BaP in Europe are domestic home-heating, in particular wood- and coal-burning, waste-burning, coke and steel production, and road traffic. Other sources include outdoor fires.

Consideration on whether a pollutant of interest is primary or secondary pollutant can help to select a monitoring location. In some cases, it may be easier to determine the source of a primary pollutant than the source of a secondary pollutant.

Pollutant concentrations may vary significantly depending on the time of day, the day of the week, and the season. These differences can be attributed to changes in emissions patterns, temperature, the activity schedule of the source (weekly traffic patterns, for example), and differences in formational processes**.**

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Daily, weekly, and seasonal variations are important considerations when developing a measurement plan, and will guide the time and conditions under which measurements should be taken. (*Williams et al., 2014*)

4.2 USES OF LOW-COST AIR SENSORS

Measurements of air pollution and greenhouse gases underpin a huge variety of applications that span from academic research through to regulatory functions and services for individuals, governments, and businesses.

Regulatory monitoring generally requires very sophisticated and well-established instrumentation to meet measurement accuracy requirements and an extensive set of procedures to ensure that data quality is sufficient. Instruments to measure air pollutants for regulatory compliance purposes must be nominated for type testing according to European Committee for Standardization (CEN) for use in the European Union. These “reference instruments” (in an air pollution context, a reference instrument is most commonly understood to be one with a certification that comes from an official regulating body and can be associated with a reference method notified in legal drivers) measure specific air pollutants to predefined criteria, such as precision, accuracy, drift over time and so on, to provide data that meets regulatory requirements (*Lewis et al., 2018*).

Electronic miniaturization has led to a growth in the prominence of so-called low-cost instruments, providing an exciting opportunity for people to use this technology for a wide range of applications beyond traditional regulatory or regulatory-equivalent monitoring. These sensor systems are often described generically as “low-cost sensors” (LCS), where “low-cost” refers to the purchase price of LCSs compared to the purchase and operating cost of reference analyzers for the monitoring of regulated inorganic pollutants and particulate matter that can easily be an order of magnitude costlier (*Karagulian et al., 2019*). LCSs can in practice have other valuable features other than cost that differentiate them from previous technologies including being of smaller size, lower weight and having reduced power consumption (*Lewis et al., 2018*). Advanced computing power for data handling and the wide choice of software packages for data visualisation have made their development and evolution even more exciting (*Snyder et al.., 2013; White et al.., 2012*) (*Kumar et al., 2015*). It should be highlighted that a very broad range of different sensor devices can conceivably be classed as low-cost, relative to the hardware cost of an equivalent reference approach and that that for some atmospheric parameters the cost differential between reference methods and LCSs is rather small (*Lewis et al., 2018*).

At present, there are six broad areas where atmospheric composition measurements are required, and which are currently serviced by established reference instruments. Each is described briefly in Table 2 alongside the key data requirements from measurements that service that application area, and how that application is supported in terms of data quality and traceability.

Table 2: Applications of the atmospheric composition measurements, related measurement requirements and evaluation. Source: Peltier et al., 2021

Application	Type of measurement, purpose, and user		Measurement requirements	Critical evaluation
	Type	Short and long-term observations of atmospheric composition	Compound-specific, generally needing quantitative measurements and statistical treatment of data Where available, traceable to	Peer-review for new methods and applications. NMIs or other

Research in atmospheric sciences	*Purpose*	Basic and applied research	identifiable reference materials/methods Reported as concentrations with uncertainty External check on data quality and measurement methods through extensive peer- review *Sensor systems are beginning to play a role in areassuch as model or emissions validation and spatial variability in pollution.*	accepted methods for calibration, i.e. those recommended by GAW, of established parameters Research labs for calibration of emerging properties
	User	Primarily research organizations/ institutes and universities		
Long-term global change	*Type*	Trends and behaviour of key atmospheric composition parameters	Quantitative, reproducible measurements Methods follow prescriptive methods / best practice guidelines High data quality and accuracy Compatibility of concentration data between operators/locations/nations Participation in international calibration protocols Adoption of methods only after extensive technical and peer evaluation of analytical performance *Sensor systems are beginning to play a role as complementary information to well established reference monitoring systems.*	Peer-review for new methods and applications NMIs, EURAMET, NOAA, etc. for calibration WMO / GCOS for best practice
Air Quality management	*Type*	Observations of air pollution concentrations	Quantified degree of compatibility with air quality compliance measurements Substantial degree of confidence in data since it forms part of decision-making Quantitative or qualitative measurements to capture baselines, trends, and other changes in pollutant concentrations Some degree of data quality standard and reliability *This is already an early application area for sensor systems.*	Variable No specific requirements for methods, calibration or best practice.
	Purpose	Operational transport authorities, local government offices and environmental agencies		
	User	decision makers at local or regional levels, for example, in transport planning or emissions		

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		control		
Air Quality compliance/ regulation	*Type*	Observations of air pollution concentrations	Quantitative measurements High data quality with traceability to identifiable reference materials/methods for legal reporting Reported as concentrations Follow fully prescribed methods and best practice Instruments certified for use based on demonstration of measurement equivalence Follow national protocols for calibration and methodologies that meet existing legally defined data quality objectives *It is unlikely for sensor systems to be adopted for these applications unless standardized protocols are developed for calibration, operation, and data usage.*	NMIs for calibration ISO, CEN, USEPA, etc. for methods
Public Information / community monitoring	*Type*	Observations of air pollution parameters	Quantitative or qualitative measurements Flexibility in reported units Indicative Methods not legally prescribed, but should avoid conflict with air quality data generated from compliance/regulatory applications *Already identified as a class of applications for sensor systems.*	Not yet defined, although cannot diverge significantly from air quality compliance
	Purpose	Support public engagement and awareness, citizen science activities, education, provide data for advocacy and local empowerment		
	User	Operational bodies, NGOs, academic researchers, businesses or private individuals		

Proxy for exposure	*Type*	Alternative exposure measurements that can be compared to official data, or in lack of official data, can provide some order of magnitude of the exposure of a population in specific areas or buildings	Quantitative measurements Measurement equivalence to regulatory observations generally preferred, but not required or always possible To support health/medical decision-making, data quality requirements would be more rigorous *An emerging application where sensor systems arealready displacing low time resolution passive sampling.*	Limited currently to research and occupational health. Peer-review for methods acceptance National/Trans-national occupational health- approved regulatory devices

It is notable that sensor systems are particularly attractive for the emerging applications such as city air pollution management or public information, where sensor system data requirements have yet to be firmly established and methods of exploiting sensor data are becoming more successful. For academic use of sensor systems, it would be expected that the overarching data quality framework associated with peer-review will persist well into the future. For those interested in using such devices for novel purposes or applications, the responsibility will be placed largely on those making the measurements to demonstrate that data meets an appropriate quality threshold, ensuring that each device used was fit for purpose, in their publications. (*Peltier et al., 2021*)

Upsurge's air monitoring networks are designed for the (scientific) environmental verification of NBS. For this purpose, a long-term observation of atmospheric composition is required. The project's air quality sensing system networks for the environmental verification of NBS to be implemented in 5 demonstrator cities will be comprised of stationary and, in order to increase low spatial resolution present in conventional static sensors due to the prohibitive cost of the devices, supplemental mobile LCS, using mobility vectors including private citizens, bicycles, public transportation and unmanned

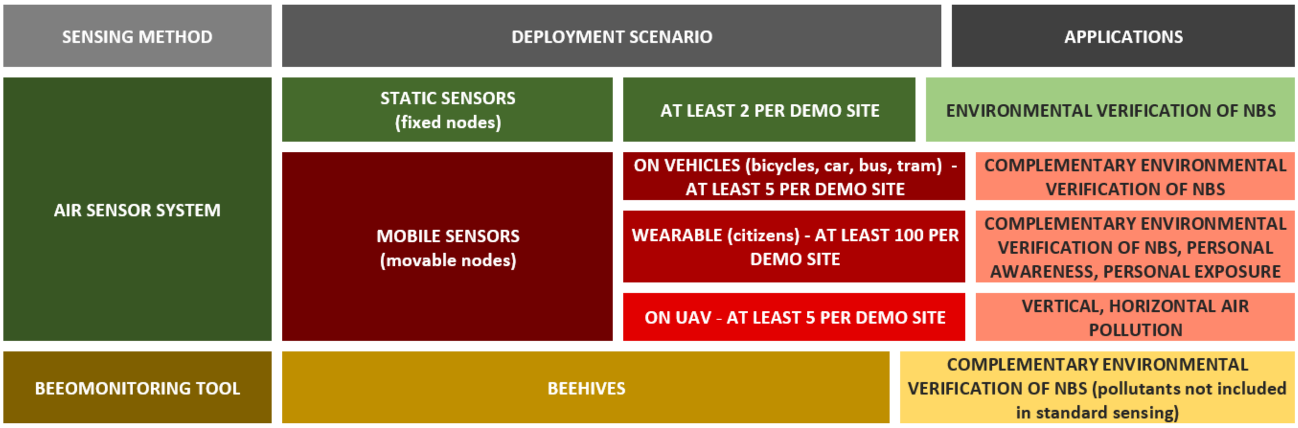

Figure 2: Upsurge's air quality sensing system network (sensing methods, deployment scenario and applications of measurements)

aerial vehicles (UAV). In addition, to include into environmental verification other pollution factors usually not considered by established sensing systems (e.g. airborne heavy metals), NBS-based sensing will be deployed. Proposed sensing methods, deployment scenario and applications of the atmospheric composition measurements in Upsurge's air quality sensing system network are illustrated in Figure 1.

Although currently, most LCS have finite lifetimes and either fail to function, lose sensitivity, or drift significantly over time making long-term trend analysis (to determine if over several years a particular pollutant is increasing or declining at a fixed location in a city) difficult, larger networks of sensors may

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be able to discern long-term trends and can be an important complementary source of information, provided that the appropriate sensor system is used, and calibration and quality control routines are in place.

The biggest benefit of projects complementary mobile monitoring applications is the increase in the spatial density of measurements as small and portable LCS, enable access where conventional instruments simply cannot be practically deployed. In addition, they place measurements in the hands of individuals and communities who, in turn, may take a greater ownership of issues related to local air quality or climate change. This, in turn, may lead to behavioural changes in individuals.

Data quality objectives and associated sensor performance characteristics required for project's application of the atmospheric composition measurements will be discussed in detail in subchapter 3.4.1.

4.3 SENSOR CHARACTERIZATION

In this chapter we briefly and in broad terms describe key hardware and software/firmware components in a sensor system, several sensor performance-related characteristics that affect air quality measurements (bias, precision, calibration, detection limit, response time, linearity of sensor response, measurement duration, measurement frequency, data aggregation, selectivity, interferences, sensor poisoning and expiration, concentration range, drift, accuracy of timestamp, climate susceptibility, data completeness, response to loss of power) and types of commonly used low-cost sensors, divided by used technology and their advantages and disadvantages.

Sensor performance-related characteristics should be carefully considered while planning for, making, and processing measurements in order to produce quality data and useful results. As described in previous chapter those making the measurements should be able to show that the quality of the data collected is sufficient to meet the performance requirements of the application and of the intended audience. Suggested air quality sensor performance goals for the environmental verification of different NBS effects that will be implemented in 5 demonstration cities (Maribor, Breda, Budapest, Belfast and Katowice) and for the follower cities will be outlined in detail in subchapter 3.4.1.2.

4.3.1 Main Components and Principles

Low-cost sensor systems are composed of core components and supporting hardware. Core components are the sensing/analytical elements used for detection and components that acquire, process, and output data. Depending on the sensor system, these are augmented with other power, security, usability, and data display features. Key hardware and software/firmware components in a sensor system include (*Peltier et al., 2021*):

- **Sensing Elements or Detectors:** A sensor system may combine multiple atmospheric composition constituent sensors as well as other sensors for non-chemical parameters such as humidity or temperature which may or may not be required for instrument operation, signal correction or data processing.
- **Sampling Capability:** Sensor elements need to be exposed to the atmosphere in a way as to be representative of the target environment. This can be achieved with passive (via inlets or apertures) or active (pump or fan) systems.
- **Operational Hardware:** On-board computational capability (e.g. microcontrollers or single board computers) is needed for sensor control, signal management, analogue to digital conversion, on-board processing, local data management and telemetry.
- **Power Systems:** Power resource access (e.g. batteries, mains, supercapacitors or solar) and power management (e.g. smoothing, stabilization, saving and backup).
- **Data Management:** This includes storage (e.g. long-term, temporary, local and remote) and transmission capability (telemetry) (e.g. WiFi, cellular mobile data networks spanning from GSM1 to 5G, or other low-power wide-area network (LPWAN)). A wide range of telemetry

options are available for a range of applications (e.g. LPWAN for dense spatial monitoring). Early examples of the General Packet Radio Service (GPRS) linked to 2G and 3G networks are now surpassed by the emerging 5G infrastructure.

- **Physical enclosure or housing:** (e.g. weatherproofing, electro-magnetic shielding, mounting) depending on application.
- **Accurate spatio temporal reference:** Knowledge of location and provision of accurate time are needed, particularly in the case of relatively dense sensing networks. This may be a reference point (i.e. a single known location and time) from which further times or positions are determined or a more active system with regular or periodic updates (e.g. GPS uplink).
- **Software requirements:** These include on-device and/or cloud-based software for data acquisition, processing, management, transfer and remote device management.
- **Data analytics:** These include techniques and processes to convert raw data into valuable information and visualize the processed data (e.g. via the cloud). Sensor systems connected to cloud servers may use cloud algorithms to process the data before final logging and display.

4.3.2 Bias, Precision and Accuracy

There are several ways to define and explain bias, precision and accuracy. According to Williams et al., 2014 the meanings are as follows:

- **Bias** means an average systematic or persistent distortion of a measurement process that causes errors in one direction. Bias can be thought of as a fixed value that is always added or subtracted from the true value of the pollutant by the sensor. Bias is usually caused by a characteristic of the sensor, by a problem with the overall measurement method, or by a persistent mistake that the operator inadvertently makes with each measurement and may be corrected by recalibrating the sensor, altering the method, or correcting operating procedures. The bias may change as a function of environmental conditions (e.g., with temperature and humidity), lifespan of the sensor, or other factors. Therefore, checking the sensor for bias is advised routinely, with frequent calibrations and/or intercomparisons with other sensors. Comparisons with high-performance instruments, or sensors that work by another measurement principle, may be valuable.
- **Precision** measures the agreement among repeated measurements of the same property under identical or substantially similar conditions. The more frequently data are collected over a given period the more confidence one has in the concentration estimate. Precision can be expressed in terms of standard deviation. Precision can be thought of as the scatter introduced into data by random (indeterminate) errors when an instrument attempts to measure the same concentration of a pollutant multiple times. The precision of an instrument can be improved by averaging more of the raw data together. Grouping data often results in fewer individual data points, but the grouped data will be more precise (i.e., a lower standard deviation) and potentially a better representation of the true value of the pollutant, provided the measurements are unbiased. The precision of an instrument can also be improved by averaging the data from multiple sensors operating at the same location.
- **Accuracy** is a measure of the overall agreement of a measurement with a known value. Accuracy includes a combination of systematic error (bias) and random error (precision). Reducing systematic and random errors will improve measurement accuracy.

4.3.3 Calibration

A calibration procedure checks and adjusts an instrument's measurements by comparing them to a standard, reference, or value. Sensor calibration is vital for producing accurate, usable data. Calibration relates the response of the instrument to the true concentration of a pollutant. (*Williams et al., 2014*)

Currently, there are two main approaches to calibrating LCS. The first is to do a calibration with standards, in which you introduce some widely accepted reference standard to the sensor. This is referred to as “laboratory calibration.” The second is to do a comparison against a reference instrument that has been calibrated with a recognized standard. This can be done by locating the sensor near an official

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reference instrument. This is typically referred to as "field co-location". (*Williams et al., 2014, Peltier et al.., 2021*) Both methods have benefits and drawbacks.

4.3.3.1 Laboratory Calibration

Laboratory calibration involves exposing LCS to different concentrations of targeted pollutants under a controlled environment (temperature and humidity) inside a chamber (*Narayana et al., 2022*). Unfortunately, the conditions under which sensors are calibrated in the laboratory do not often overlap with the full range of conditions encountered in an ambient environment. These differences include the presence of cross-sensitive gaseous species (*Lewis et al.. 2016*), changes in relative humidity and temperature, and ever-evolving aerosol physical and optical properties, all of which are known sources of error for LCS measurements. Laboratory experiments are also limited to those with the resources and/or opportunity to access the necessary equipment. (*Peltier et al.., 2021*)

Laboratory calibration alone is not enough to deploy sensors in real-time since it does not reflect all the characteristics of a specific location that they will be deployed. Hence, in-field calibration is a necessary step following laboratory calibration. Several recent studies explored direct infield calibration without laboratory evaluation and reported good agreement between the sensor and standard methods. (*Narayana et al.., 2022*)

4.3.3.2 In Field Co-Location

In field co-location the sensor (or sensors) is placed in the field near a reference instrument for a period of time to provide a direct comparison of the LCS's output to that of a calibrated reference instrument. Ideally, sensors and reference monitors should be within 10 meters of each other, and the inlets (where air enters the sensor/monitor) should be at about the same height. In addition, the movement of air around the sensor should not be blocked or hindered by any other structure or device and sensors should be protected from the weather (*EPA*). It can be difficult however to experience the entire dynamic range of target species, cross-sensitive species/pollutants and environmental parameters in a short period of time and this can make comprehensive calibrations rather time intensive (*Hagler et al.. 2018*). Access to locations and calibrated reference equipment can also be an issue. The seasonal change of the field environmental conditions should be considered (in addition to the LCS drift) to determine the frequency of the field co-location calibration (*Peltier et al., 2021*). As there may be significant measurement differences between identical models of LCS measuring the same environment, where logistically and economically feasible, as suggested by *Peltier et al., 2021*, it is best to calibrate all LCS as an ensemble. If not, the batch calibrations may be effective to characterize and quantify these differences within a single LCS model.

Recent advances in data analytics using statistical methods and machine learning can contribute to the development of in-field corrections for LCS networks (*Karagulian et al.. 2019; Wang et al.. 2020a*). To develop a data adjustment method, the sensor device is usually collocated with a reference-grade monitor in an environment that is representative of the sampling conditions. This collocation time frame serves as the training period for which a correction algorithm is developed that incorporates the sensor raw data and adjusts the data to most closely match the reference-grade data. Thereafter, the sensor device is relocated to another environment for ongoing use and the correction algorithm is applied, based upon the presumption that the ongoing sampling conditions are within range of the calibration period. In some approaches, sensor data at one location are adjusted based upon measurements in other places, assuming there is homogeneity in air pollution concentrations over a specific geographic area and time frame. Calibration models (such as multiple linear regression or random forest regression) are also being trained on a few sensors either in-field or in the laboratory that is then expanded to a larger sensor network (*Simmhan et al.. 2019; Wang et al.. 2020a*) with the aim to develop sensor prediction models. (*Peltier et al., 2021; Hagler et al., 2018*) However, these strategies for sensor data processing raise important questions as stated by *Hagler et al.l, 2018*:

a) How confident are we that calibrated sensors provide a sufficient data quality when deployed at other locations?
b) What are the appropriate parameters to include in sensor data adjustment algorithms?
c) At what point do adjusted sensor data depart from an independent measurement?

Hagler et al.., 2018 present a scheme for the type of parameters that can be used for sensor data treatment (defendable parameters) and those that should not be used (questionable parameters).

A helpful guidance on conducting a successful collocation evaluation of low-cost air sensors with regulatory grade monitors for all users – experts and non-experts alike is *US EPA's Air Sensor Collocation Instruction Guide*, which also introduces users to EPA's Excel-based macro analysis tool for comparing and interpreting air sensor data.

A range of potential collocation options exist to meet various logistical and budgetary constraints. A combination of approaches can be used depending on the length of the project, the desired data quality, and other project constraints or needs:

- **Periodic All Sensor Strategy**. All sensors are collocated with a fixed reference instrument at the beginning and end of the monitoring study. Depending on the length of the study, the collocation may happen periodically (e.g., seasonally, every 6 months, annually) throughout the study. Strengths: all sensors are tested at the same time letting you know how they compare, all sensors are compared to a reference instrument for a limited time, there are no additional equipment costs if you can use an existing reference instrument, sensors from smaller networks can be moved without major effort. Weaknesses: weather and air pollution conditions during the collocation may not be representative of the actual conditions encountered by the sensors when deployed at their sites, it will be more difficult to detect subtle changes in sensor performance over time or changes in performance due to a unique or short-term pollution events (e.g., short-lived seasonal dust storm) because a sensor is not permanently located next to the reference instrument, moving sensors back and forth between the collocation site and their permanent sites can be labor intensive and increase the likelihood of damage, for large networks, there may not be enough space or power available at the collocation site for all of the sensors to be collocated at once.
- **Continuous Subset Strategy**. All sensors are first collocated at a reference site. Then, some sensors are continuously operated next to a reference instrument while others are deployed to a different location(s). Strengths: because some sensors remain collocated with a reference instrument, sensors are tested under a wide range of weather and pollution conditions, and you can detect performance changes over time, however, this approach assumes that all sensors perform similarly to one(s) that are continuously collocated, all sensors are tested at the same time letting you know how they compare, all sensors are compared to a reference instrument; some only for a limited time, there are no additional equipment costs if you can use an existing reference instrument, sensors from smaller networks can be moved without major effort. Weaknesses: moving sensors between the collocation site and their permanent sites can be labor intensive and increase the likelihood of damage, for large sensor networks, there may not be enough space or power available at the site for all of the sensors to be collocated at once, if the collocated sensor fails and needs to be replaced, you no longer know how the new sensor's performance compared to the other sensors in the network, you might consider leaving several sensors collocated with the reference instrument.
- **Reference Transfer Strategy.** A reference instrument visits each sensor for a short period of time. This strategy can be useful for characterizing the performance of a network of sensors over the course of the long-term study. Strengths: all sensors are compared to a reference instrument for a limited time; both the sensor and reference instrument experience the same pollution sources and concentrations and weather conditions during collocation, sensors do not need to be moved to another location after their initial deployment, thereby minimizing the chances of damage. Weaknesses: weather and air pollution conditions or sensor performance may change between collocation periods, does not test all sensors at the same time, under the

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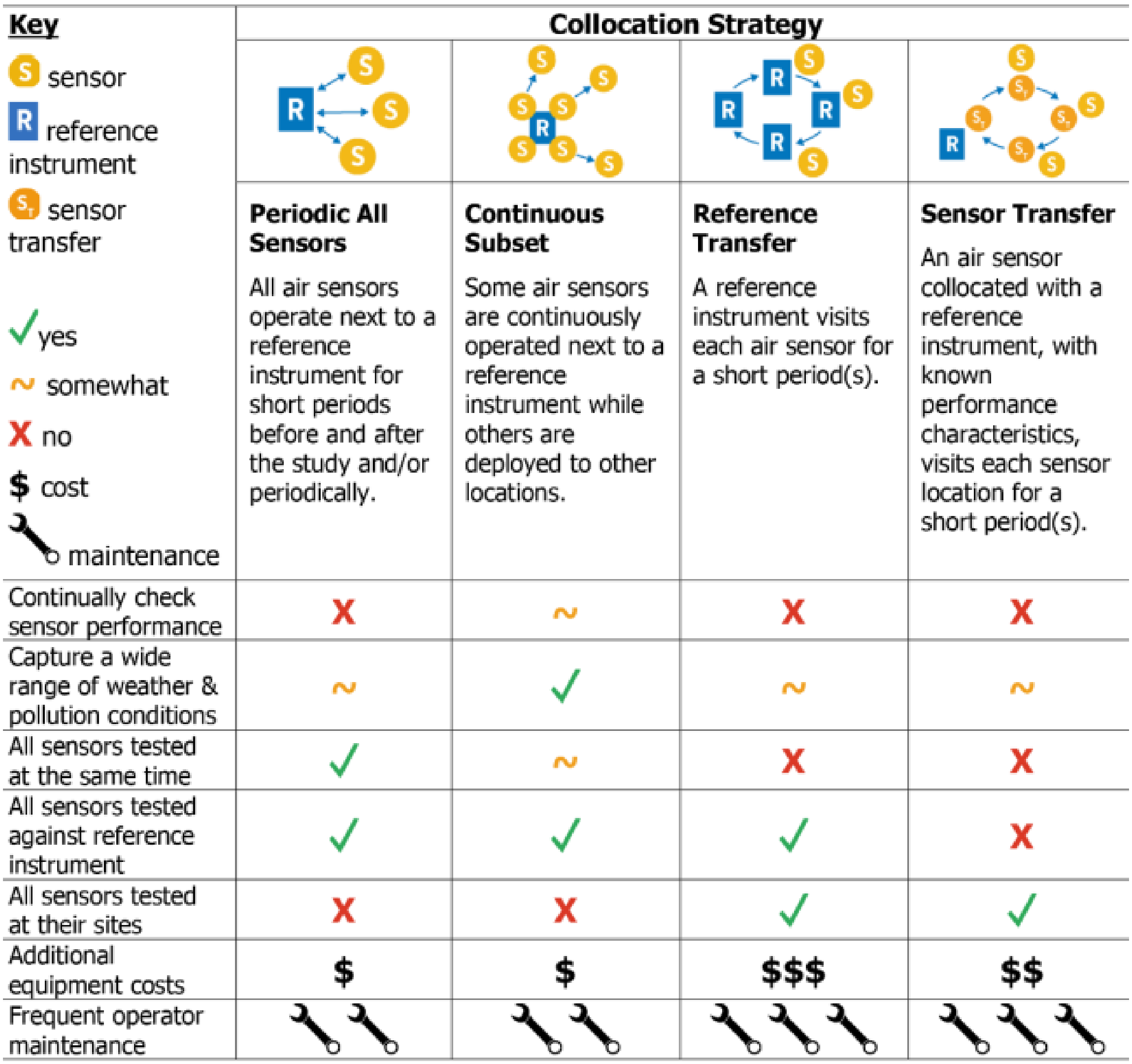
same conditions, can be costly to obtain, operate, move, and maintain a reference instrument(s), some sensor sites may not be able to accommodate a collocated reference instrument (e.g., the sensor is mounted on a pole or in an unsecured area).

- **Sensor Transfer Strategy**. A sensor, or research grade instrument, with known performance characteristics, is brought to each location where a sensor is deployed. In order to best know the sensor performance characteristics, sensors used in this strategy are usually left collocated with a reference instrument when not being moved around the network. Strengths: all sensors are compared to a sensor or research grade instrument with known performance for a limited time; both experience the same pollution source and concentrations and weather conditions during collocation, it is less costly and labor intensive to transport a sensor or research grade instrument around the network. Weaknesses: assumes that the performance of the traveling sensor or research grade instrument does not change when moved from site to site which may not be true if pollution sources or concentrations change, difficult to detect subtle changes in performance over time, the deployed sensors are not tested against a reference instrument, which makes it more difficult to quantify the accuracy of each sensor, sensors are not tested at the same time,



Key	Collocation Strategy			
S sensor; R reference instrument; S_T sensor transfer; ✓ yes; ~ somewhat; X no; $ cost; 🔧 maintenance	**Periodic All Sensors** All air sensors operate next to a reference instrument for short periods before and after the study and/or periodically.	**Continuous Subset** Some air sensors are continuously operated next to a reference instrument while others are deployed to other locations.	**Reference Transfer** A reference instrument visits each air sensor for a short period(s).	**Sensor Transfer** An air sensor collocated with a reference instrument, with known performance characteristics, visits each sensor location for a short period(s).
Continually check sensor performance	X	~	X	X
Capture a wide range of weather & pollution conditions	~	✓	~	~
All sensors tested at the same time	✓	~	X	X
All sensors tested against reference instrument	✓	✓	✓	X
All sensors tested at their sites	X	X	✓	✓
Additional equipment costs	$	$	$$$	$$
Frequent operator maintenance	🔧🔧	🔧🔧	🔧🔧🔧	🔧🔧🔧

Figure 3: Different Types of Air Sensor Collocation Strategies; Source: EPA, 2022

so you cannot determine how one sensor compares to another.

4.3.3.3 Post-Deployment Calibration

Though sensors undergo rigorous evaluations in the lab and field, data reliability is questionable for long duration deployments due to sensor signal drift. Frequent recalibration (post-deployment calibration) can address this issue. As it is not always possible to maintain reference stations everywhere, various calibration strategies for post deployment calibration have been elaborated, i.e. Blind calibration, Collaborative calibration and Transfer calibration (*Narayana et al., 2022*):

- **Blind calibration:** In blind calibration, sensors are calibrated to the nearby reference stations when it is believed that both the sensors and the reference stations are exposed to the same concentrations. **Advantages:** • Simple • Can calibrate both stationary and mobile sensors **Limitations:** • Has to wait until certain condition is reached like concentration is below certain level. • Possible to calibrate only gain and offset.
- **Collaborative calibration:** In collaborative calibration, a mobile sensor is calibrated to a reference station when they meet in space and time, and it is called as sensor rendezvous with a reference station. **Advantages**: • Able to calibrate mobile sensors • Possibility of better calibration accuracy when compared to other methods. **Limitations**: • Able to calibrate mobile sensors • Possibility of better calibration accuracy when compared to other methods.
- **Multi-hop calibration:** Multi-hop calibration extends the collaborative calibration. In Multi-hop calibration a freshly calibrated sensor instead of reference station/instrument is used to calibrate another sensor when they meet in space and time. Then the calibrated sensor is used to calibrate another sensor and the chain continues until the calibration finished for all the sensors. **Advantages:** • No need of reference station/instrument everywhere in the measurement process. • Suitable for mobile sensor monitoring **Limitations:** • Sensors are used to calibrate other sensors instead of reference instrument/station that causes error accumulation. Hence, sensors at the end of the chain are more prone to wrong calibration. • Linear calibration models are not suitable due to error accumulation problem.
- **Transfer calibration:** Calibration transfer can be done by transferring the calibration parameters of a source sensor to a target sensor. Here the target sensor is the sensor of interest to calibrate and the source sensors is the one which is having access to the reference station. At first the source sensor is calibrated to the reference station then the calibration parameters are transferred to the target sensors based on some learning theory. **Advantages:** • Both stationary and mobile sensors can be calibrated. **Limitations**: • Need identical sensors.

4.3.3.4 Tests and Calibrations by Manufacturers, Data Treatment of LCS

Manufacturers test their passive samplers, or low-cost sensors, mainly to ensure operational performance and to understand technical malfunctions. The manufacturer or a research institution calibrates the devices in the laboratory using measurements of known mixes of gases and particulate matter concentrations (*EEA, 2019*). Calibration of LCS involves determining a model that can be used to convert the measured parameter (e.g. light absorption, voltage, or conductivity) into desired output variable (e.g. pollutant/species concentration) (*Peltier et al., 2021*). For some sensors, the factory calibration settings are published in data sheets, while for other sensors applied data conversion model remains unknown to users. Hence the data treatment of LCS can be classified in two distinct categories (*Karagulian et al., 2019*):

I. Processing of LCS data performed by “open source” software tuned according to several calibration parameters and environmental conditions. All data treatments from data acquisition until the conversion to pollutant concentration levels is known to the user. Usually, outputs from these LCS are already in the same measurement units as the reference measurements. In this category, LCS devices are generally connected to a custom-made data acquisition system to acquire LCS raw data.

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Generally, users are expected to set a calibration function in order to convert LCS raw data to validate against reference measurements.

II. LCS with calibration algorithms whose data treatment is unknown and without the possibility to change any parameter have been identified as “black boxes”. This is due to the impossibility for the user to know the complete chain of data treatment. In most cases, these LCS are pre-calibrated against a reference system or, the calibration parameters can be remotely adjusted by the manufacturer. This is a limitation as the LCS might need a-posteriori calibration other than the one provided by the manufacturer, but raw- data are unavailable.

Many manufacturers routinely provide factory setting sensor calibration data, which is often developed under proprietary laboratory conditions. However, factory calibrations for many sensors are not yet sufficient for robust, long-term accuracy across the range of possible environments in which the sensor may be used and therefore, reliance on manufacturer calibrations alone, without reference comparison, is insufficient for quantitative data applications (*Peltier et al., 2021*).

4.3.4 Detection Limit

Limit of detection (LOD) for a sensor is defined as the lowest concentration of a pollutant that can be significantly differentiated from zero concentration (*Rai et al., 2017*). Below this boundary the noise of a sensor signal starts to dominate and it becomes impossible to differentiate between concentration levels.

Environmental pollutants can often be present in very low concentrations, particularly when measurements are being made far from the source of the pollution (*Williams et al., 2014*). It is therefore desirable to have the LOD as low as possible since it determines the lowest detectable concentration.

Low-cost sensors often have a LOD that is close to the range of interest or even surpasses it. As a result, measurements at low pollution concentration are subject to high noise. Especially PM and electrochemical sensors are known to be significantly affected by low signal-to-noise ratios at low concentrations. It is important that calibration procedures are applied with respect to these limitations (*Maag et al., 2018*).

4.3.5 Response Time

Response time is the amount of time required for a sensor to respond to a change in concentration. A sensor that responds quickly may be useful for mobile monitoring and for observing very rapid changes in pollutant concentrations. A sensor that responds slowly may be more suited to stationary monitoring of pollutants that vary in concentration gradually. The measurement duration and frequency are governed by the sensor response time (*Williams et al., 2014*).

4.3.6 Sensor Response

A useful sensor response is composed of a unique response for each concentration measured. Such a response is called a monotonic increase (*Williams et al., 2014*). Sensor responses to pollutant concentrations are normally related using a mathematical equation, and they are typically single valued (i.e., unique to each pollutant concentration) in the region of interest (*Williams et al., 2014*).

Due to the nature of certain low - cost sensing techniques non-linear relationships between a sensor and a references response are unavoidable. Non-linear behavior is known to be an issue particularly for a wide range of particulate matter sensors and metal oxide sensors. Often sensor manufacturers already linearize the sensor response, e.g., by internal signal processing, or provide information about typical non-linear behavior in the datasheet. However, additional factors such as environmental conditions are known to cause non-linear behavior as well. (*Maag et al., 2018*) The sensor response does not need to be linear, but it needs to be quantifiable through an equation; polynomial, power law, or exponential equations are all acceptable (*Williams et al., 2014*), although a linear relationship is in general favorable because it allows the use of simple calibration models (*Maag et al., 2018*).

4.3.7 Measurement Duration

Measurement duration is the length of time over which a measurement is collected (e.g., 1 minute, an hour) (*Williams et al., 2014*).

Shorter measurement times allow you to see more rapidly changing concentrations. The minimum measurement duration depends on the sensor response time and other factors. There are situations in which you might want to average measurements over longer time durations to:

- Improve the precision of measurements from less precise sensors, or
- Reduce the size of a data set to make it more manageable during processing.

It is important to ensure that the measurement duration of sensor is compatible with its application. In order to capture variations in concentration by location, a sensor on a mobile platform (e.g., walking) may require a shorter measurement duration than a stationary sensor would require. (*Williams et al., 2014*)

4.3.8 Measurement Frequency

Measurement frequency describes the number of measurements collected per unit of time. Measurement frequency refers both to how often you make measurements (i.e., one hour per week) and how often measurements are made during this time (i.e., one measurement per minute). This will affect how much data coverage you have to describe the problem or process you are looking at. If you intend to evaluate a long-term trend in concentrations at a particular location, you may choose to collect measurements every five minutes for an hour, on a different day each week for a year. On the other hand, if you would like to evaluate how concentrations change over the course of a day next to a source location, you may want to collect measurements once every minute for 24 hours over several consecutive days. The more frequently data are collected over a given time period, the more the data's precision increases, because there are more data to cancel out random errors in the measurements. However, there is a point at which collecting data more frequently produces diminishing returns on improving precision and instead gives you too much data to manage (*Williams et al., 2014*).

4.3.9 Data Grouping

Data grouping involves averaging data over time and/or space. Data are often grouped to facilitate comparison to measurements from another instrument, health-based benchmarks, or environmental standards. Data grouping helps improve the quality, usefulness, and manageability of data. The exact type of grouping will depend on the application and the question trying to answer. For example, if you are interested in observing a pollutant concentration trend over the course of a month, you may want to group your data in 1- hour or 24-hour averages. You will be able to see how the concentrations change, but averaging will reduce the amount of data you are working with to a manageable size. On the other hand, if you would like to understand how a plume of gas coming from an industrial facility moves over your community, you may prefer to use a shorter averaging period, such as 1-minute, to capture its movement. (*Williams et al., 2014*)

4.3.10 Interferences

Interferences are factors that hinder, obstruct, or impede the ability of a sensor to make accurate measurements. Specifically, sensor readings may be affected by (*Williams et al., 2014*):

- pollutants or other chemical compounds that are not of interest
- weather conditions (e.g., fluctuations in wind speed, humidity, and temperature)
- radio frequencies
- power fluctuations
- vibration

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- dirt, dust, and insects.

4.3.11 Selectivity

The ability of a sensor to respond to a particular pollutant, and not to other pollutants, is called selectivity (*Williams et al., 2014*). Selectivity indicates how the sensor performs in the presence of other interfering pollutants; for example, the NO2 gas sensor is often sensitive to O3, that means the presence of O3 affects the performance of NO2 sensor, and this is also called as NO2 sensor cross-sensitive to O3 (*Narayana et al., 2022*).

Typical metal oxide and electrochemical sensors suffer from low selectivity. Especially in complex outdoor air these cross-sensitivities impose a fundamental challenge for low-cost gas sensors. Particulate matter sensors are usually not affected by cross-sensitivities because they are intended to detect a composition of different particles. However, in some cases where low-cost particulate matter sensors are either used to detect particles from certain sources like car exhaust or to distinguish different particle sizes, cross-sensitivities are also considered as a fundamental error source. Compared to environmental dependencies, the low selectivity problem is caused by purely chemical inferences and requires more sophisticated calibration efforts. (*Maag et al., 2018*)

4.3.12 Climate Susceptibility

Changing environmental conditions can cause problems that almost any low-cost sensor is facing. Various laboratory reports show that certain physical ambient properties, especially temperature and humidity conditions, can have a serious effect on a sensors response. For instance, increasing humidity is notably decreasing the sensitivity of metal oxide, electrochemical and particulate matter sensors. As a result, low-cost sensors usually perform significantly worse in field deployments than in a laboratory setup. Further, environmental dependencies can also be responsible for non-linear responses, e.g., for electrochemical sensors. (*Maag et al., 2018*)

Climate susceptibility is a measure of an instrument’s ability to endure variation in meteorological conditions, including changes in temperature, humidity, and sun exposure. A sensor is most useful if it can operate robustly in many different environments, but it needs to operate well in the intended use environment at the very least. It is important to consider which sensor is best suited for the climate of the study location and whether the instrument enclosure would benefit from being air-conditioned, or whether environmental effects on the measurements can be corrected after data collection. (*Williams et al., 2014*)

4.3.13 Sensor Decay and Expiration

In general, sensors have an operational lifetime. Operational lifetime can be defined as the time duration that a sensor can work within the prescribed levels of accuracy. Manufacturer provides the operational lifetime on the sensor data sheet. However, there is a lack of credibility on the manufacturer information. When determining the operational lifetime of a sensor it is important to bear in mind that sensors’ operational lifetime depends on the lifetime of internal components of the sensors. The lifetime that is least among the internal components of a sensor is the operational lifetime of that sensor. (*Narayana et al., 2022*).

4.3.14 Drift

A gradual change in instrument response to a constant, quantitative characteristic (i.e., a standard concentration or zero air) is called drift. Instrument drift may lead a user to inaccurately conclude that concentrations have increased or decreased over time. Drift can be positive or negative, and it may occur due to a variety of reasons (e.g. changes in weather conditions, sensor poisoning, or, in the case of optical sensors, to light sources becoming less powerful or less efficient over time). One way to overcome drift is to calibrate the sensor frequently so that the instrument only drifts a small amount between each recalibration. The frequency of calibration needed will depend on how much drift occurs. (*Williams et al., 2014*)

Low-cost sensors generally cannot maintain a stable measurement performance over a long time. This usually happens due to aging and impurity effects, and leads to a slow drift of the sensor's sensitivity. Signal drift is one of the most common error sources and seriously impedes long-term deployments with low-cost sensors. (*Maag et al., 2018*) Identification of unusual drifts in the sensor output and sensor output trend reversal when compared with reference instruments values and continuous outliers also helps to recognize the requirement of sensor replacement prior to the end of operational lifetime (*Narayana et al., 2022*).

4.3.15 Accuracy of Timekeeping

Timestamp accuracy describes the correctness and reliability of the time value recorded as each measurement is collected. Time keeping accuracy is most important when comparisons of measurements made by different instruments are needed. This type of accuracy becomes more critical for comparing data showing large, rapid changes in concentration or data from instruments with high measurement frequencies. (*Williams et al., 2014*)

4.3.16 Data Completeness

The amount of valid data obtained from a measurement system, compared to the amount that was expected to be obtained under correct, normal conditions, is called data completeness. Data completeness is a key to producing high-quality, representative data. Missing data can significantly hinder analyzes, minimizing the strength of conclusions drawn. Commonly, reductions in data completeness are due to data transmission problems; data storage errors; power loss and the time required for subsequent restart; the need for frequent or long-duration calibrations; and time the instrument is offline for repair. For data transmission, if data will be transferred using a wireless connection, the reliability of the connection is very important. Onsite data storage may also be considered so that data are not lost if the wireless connection is interrupted. (*Williams et al., 2014*)

The EU Air Quality Directive (2008/50/EC) includes a requirement to achieve 90% (75 % during winter for fixed measurements of ozone and related NO and NO2) data completeness over the required period of time for fixed and indicative measurements (*Table A of Annex I of the Directive 2008/50/EC*). The requirements for minimum data capture and time coverage do not include losses of data due to the regular calibration or the normal maintenance of the instrumentation.

4.3.17 Response to Loss of Power

This refers to the amount of time that an instrument requires after shutdown to warm up and resume measurement, as well as the consistency of the sensor response prior to and after shutdown. If a sensor requires a large amount of time to warm up and resume measurement after a loss of power, data continuity and completeness can be significantly affected. Once the sensor resumes collecting measurements, its response should ideally be the same as before the loss of power. (*Williams et al., 2014*)

4.3.18 Types of Sensors

There are several categories of sensors available (*Gerboles et al., 2017*)- electrochemical sensors, metal oxide sensors, photo ionization detectors, optical sensors and optical particle counters.

4.3.18.1 Electrochemical (EC) sensors

Electrochemical (EC) sensors used to measure NO2, SO2, O3, NO, CO, are based on a chemical reaction between gases in the air and the electrode in a liquid inside a sensor.

Advantages:

- Medium cost: around 50 - 150 € for a sensor.
- Good sensitivity, from mg/m3 to µg/m3.

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- Fast response time (30-200s).

Disadvantages:

- Highly sensitive to temperature and humidity variations (change in meteorology) depending on electrolyte.
- Selectivity: show cross-reactivity with similar molecule types.

Accuracy (i.e. how well sensor output agrees with that of co-located regulatory-grade monitors) appears to be a strong function of the specific sensor and electronics, the calibration used (i.e. factory calibration vs. one determined by the user), and the environment being studied. In the last several years there has been substantial work aimed at developing calibration approaches mostly developed by co-locating sensors with higher-grade monitors, which include corrections for baseline drift (*Mead et al.. 2013*) as well as various multivariate (e.g. machine learning-based) approaches for decoupling interferences by temperature, relative humidity, and other pollutants (*Cross et al.. 2017; Hagan et al.. 2018b; Malings et al.. 2020; Zimmerman et al.. 2018*). This ongoing work shows real promise for obtaining accurate measurements from EC sensors. (*Peltier et al., 2021*)

4.3.18.2 Metal oxide sensors (MOS)

In a metal oxide sensor (MOS) (resistive sensor, semiconductor) (used to measure NO2, O3, CO) gases in the air react on the sensor surface and modify its resistance.

Advantages:

- Low cost: around 10 - 15 € for a sensor.
- Good sensitivity, from mg/m3 to µg/m3.

Disadvantages:

- Results are affected by temperature and humidity variations.
- Long response time (5 – 50 min).
- Output depends as well on history of past inputs.
- Instability can be observed.

Compared with electrochemical sensors, the cost of MOS sensors is lower, but the sensitivity and performance is lower as well.

4.3.18.3 Photo ionization detector (PID)

A photo ionization detector (PID) ionises volatile organic compounds and measures the resulting electrical current.

Advantages:

- Moderate price: 400 € for a sensor to 5000 € for handled device.
- Good sensitivity, down to mg/m3, some down to µg/m3.
- Limited temperature dependence and humidity effects.
- Very fast response time (few seconds).

Disadvantages:

- Not selective: reacts to all VOCs that can be ionised by the UV lamp.
- Significant signal drift.

4.3.18.4 Optical sensors

Optical sensors used to measure CO, CO2 detect gases like carbon monoxide and carbon dioxide by measuring the absorption of infrared light.

Advantages:

- Moderate cost: 100 – 350 € for sensor to 2000 € for handheld device
- Good sensitivity for CO2 (350 – 2000 ppm)
- Selectivity is good through characteristic CO2 IR spectra
- Response time 20 – 120 s.
- Limited drift over time of the sensor calibration.

Disadvantages:

- Need for correction for the effects of temperature, humidity and pressure.

4.3.18.5 Optical particle counters

Optical particle counters used to measure PM detect particulate pollution by measuring the light scattered by particles.

Advantages:

- Moderate cost: 300 € for a sensor to 2000 € for handled device.
- Fast response time (1 s).
- Sensitivity in the range of 1 μg/m³.
- Able to identify the size of the particle (PM10, PM2.5, etc.).

Disadvantages:

- Conversion from particle counts to PM mass is based on theoretical model.
- The measured signal depends on a variety of parameters such as particle shape, color and density, humidity, refractive index.

There are a large number of particulate matter (PM) sensors on the market. Most sensors report in data in units of ug/m3 but some still report particle counts. The conversion between particle number and mass concentration is not straightforward. PM sensors have progressed over the past 10 years with newer sensors showing better linearity compared with reference measurements. Very small particles (<0.5 µm) are often not detected because the sensors use optical principles for particle detection. Most PM2.5 sensors have response times on the order of a minute or less, but require comprehensive calibrations to make reported concentrations more comparable to reference concentrations (*Feenstra et al.. 2019; Jayaratne et al.. 2020*). Air sensors may over or underestimate concentrations and be impacted by saturation effects, where sensors are unable to quantify about certain high concentration; this varies by sensor model and technology. Most PM10 sensors underestimate concentrations often as a result of low flow rates and poor aspiration which makes it difficult for air sensors to sample coarse particles (*Qin et al.. 2020; Tagle et al.. 2020*). In locales where the coarse fraction of particulate is low and PM2.5 dominates, PM10 sensors can perform well. (*Peltier et al., 2021*)

4.4 DEPLOYMENT OF AIR SENSOR SYSTEMS

Steps involved in the process of deploying (low cost) sensor technology to measure air pollutants are illustrated in Figure 2. The process flow for AQM with LCS is explained in the following steps:

- **Step 1:** Select appropriate sensors for the given set of conditions and applications.
- **Step 2:** Calibrate the selected sensors in a laboratory under controlled environmental conditions at different concentrations of pollutants Once the laboratory calibration is finished, check the performance of the sensors with different evaluation metrics. If the performance (in terms of accuracy or precision) is not satisfactory, then repeat step 1, i.e., selection of sensors; otherwise, go to step 3.
- **Step 3:** Calibrate the sensors in the field and evaluate their performance. Once the field test is completed, they are ready to deploy in real-time in the field. Note: However, some studies have taken direct field evaluation steps without laboratory evaluation.
- **Step 4:** Do frequent post-deployment analysis to check for data quality in real-time, which will help to identify the re-calibration requirement.

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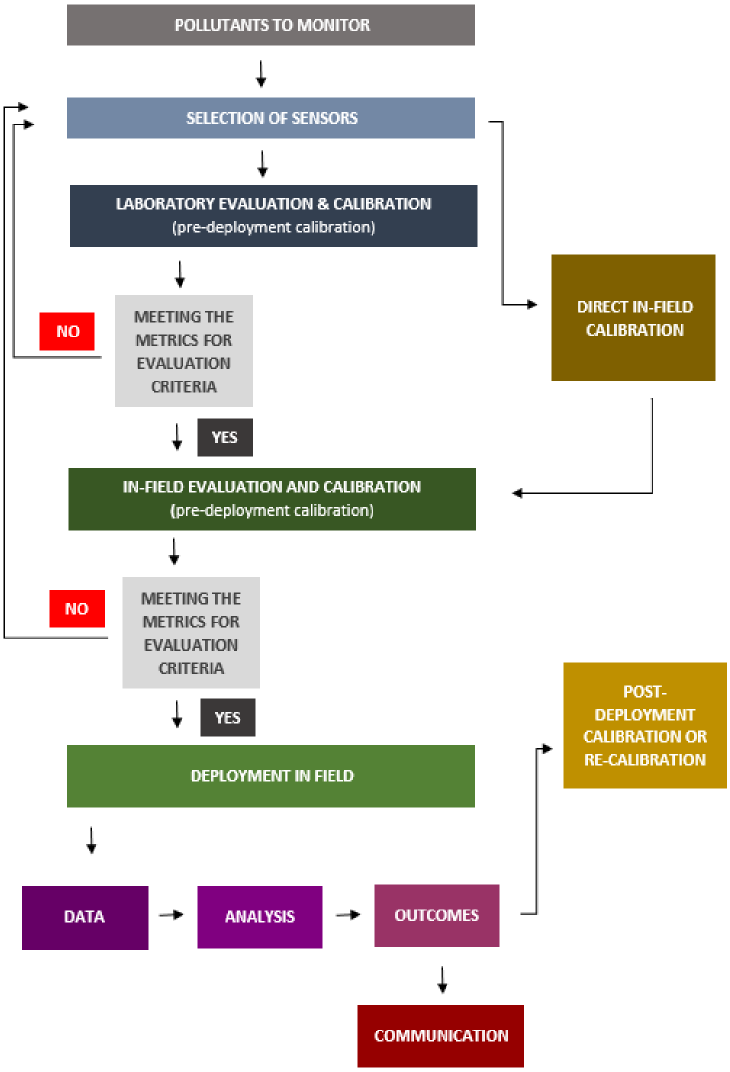
- **Step 5:** Communicate about LCS, LCS data, and information derived from LCS data in an open and transparent way.



Upsurge's air quality sensing system network with proposed deployment scenarios and applications of the atmospheric composition measurements is illustrated in Figure 1 and each concrete step in the process of the sensing system network deployment is discussed in detail in the subsequent sections. Requirements for the quality of data produced and with data quality objectives associated sensor performance characteristics as basis (besides the selection of a target pollutant) for selection of air sensors of Upsurge's air quality sensing system network are, along with approaches for QA and QC of LCS, discussed in subchapter 3.4.1 and 3.4.2. Practical aspects of deployment in field (determining sensor location, GDPR privacy implications for wearable mobile deployments, rules and procedures for the operation of UAV, sensor maintenance) are discussed in subchapter 3.4.3. Establishment of data management system and data processing for the project Upsurge are discussed in subchapter 3.4.1.2.2.3. Elements that need to be considered when interpreting and communicating LCS (and LCS network) data are discussed in subchapter 3.5.

Figure 4: Process flow for AQM (with LCS)
Source: Narayana et al., 2022; EEA, 2019

4.4.1 SELECTION OF AIR SENSORS

4.4.1.1 Selecting a target pollutant

First step in sensor selection is the identification of the pollutant of interest. *Task 2.2* will define the methodology for assessing the NBS performance during the project execution in demo cities in WP 5. As part of this task, key performance indicators (KPIs) for the evaluation of NBS functionality and impact will be defined. KPI list will include, among others, parameters (pollutants) needed to be measured for each one of the specific (air quality) KPIs of interest to be used for the performance evaluation of the NBS implemented in cities.

4.4.1.2 Suggested performance goals

4.4.1.2.1 Data Quality Objectives

As discussed in subchapter 3.2, sensor systems have the potential to be used across specific air quality measurement applications, which can range from those requiring relatively high-performing measurements to informal projects with minimal data quality requirements.

The EU Air Quality Directive (2008/50/EC) indicates that measurement uncertainty shall be the main indicator used for the evaluation of the data quality objective of air pollution measurement methods (*Karagulian et al., 2019*). Additional data quality indicators and associated performance characteristics required for regulatory monitoring and other applications requiring higher data quality are data averaging time and data completeness (*Williams et al., 2014*).

The EU Air Quality Directive (2008/50/EC) provides for the use of "indicative measurements" (i.e. measurements which meet data quality objectives that are less strict than those required for fixed measurements). These measurements can be used to supplement "fixed" (or "regulatory") measurements (i.e. measurements taken at fixed sites, either continuously or by random sampling, to determine the levels in accordance with the relevant data quality objectives) to provide information on the spatial variability of pollutant concentrations. These supplementary measurements have less stringent requirements for data quality. The performance requirements for the fixed and indicative measurements are defined below (*from Table A of Annex I of the Directive 2008/50/EC*):

Type of Measurement	Maximum Uncertainty* Allowable in Pollutant Measurement			
	SO2 , NOx, CO	Benzene	PM & Lead	Ozone
Regulatory (fixed)	15%	25%	25%	15%
Supplemental (indicative)	25%	30%	50%	30%

Table 3: Table A of Annex I of the EU Air Quality Directive (2008/50/EC)

** Note: The EU Air Quality Directive (2008/50/EC) requirements specify a maximum uncertainty, and do not address precision and bias separately.*

The EU Air Quality Directive (2008/50/EC) further on includes a requirement to achieve 90% (75 % during winter for fixed measurements of ozone and related NO and NO2) data completeness over the required period of time for fixed and indicative measurements (*Table A of Annex I of the Directive 2008/50/EC*). The requirements for minimum data capture and time coverage do not include losses of data due to the regular calibration or the normal maintenance of the instrumentation.

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In order for sensor system measurement to be incorporated into the legal framework set by the Air Quality Directive in Europe, they shall satisfy one of the above stated data quality objectives of the Directive. Although, the objective of sensor systems is to provide the most accurate air pollution measurements, it is most likely that the data quality objectives for reference measurements is out of reach while it is believed that by improving the sensor calibration procedures the data quality objectives of "Indicative Measurements" could be met at fixed monitoring sites (*Karagulian et al., 2019*).

With (scientific) environmental verification of NBS being the main purpose of Upsurge's air quality sensing system network (in static and mobile deployments), the relatively high requirements for the quality of data produced and their traceability to reference instruments defined in the EU Air Quality Directive (2008/50/EC) for supplemental monitoring should be striven to achieve. The relevance of the targeted pollutants and the metrological quality of the measurements should be the most important criteria for evaluating sensor systems to be deployed, while other criteria, such as cost (to a certain extent) should be secondary.

4.4.1.2.2 Sensor Characterization for Upsurge's Sensing System Network

With suggested data quality objectives associated sensor performance characteristics (i.e. detection range and detection limit, precision and bias, calibration procedures, and others, each of which was discussed in subchapter 3.3) of Upsurge's air quality sensing system network are discussed in the following subchapters, separately for static and mobile deployments.

Air Quality Station allows you to measure the most relevant pollutants and key parameters required in Upsurge project.

- Particulate matter (PM2.5, PM10)
- Different gases: CO, NO2, NO, O3, SO2
- Weather Station: Wind and compass, precipitation, temperature, humidity and pressure or solar radiation
- Noise Level

Highlighted in yellow in Table 4 are the reference sensors for the Upsurge project. Sensing and characteristics of sensors used for sensing of other environmental parameters, not related to air pollution monitoring, is discussed in detail in chapter 4.

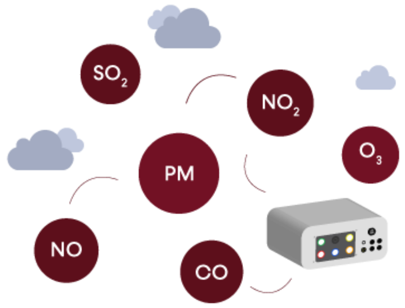

Figure 5: Air Quality Station system design

4.4.1.2.2.1 Sensor Characterization in Stationary Deployment

In static deployments sensors are placed in a fixed place throughout the monitoring period. The sensing systems to be deployed in 5 demonstrator cities are expected to be comprised of at least 2 stationary sensors per demonstration site.

This is a long-term deployment (> 1 year), the purpose of which is observation of key atmospheric composition parameters before and after the implementation of NBS, where quantitative measurements with high data quality and accuracy (as discussed in subchapter 3.4.1.2.1) are needed to capture baselines, trends, and other changes in pollutant concentrations. LCS have finite lifetimes and either fail to function, lose sensitivity, or drift significantly over time, all of which can make present long-term trend analysis difficult. Therefore, it is **recommended that at least 1 of the stationary sensors at each demonstration site is reference instrument** (i.e. one with a certification that comes from an official regulating body and can be associated with a reference method notified in legal drivers). Besides being able to measure air pollutants for regulatory compliance purposes and for measurements to be incorporated into the legal framework set by the Air Quality Directive (2008/50/EC) in Europe, reference instrument at demonstration site would ease in field co-location in terms of logistics. If this is (economically, or because of other reasons) not feasible, high quality LCS with performance characteristics, evident from Table 4, are recommended. It should be noted that **larger networks of LCS may be able to discern long-term trends and can be an important source of information, provided that the appropriate sensor system is used, and calibration and quality control routines are in place.**

Table 4: Recommended LCS performance characteristics

Parameter	Range	Accuracy
Temperature	-40 to +85 ºC	Calibrated ±1 ºC (±0.5 ºC at 25 ºC)
Humidity	0 to 100% HR	Calibrated ±3% RH (at 25 ºC, range 20 ~ 80% RH)
Pressure	30 to 110 kPa	Calibrated ±0.1 kPa (range 0 ~ 65ºC)
Carbon Monoxide for high concentrations (CO)	0 to 500 ppm	Calibrated ±1 ppm
Carbon Monoxide for low concentrations (CO)	0 to 25 ppm	Calibrated ±0.1 ppm
Carbon Dioxide (CO2)	0 to 5000 ppm	Calibrated ±50 ppm (range 0~2500 ppm) ±200 ppm (range 2500~5000 ppm)
Molecular Oxygen O2	0 to 30%	Calibrated ±0.1%
Ozone (O3)	0 to 18 ppm	Calibrated ±0.2 ppm
Nitric Oxide for low concentrations (NO)	0 to 20 ppm	Calibrated ±0.2 ppm
Nitric Dioxide (NO2)	0 to 20 ppm	Calibrated ±0.1 ppm
Sulfur Dioxide (SO2)	0 to 20 ppm	Calibrated ±0.1 ppm

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Ammonia for low concentrations (NH_3)	0 to 100 ppm	Calibrated ±0.5 ppm
Ammonia for high concentrations (NH_3)	0 to 500 ppm	Calibrated ±3 ppm
Methane and other combustible gases (CH_4)	0 to 100 % / LEL	Calibrated ±0.15 % LEL
Molecular Hydrogen H_2	0 to 1000	Calibrated ±10 ppm
Hydrogen Sulfide H_2S	0 to 100 ppm	Calibrated ±0.1 ppm
Hydrogen Chloride HCl	0 to 50 ppm	Calibrated ±1 ppm
Hydrogen Cyanide HCN	0 to 50 ppm	Calibrated ±0.2 ppm
Phosphine PH_3	0 to 20 ppm	Calibrated ±0.1 ppm
Ethylene Oxide ETO	0 to 100 ppm	Calibrated ±1 ppm
Chlorine Cl_2	0 to 50 ppm	Calibrated ±0.1 ppm
Particle Matter – Dust	0.35 to 40 μm (24 steps) (includes PM1, PM2.5 and PM10)	Calibrated
Noise Level	50 dBA to 100 dBA	Calibrated ±0.5 dBA (1 kHz)

Performing laboratory calibration is not foreseen in the project, however it is recommended that laboratory calibration of LCS is performed by manufacturers. As already discussed, laboratory calibration alone is not enough to deploy sensors in real-time, as it does not reflect all the characteristics of a specific location that they will be deployed. Hence, in-field calibration is a necessary step following laboratory calibration. Long-term calibration of sensors is challenging for several reasons (*Peltier et al., 2021*):

I. Some of the measured pollutants (including O3, VOCs, PM, and NO2) have seasonal characteristics in nature, exhibiting clear profiles that vary with season. As a result, **sensor performance is improved if calibration exercises are performed across different seasons.**

II. For long-term monitoring, **weatherproof is a necessary consideration** to avoid interference of weather conditions for such applications. The needed frequency of evaluation to ensure data quality in different real-world conditions is an area of active research. The possibility of in-situ calibration by machine learning techniques or other data analysis methods are currently explored by the research community (*Delaine et al.. 2019; Maag et al.. 2018; Smith et al.. 2019*)

III. Environmental factors vary greatly with the season, which presents **challenges to the calibration algorithm.** Seasonal variability in factors, such as temperature or relative humidity, can play a critical role in sensor performance, with different environmental variables impacting sensor performance across the range of encountered conditions. A number of efforts have been made in literature to develop methods for correcting the environmental conditions and improving the long-term performance of LCS. For example, *Peng et al. (2020)* designed a look up table (LUT) as a function of temperature interval to improve the sensor data quality in the long-term measurement covering different seasons. The method is a principle-based algorithm built on the known impact of temperature on sensor sensitivity and baseline. The comparison with multiple linear regression method and machine learning methods shows it produces significantly improved performance for sensors in long-term deployment.

IV. The lifetime of low-cost gas sensors is relatively short, generally on the order of one or two years, which makes them unable to perform over the long-term. Thus, **replacement sensors are needed** in any long-term monitoring, and these require **repeated calibration** (*Malings et al.. 2020*). Best practices for reference monitoring replacements usually require substantial collocation and overlap between new and old instrumentation. The amount of time requires likely varies substantially across measured constitution, technology used, and the heterogeneity of the environment to be sampled.

V. The generation of particulate matter is more difficult than that of standard gas, and the evaluation of particulate matter sensors is usually realized by running in parallel with standard instruments in the field environment. Recent studies have also focused on long-term assessments of particulate matter sensors performance with seasonal impact and PM episodic events, such as winter cold air pools, fireworks, and wildfires (*Bathory et al.. 2019; Liu et al.. 2019*), finding that particle size selectivity may play an essential role in the sources of errors (*Kuula et al.. 2020*) and the long-term field performance is driven by size distribution and chemical composition of the factory calibration aerosol and the ambient aerosol (*Malings et al.. 2020*).

4.4.1.2.2.2 Sensor Characterization in Mobile Deployments

Mobile monitoring applications encompass all situations in which a subset or all devices in a deployment are not static. Mobile sensing systems to be implemented in 5 demonstrator cities will be using different mobility vectors including private citizens, bicycles, public transportation vehicles and unmanned aerial vehicles, in order to increase the spatial coverage of the sensor network. Mobile sensing devices will present a complementary solution, which will be implemented in the following ways:

A. <u>Creating citizen infrastructure</u> comprised of at least 100 citizens per demo location to monitor pollution and environmental conditions that users are exposed to in their daily lives
B. <u>Creating transport-based moveable sensing units</u> - 5 in each demo location by installing sensing devices on periodically moving transport modes geographically connected to implemented NBS locations with careful consideration to their properties in order not to distort the results
C. <u>Creating unmanned aerial vehicle (drone, UAV) moveable sensing units</u> - 5 mounted sensors on unmanned aerial vehicles at each demo location to study the higher dimensional air pollution profile (horizontal and vertical directions).

The use of mobility sensors implies a number of challenges for both system implementation and evaluation.

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Besides meteorological performance metrics (e.g. drift, sensitivity, precision, etc), the **portability, energy source, and form factor of the device (i.e. volume and mass) should be considered for devices targeting mobile applications.**

The **sensor response time** is an important metrological metric in in mobile deployments. Electrochemical and metal oxide sensors have response times that range from tens of seconds to multiple minutes. While for static deployments, this issue can be largely neglected, for mobile sensing systems it can induce significant distortion of the measured signal with respect to the underlying concentration levels. The severity of the distortion will vary depending on the speed of the mobile platform (*Arfire et al.. 2016*) and will need to be evaluated. The **sensitivity of electrochemical sensors to variations in relative humidity** can also be a challenge for mobile measurements that include various different types of environments (e.g. both indoor and outdoor). For all low-cost sensor systems used for mobile applications (i.e. including PM sensors), special care needs to be given to the **design of the air sampling system** to reduce performance degradation due to poorly controlled flow conditions. (*Peltier et al., 2021*)

Very **frequent calibration** is needed in case of mobile deployments due to sensor exposures to various environments, introducing different bias values in the calibration model.

In terms of the evaluation protocol, the reference material to which the sensor systems will be compared should ideally be mounted on the same test vehicle. Rendezvous comparisons with static stations could be interesting for a cross-analysis but would generally be impractical to obtain reliable statistics. This aspect presents a challenge in itself as not all reference material can tolerate mobility. (*Peltier et al., 2021*)

Non-linear calibration models are more feasible for wearable LCS debhujumn bvices. In case of UAV equipped with LCS turbulence effect on sensor inlet airflow, electronic interference from drone operation, changing pressure values with altitude, vibrations, tilting of sensors during the flight are possible additional errors. As already mentioned, collocated data of LCS and reference devices are needed for calibration, which is impossible here since carrying heavier reference equipment on drones is not feasible. Limited studies have explored the usage of LCS on drones and reported inaccuracies. Since there are additional error sources mentioned above, the calibration methods explored so far may not be applicable in the case of UAVs. **The inclusion of additional error sources while calibration and advanced sensors resilient to vibrations and electronic interference can be a better choice for UAV applications**. (*Narayana et al., 2022*).

Mobile sensors require higher temporal resolution to represent more accurate spatial locations, which means that the data set of mobile sensors is larger and more complex. The implementation of sensors on mobile platforms can, however, lead to a significant degradation of the sensor's performance, depending on the underlying sensor technology, but also on its integration within a sensing system. Therefore, **careful data analysis methods** are very important in the application of mobile sensors. (*Peltier et al., 2021*)

4.4.1.2.2.3 Data Management System and Data Processing

OPERATE is responsible for establishment of data management system and data processing for the project Upsurge.

4.4.1.2.2.3.1 Introduction

The data transmitted by IoT devices is critical to air quality monitoring research, such as in the context of analysing patterns and understanding trends affecting air quality. Generally speaking, both IoT and cloud solutions should act in support to data capture infrastructure with real-time control and intelligence monitoring capabilities.

4.4.1.2.2.3.2 Choosing the provider

Fixed monitoring stations measure air quality to extremely high levels of accuracy, with some gases measured in parts per billion (ppb). In our analysis we detected a few different IoT providers sporting an open or proprietary cloud platform to interact with. Please note that in general IoT devices are focused on offering one or more sensors.

System requirements needed include:

- The ability for a third party to collect data, ideally from a sizeable pool of devices;
- Storing capabilities; and lastly
- Data analytics: these include techniques and processes to convert raw data into valuable information and visualize the processed data.

The figure below illustrates the two different approaches we took into consideration:

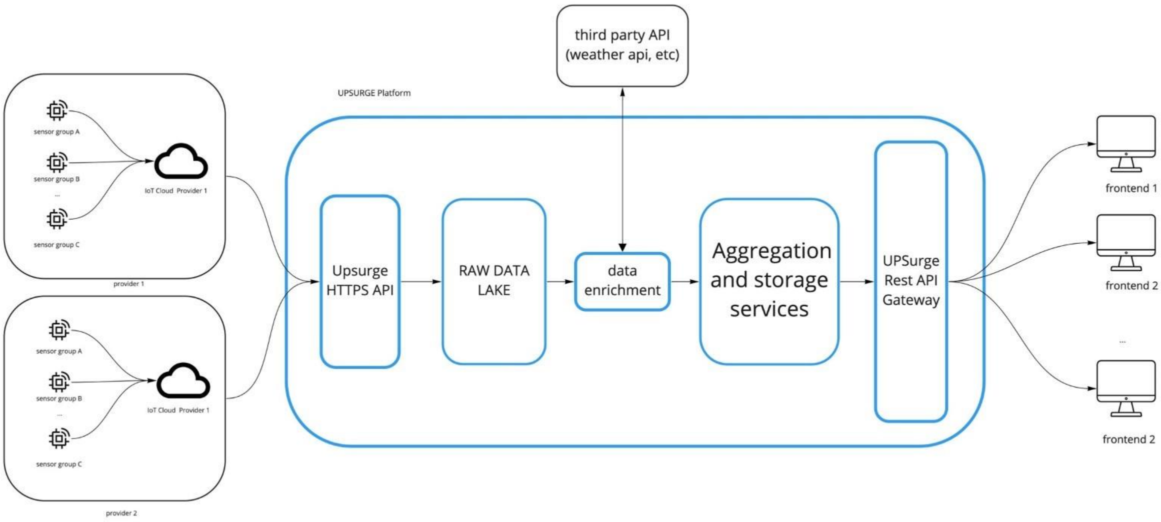

Figure 6: Different approaches in choosing the IoT provider

Solution has proven to have the following advantages:

- Lower integration cost – As we have to talk to one platform only.
- Lower integration time - For the software development connecting both platforms share the same development time.
- Lower monitoring costs and time - For data has only one single source of truth and follow one flow (that is, from the provider to Operate's cloud platform)

4.4.1.2.2.3.3 Data flow

Once the provider in near real-time relays the data to our platform, Operate cloud must be able to support:

- Saving raw data (data lake layer)
- Data cleaning and adding metadata to IoT data

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- Enrich raw data with third-party data such as weather data (more have to be defined)
- Data aggregation, such as organising data insights and data time series (aggregation layer)
- Exposing the data via web services (API layer)

4.4.1.2.2.3.4 Co-location and calibration against Reference Station

Even when LCS are factory calibrated, a calibration model should be applied to further optimize for local conditions and pollutant profiles to obtain the most accurate measurements. Researchers have found that the main challenge for a large majority of LCS air quality monitoring projects is developing appropriate calibration models to ensure data quality that’s why in Upsurge Project we perform Remote Calibration as part of our Sensing-as-a-Service model.

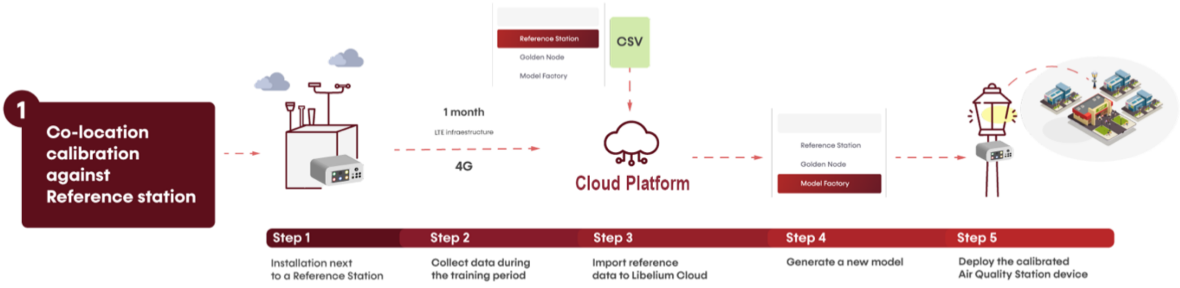

Figure 7: Process flow for in field co-location

Step 1: Co-location phase: Air Quality Station will be deployed next to the reference station to collect data for 1 month. This is needed in order to calibrate Air Quality nodes against scientific reference stations.

Step 2-3: Data from the Reference station will be sent to Cloud through a CSV file. Meanwhile, all data gathered by Air Quality Station has been collected in the cloud.

Step 4: Then the calibration process starts in the Model Factory section from our Cloud. This is where Artificial Intelligence takes part, allowing the user to start predictive models.

Step 5: Once the Air Quality Station node has been calibrated and trained it is ready to be deployed.

4.4.1.2.2.3.5 Baseline Data Collection and Requirements

In the context of NBS, the establishment of a baseline involves collecting a set of data that allows the description of the geo-morphological, socioeconomic conditions, living standards and livelihoods of NBS project-affected communities and their potential hosts prior to any NBS intervention. Those data will be used as a reference for monitoring the impacts of the NBS on the involved territories, thus allowing a comparison between the pre-project implementation state of play and the post-project implementation situation. *(EC, 2021)*

For physicochemical constituents, the baseline conditions should ideally be established prior to NBS implementation. As pollutant concentrations may vary significantly depending on the season, **a one year pre-demostration implementation monitoring period is recommended.**

In cases when the baseline measurements are not available, **a site with similar conditions could be employed as a “proxy baseline”.** The latter approach naturally has its limitations in the representativeness as the reference site will not have the same exact conditions, and the results may be biased. Special regionalization methods could be employed to minimize the representativeness issues (e.g., selection of multiple sites with available measurements having similar characteristics to the NBS implementation site, in order to have a more representative sample). **Spatial data can be employed for assessing the baseline conditions when combined with in situ measurements.** However, historical and statistical datasets may have variable spatial and temporal resolutions, and they may not be consistent within a single urban area. **Data aggregations or modifications may be necessary to overcome these challenges in applying the available datasets for pre-NBS baseline establishment**. (EC, 2021)

If baseline data need to be reconstructed, there are several approaches which can be used to achieve a discreet result (Bamberger, 2010):

• Secondary data: checking documentary sources, such as annual reports of governmental agencies;

• Administrative data: feasibility and planning studies made prior to an intervention on a specific territory, monitoring reports, application / registration forms, etc.;

• Recall: technique based on surveys or individual / group interviews, particularly useful for recalling major events or impacts of a new service (including ecosystem service), albeit subject to biases;

• Key informants: in-depth interviewing and involvement of external stakeholders (representatives of a society or a specific target group) that combine “factual” information with a particular point of view.

However, no data collection method is free from the possibility of inaccuracy. Due to this, the above-mentioned methods, and especially the ones relying on surveys and interviews, are usually accompanied by the Triangulation method, which allows to verify the results against data collected from other sources, to confirm accuracy and precision of the reconstructed baseline. *(EC, 2021)*

Possible lack of baseline data due to shorter pre-demonstration implementation monitoring period than recommended and details about pre-NBS baseline establishment/reconstruction should be communicated. Data collection and processing in the evaluation of the KPIs for each one of the demos, performed by partners in charge of monitoring air quality and other parameters defined in *Task 3.3*, considering the data collected before and after the implementation of the NBS, should be described and considered in the environmental NBS functionality assessment of collected data *(Task 6.1)*.

4.4.1.2.2.4 LCS Evaluations

Many different organizations have LCS performance evaluation programmes in place, all seeking to evaluate in quantitative terms how LCSs compare to reference measurements in laboratory and ambient field sampling conditions (e.g. the Air Quality Sensor Performance Evaluation Center (AQ-SPEC), the European Union Joint Research Centre (EU JRC), the United States Environmental Protection Agency (US EPA), AIRLAB). The results of the sensor evaluation programmes can be viewed on their websites. Complementary to this, a number of projects have demonstrated the use of sensor systems for a variety of applications. EU JRC has done an exhaustive review of existing literature on LCS evaluation and issued a report presenting the collected results of quantitative studies of the performance of low-cost sensors against reference measurements (*Karagulian, F., Gerboles, M., Barbiere, M., Kotsev, A., Lagler, F., Borowiak, A., Review of sensors for air quality monitoring, EUR 29826 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-09255-1, doi:10.2760/568261, JRC116534*). As already mentioned, the EU Air Quality Directive (2008/50/EC) indicates that measurement uncertainty shall be the main indicator used for the evaluation of the data quality objective of air pollution measurement methods. However, the evaluation of this metric is cumbersome and it is not included in the majority of sensor studies. For the performance criteria used to evaluate air quality modelling applications, the set of statistical indicators includes the Root Mean Square Error (RMSE),

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the bias, the Standard Deviation (SD) and the correlation coefficient (R), of which RMSE is thought to be the most explicative one. Authors of this work therefore had to rely on the most common metrics, i. e., the coefficient of determination R^2, the slope and intercept of linear regression line between LCS data and reference measurement. R^2 can be viewed as a measure of goodness of fit (how close evaluation data is to the reference measurements) and the slope of the regression as level of accuracy. R^2 measures the strength of the association between two variables but it is insensitive to bias between LCS and reference data, either relative bias (slope different from 1) or absolute bias (intercept different from 0).

Although there are reviews published in the scientific literature, there is still not a standard protocol for comparing and evaluating the agreement between sensor systems and reference observations. There is a European joint effort to create standards (*CEN/TC 264 Air Quality-Performance evaluation of air quality sensors-Part 1: gaseous pollutants in ambient air and Part 2: Performance evaluation of sensors for the determination of concentrations of particulate matter in ambient air*). This ongoing work on the calibration of sensor systems led by the European Committee for Standardization (CEN) could lead to a standardisation and approval procedure for sensor systems and this may then be translated into requirements for manufacturers that can lead to improvements in data quality (*EEA, 2019*).

It is though important to note that the field of low-cost sensors is rapidly evolving: new generations of sensors are released regularly by manufacturers, and approaches for sensor characterization and data analysis are continually being improved upon. Nonetheless, the key points discussed (the need for calibration, correcting for interferences, and monitoring long-term drift) are likely to remain important considerations for the foreseeable future. (*Peltier et al., 2021*)

4.4.1.2.2.5 Other Considerations in LCS Selection

Another important consideration when selecting the sensors is that price of sensor systems can vary depending on the number of sensors included (i.e. geophysical variables measured), the quality of the electronics and housing, and also the extended services (e.g. web visualization, data treatment, user support). Despite all units on the market are sold for significantly lower prices than reference analyzers, there are large price differences between them. Moreover, it is important to note that the life of the sensing component is about 1–5 years, and it is not always possible to replace the sensing component without replacing the full sensor system. Thus, **when evaluating the cost of sensor systems, it is important to consider both the expense of the initial purchase of the sensor system and then the (usually) considerable ongoing costs of operation, including power, servicing, data processing, calibration and data quality assurance.** While comparing the cost of the sensor system with a reference one, the sensor lifetime and the total cost of the continuous update of the system during the typical lifetime of the reference system (with a one-time investment) should be taken into consideration (*Peltier et al., 2021*).

Deployment of LCS in a network requires more advanced planning, and additional maintenance and operations costs. Users may need to establish data management systems. If devices are owned by a user, but maintained or operated by a third-party institution, there may be meaningful post-processing costs required for a vendor to convert raw data to finalized data prior to delivery to the owner. There are a number of business models which seek to provide these services as costs to a user (*Peltier et al., 2021*): for example, there are different models in which an individual can purchase a sensor and integrate its data into his own data management system, another where you can purchase a sensor that is delivered with its own data management system, as well a third where everything is provided in a 'sensors-as-a-service' framework. Each model has advantages and disadvantages. Proposed models for the project Upsurge are discussed in detail in subchapter 3.4.1.2.2.3.

4.4.2 QUALITY ASSURANCE AND QUALITY CONTROL

LCS are in many ways different from reference instruments and therefore require adoption of new and different approaches for quality assurance (QA)/quality control (QC) to those currently used for the measurement of air pollution and greenhouse gases using reference instruments**. It is however important that the data processing performed during QA/QC of LCS is transparent and properly documented.** Peltier et al., 2021 defines and explains the terms of QA and QC in following way:

Quality assurance as the process of ensuring that the data arising from a sensor is consistent with the same data arising from a known standard measurement is usually performed using calibration techniques.

Quality control is the act of monitoring the long-term performance of a LCS during deployment in a sensor network to ensure it remains in calibration, and can help notify the appropriate party when a LCS needs to be corrected or removed and undergo re-calibration, likely when the bias exceeds the measurement uncertainty. It is an assessment of whether or not a sensor is performing in a manner consistent with its requisite design for data quality and is an assessment of sensor performance. Quality control is also the method for determining end-of-life for a sensor. Several approaches to quality control have been proposed in the literature:

One approach is to periodically compare the values obtained with a LCS to a nearby (but not co-located) reference monitor (*Mueller et al.. 2020; Mueller et al.. 2017*). In locations throughout Europe reference data are made available by regulatory agencies and can be accessed either through their websites or via public groups such as OpenAQ (*https://openaq.org/#/*). However, it is important to be aware of possible limitations with this approach, since the concentrations of gases and particles may vary significantly near sources and sinks, even over modest spatial lengths of a few meters, and thus these efforts should be viewed as quality control activities designed to evaluate a sensor's performance to produce quality data, and not specifically a measurement of concentration differences.

A second approach is to use knowledge of regional atmospheric chemistry in combination with a small number of anchor points (reference stations) to perform remote calibrations (*Kim et al.. 2018*). Similarly, statistics-driven quality control checks based on transport phenomena could provide information on relative differences amongst sensors within a localized network. However, the use of regional chemistry models can also lack the necessary spatiotemporal granularity to sufficiently eliminate uncertainty.

A third approach may include the establishment of 'mission-specific' platforms designed for routine and periodic calibration activities. These can be employed either in a centralized location where LCS are returned for regular performance assessment, or they can be employed in a mobile setting, where reference instrumentation could be brought on site.

Table 5: Sample Table of Common QC Checks; Source: EPA, 2022

QC Check	Description
Units	Check that the sensor reports data in the correct units of measure.
Time	Check that the sensor reports data at the correct time and in the right time zone. Check times after any seasonal time changes (e.g., daylight savings time).
Timestamp	Determine the timestamp, which is the time when data are stamped (i.e., tagged) by an instrument. Measurements and data averages will have times that either represent the beginning of the time period (time beginning) or the end of the period (time ending).
Matching Timestamps	Check the time zones and timestamps for each dataset to make sure they are similar when comparing measurements made by different instruments.
Data Review	Check data frequently (e.g., daily, weekly) to detect problems early, identify trends in the data, ensure that maintenance activities were completed, and become familiar with recurring patterns.

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Data Completeness	Completeness measures the amount of data a sensor collects compared to the amount of data that was possible to collect if the sensor operated continuously, without data outages, during a period (e.g., 1-hour, 1-day). A 75% completeness level is a useful criterion to meet as the averaged data is generally representative of that time period. For example, at least 45, 1-minute measurements are needed to make a valid 1-hour average at 75% completeness.
Automatic Data Checks	Software can check data for problems and outliers. Check your data management system for these and other data checks. Note that some data checks may not catch subtle problems (e.g., a gas sensor degrading and slowly losing its response) or may flag an infrequent event or very high concentrations (e.g., high PM2.5 concentrations from wildfire smoke) as bad data. Do not solely rely on automatic QC to check data quality; always do frequent manual data reviews.
Manual Data Validation	Evaluate the data quality during the collection phase of the project to identify Validation and correct potential problems that may arise. To accomplish this, analyze data to identify seasonal, day/night, and weekday/weekend patterns and weather changes. An absence of expected patterns may indicate a problem with the sensor or with the measurement approach.

Exact approaches for QA and QC of LCS to be adopted in each of the five demonstrator cities will be defined in Deliverable D.3.2 "Tailor-Made Plans for Operation of Sensing Systems at Demonstration Cities".

4.4.3 Deployment in Field

4.4.3.1 Determining Sensor Location

4.4.3.1.1 General Location

Carefully locating the sensors plays a significant role in determining whether the data collected are representative and useful.

Many pollutants have high spatial variability, that is, their concentration varies over long or even short distances. Concentrations for most pollutants will almost always be highest near the source, and will decrease rapidly within the first hundred meters of the source. If multiple sources are widely distributed within a given area, pollutant concentrations may be more similar but will still experience change from location to location. Other factors also influence the concentration variability of a given pollutant (*Williams et al., 2014*):

- **Pollutant type:** primary pollutants are often more localized (i.e. near the source) and may have a greater variability over distances than secondary pollutants; whether a pollutant comes from man-made or natural sources (or both) is also an important consideration: while measurements typically focus on man-made sources of pollution, all known sources should be considered - pollutants coming from unknown sources can compromise the utility and accuracy of conclusions drawn from data;
- **Wind and local atmospheric conditions** (including sunlight, temperature, humidity and clouds): e.g. stagnant air can lead to pollutant concentrations that gradually increase, whereas strong winds can decrease concentrations by spreading pollutants over a larger geographic area.

To ensure these results are as accurate as possible, a sensor or instrument should be placed in a location where it can measure the atmosphere or source of interest with minimal interference. A well-placed site would yield data that are representative of the area being monitored. (*Williams et al., 2014*)

To answer the question what the air quality is in demonstration sites and how implemented NBS in demonstration sites impact air quality, a site that is representative of the demonstration area needs to be selected. A sensor used for environmental verification of NBS should not be placed in an area in demonstration site near a very localized source like a smoking station that will impact only a small area intermittently. Rather, a sensor should be in an area in demonstration site that is exposed to air from many directions to capture the influence of many possible pollutant sources. It should be located so that its pollution level is influenced by the integrated contribution from all sources upwind of the sensor. The pollution level should not be dominated by a single source unless such a situation is typical for a larger demonstration area. Those sampling points shall, as a general rule, be representative for several square kilometres. [6]

Exact locations of stationary sensors and mobile (on vehicles, wearable, on UAV) deployment routes (together with agreed measurement frequencies) will be determined in Deliverable D.3.2 "Tailor-Made Plans for Operation of Sensing Systems at Demonstration Cities".

4.4.3.1.2 Other Key Logistical Considerations and Recommendations for Determining Sensor Location[7]

Access: Although easy to use, air sensors are generally not something you can "set and forget." Access to site to install and periodically check on the sensors is needed. If the user doesn't control the site, permissions, access requirements, and any limitations on access frequency or timing need to be determined during the planning stage. Formal access agreements can be helpful in explicitly laying out these conditions.

Power: Air sensors may need to be plugged-in, may have solar panels, or may offer both options. Some sensors that offer power options may operate differently depending on which option is used (e.g., the data reporting frequency may change). Sensor manufacturer needs to be consulted to understand the implications. It can be expensive and time consuming to deliver power to a location that does not have the existing infrastructure. Extension cords may be needed for optimal sensor placement. Solar panels may not be adequate if the location does not get enough sun and they will need periodic maintenance to remove dust. Areas that experience public safety power shutoffs may benefit from solar power to prevent monitoring interruptions.

Communications: Sensors may communicate data to a cloud-based interface using a variety of technologies (e.g., cellular, WiFi, LoRa). Some may offer just one option, while other sensors may provide multiple options. Manufacturer needs to be consulted to understand specific requirements such as network limitations (e.g., 2G, 5G), carrier limitations, area coverage, and signal strength needs. If supplying your own mobile hotspot, you may also want to know the typical data use and if the sensor settings can be adjusted to reduce data use.

Security: Sensors and their peripheral equipment (such as solar panels) are subject to tampering and theft. Users will want to consider placing sensors in secure locations. Ideas include mounting a sensor overhead out of arms reach, in an inconspicuous location, or behind a locked gate or fence. When considering secure locations, the fact that that sensors need a free flow of air should be kept in mind, and physical safety when visiting the area or even while climbing a ladder or stepstool for installation or maintenance should be considered as well.

Placement: It is ideal to place sensors near the typical breathing zone height (1 – 2 m). Sensors should be placed away from pollutant sources (e.g., fire pit or grill) or pollution sinks (e.g., tree or shrub barrier) to get a more representative measure of air quality. Sources of gases that can react with the pollutant of

[6] See also macroscale siting criteria for urban (background) station defined in Annex III and Annex VIII of The EU Air Quality Directive (2008/50/EC)

[7] US Environmental Protection Agency, https://www.epa.gov/air-sensor-toolbox/guide-siting-and-installing-air-sensors, accessed 15 March 2022

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interest should be avoided. (e.g. ozone is depleted very quickly by certain organic compounds, as well by nitric oxide from tail pipes). Sensors should also be located to allow for free air flow to the sensor. Placement near high voltage power lines, which may create electronic interferences, should be avoided. The inlets to wearable sensors should have access to the air the person is exposed to. For example, a personal exposure sensor will not make representative measurements if kept in a purse or pocket. Inlets for personal samplers can be close to person's body or clothing as long as they are sampling air outside person's clothes. PM is a special case, since clothing is a source of PM.

Top five considerations for setting up an outdoor sensor:

1. **Site away from pollution sources or sinks:** Consider what sources or sinks may be impacting your sensors. Hyperlocal pollution sources may release brief, but high concentrations of pollutants, which may be interesting but can complicate measurement and interpretation of the local air quality conditions. Hyperlocal pollutant sources can include dusty roads, barbecue grills, smoking areas, or building exhausts. Pollutant sinks are localized places where pollutant concentrations are lower because of chemical reactions (e.g., ozone reacting with vegetation) or deposition (e.g., particulate matter being filtered by trees).
2. **Allow free air flow around the sensor:** Sensors need to have free air flow to measure the pollutant. Buildings, fences, trees, plants, and other equipment can prevent the free movement of air and can cause pollutant measurements to be biased or noisy. The sensor’s user guide or manual may describe where air enters and leaves the unit and these openings must not be blocked, even partially.
3. **Install about 1-2 m above ground:** Often sensor users are interested in understanding a person’s exposure to air pollution and that is best measured by placing the sensor near where a person might breathe. Users may wish to install a sensor at a slightly elevated position (above 2m or nearly out-of-reach) to provide additional security or at slightly lower positions to provide easy access. Sensors should be placed at least 1 m above ground to protect the sensor from splashing water and other ground effects.
4. **Keep away from structures:** As previously mentioned, structures like buildings or fences can prevent free air flow to the sensor. But, for some pollutants, nearby structures may also serve as a sink by reacting with or filtering out the pollutant of interest. Sensors near these structures might report lower pollutant concentrations than in the surrounding area.
5. **Look for sites that support your needs:** The infrastructure needed to mount, power, operate, and secure a sensor will largely depend on the make/model of the sensor and its features. Be sure to consider the power and communication (e.g., WiFi, cellular) needs of the sensor and the distance or range it must be from these services. Finding a site that can fill all of these needs is often cheaper than finding a way to provide them yourself. Security concerns not only include keeping the equipment and data safe but also your physical well-being when installing or checking on equipment.

4.4.3.1.3 Sampling Site Evaluation

After placing the sensor, taking some preliminary measurements is advised. Review of the captured data can help to determine if the site is representative of local area conditions or may be impacted by a hyperlocal source or environmental conditions. Some suggestions include[8]:

- Create and review a time series of data (concentration vs. time) using the highest time resolution possible (no data averaging).

[8] US Environmental Protection Agency, https://www.epa.gov/air-sensor-toolbox/guide-siting-and-installing-air-sensors, accessed 15 March 2022

  - Does the graph show spikes? This could be indicative of a hyperlocal source like smoking or cooking.
  - Are spikes routine? This could be indicative of a cyclic operation like an air conditioning fan turning off and on.
  - Are spikes random? Spikes may also be caused by fluctuations in the power supply to the sensor.
- Average the sensor data to hourly or daily averages and compare it to a nearby regulatory station or several other sensors. Nearby regulatory monitors can be found on OpenAQ (https://openaq.org/#/).
  - Do the long-term air pollution trends agree? Some sensors do not report accurate concentrations so, when making this comparison it is more important to identify if the sensor concentration increases and decreases along with the nearby monitors. If not, the sensor may be influenced by a hyperlocal source or nearby structures.

If the data review suggests that any of these scenarios are impacting the measurements, sensor should be relocated. Re-visiting this analysis periodically is advised as sites may change over time (e.g., traffic patterns change, trees grow).

4.4.3.2 Legal Considerations

Although participatory sensing systems provide novel opportunities in terms of sensing, they can put the privacy of the participants and end users at stake. Most applications collect spatiotemporal information about the participants. This information is usually used to annotate the collected sensor measurements in regards to pollution. As a result, they can provide a wealth of insights about the participants, ranging from their current context to their behaviour. The sensor readings themselves may also reveal sensitive information about the contributing participants. Even end users who query application results may disclose their current location and potential interests. *(Delphine, 2016)*

Data protection is both a central issue for research ethics in Europe and a fundamental human right (*EC, 2018*). The protection of personal data (POPD) is an essential part of the ethics requirements for projects funded from the H2020 framework. The UPSURGE consortium partners regard privacy and data protection as a fundamental principle and hence apply a strict policy on this matter. They will adhere to the provisions set out in the Regulation (EU) 2016/679 - General Data Protection Regulation (GDPR). The management of the POPD process in the implementation of project UPSURGE is described in detail in Deliverable 9.1 “Protection of Personal Data Requirements no. 3”. Particular points of GDPR privacy implications for wearable mobile sensor deployments in the project implementation and for the follower cities will be set out in subchapter 3.4.3.2.1.

Rules and procedures for Unmanned Aircraft Systems (Regulation (EU) 2019/947 and Regulation (EU) 2019/945) are discussed in subchapter 3.4.3.2.2.

4.4.3.2.1 GDPR Privacy Implications for Wearable Mobile Deployments

In article 4(1) of the GDPR personal data are defined extremely broadly and include any information relating to an identified or identifiable natural person. An identifiable natural person, or data subject, is one who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person. Data processing includes any operation or set of operations which is performed on personal data or on sets of personal data, whether or not by automated means, such as collection, recording, organisation, structuring, storage, adaptation or alteration, retrieval, consultation, use, disclosure by transmission, dissemination or otherwise making available, alignment or combination, restriction, erasure or destruction (Article 4(2) of the GDPR). Article 5 of the GDPR lays down the guiding principles to be observed during personal data processing: lawfulness, fairness and transparency; purpose limitation; data minimisation; accuracy; storage limitation; integrity and confidentiality; and accountability. As participatory sensing applications involve processing data about identifiable persons (spatiotemporal information) compliance with EU (and national) data protection laws is demanded.

The basic rule should be applied and given to participants in wearable mobile sensor deployments absolute right to privacy and to the protection of their own personal data. Data that participants will give to a research collection should be treated such and accessible only by individual researchers involved. The recruitment of participants should be made on a strong voluntary basis and following the participants interest/willingness to participate in the sensing projects' activities. Personal data should be collected only when necessary and strictly used for projects' purposes.

4.4.3.2.1.1 Informed consent to data processing

Persons involved in the participatory sensing should receive a clearly formulated document of **'informed consent'** in advance, describing the aims, methods and implications of the project activity, and the nature of their participation. The Upsurge project partners and follower cities will be responsible for informing the involved participants and collecting their informed consents. They will need to ensure that language is appropriate and intelligible to the targeted participants. For consent to data processing to be 'informed', the data subject should be provided with detailed information about the envisaged data processing in an intelligible and easily accessible form, using clear and plain language. As a minimum, this should include (EC, 2018):

- the identity of the data controller and, where applicable, the contact details of the data protection officer;
- the specific purpose(s) of the processing for which the personal data will be used;
- the subject's rights as guaranteed by the GDPR and the EU Charter of Fundamental Rights, in particular the right to withdraw consent or access their data, the procedures to follow should they wish to do so, and the right to lodge a complaint with a supervisory authority;
- information as to whether data will be shared with or transferred to third parties and for what purposes; and
- how long the data will be retained before they are destroyed.

The data subjects must also be made aware if data are to be used for any other purposes, shared with research partners or transferred to organisations outside the EU (see article 13 of the GDPR). If the data processing entails potential risks to the data subjects' rights and freedoms, they must be made aware of these risks during the informed consent procedure.

If the participants in the sensing network are children the **consent of a parent/legal representative** and, where appropriate, the assent of the child should be obtained. It is imperative that any information addressed to a child is in age-appropriate and plain language that they can easily understand.

Records documenting the informed consent procedure, including the information sheets and consent forms provided to research participants, and the acquisition of their consent to data processing must be kept as these may be requested by data subjects, funding agencies or data protection supervisory authorities.

Personal data should be kept internally and should not be published or addressable to external organisations or individuals. No personal data should neither be centrally stored nor made available to any entity not specified in the informed consents, without anonymization or pseudonymisation. It also needs to be indicated that potential transfer of personal data from non-EU countries is subject to strict data protection requirements under Chapter V of the GDPR.

4.4.3.2.1.2 Data Security

The GDPR requires all data controllers and processors to implement appropriate technical and organisational measures to ensure a level of data security that is commensurate to the risks faced by the data subjects in the event of unauthorised access to, or disclosure, accidental deletion or destruction of, their data (art. 32 of the GDPR).

General procedures for data storage, protection and retention that will be followed in the project Upsurge are described in Deliverable 9.1 “Protection of Personal Data Requirements no. 3”. These include the pseudonymisation and encryption of personal data and policies and procedures to ensure the confidentiality, integrity, availability and resilience of processing systems.

As already discussed, in a participatory sensing application, the sensing data uploaded by users are invariably tagged with the location (obtained from the embedded GPS in the phone or using Wi–Fi based localization) and time when the readings are recorded, since these provide important contextual information. This can have serious implications on user privacy, since the sensor reports uploaded by users may reveal their locations at particular times. Furthermore, it may be possible to link multiple reports from the same user and deter-mine certain private information such as the location of his/her office and residence. Simple techniques such as using pseudonyms or suppressing user identity may not always work. For instance, if an adversary has a priori knowledge of a user’s movement patterns, it is fairly trivial to deanonymize his/her reports. *(Huang et al., 2010)* Thus several privacy preserving mechanisms tailored to the characteristics of participatory sensing have been published and proposed. *Delphine, 2016* classifies them based on the following participatory sensing architecture:

4.4.3.2.1.2.1 Tasking

The campaign administrators or end users can first determine the sensing tasks to be executed, which are then distributed to the participants’ mobile phone. While this possible first step may seem innocuous, it may already provide insights about the participants’ identity, device, as well as current location when, e.g., downloading the tasks to be executed.

To prevent the campaign administrators from inferring this information, different solutions have been proposed, such as using tasking beacons, attribute-based authentication, location privacy-preserving routing schemes, or downloading the tasks in densely populated locations. Additionally, the PiRi scheme proposes to rely on the participants to distribute the tasks among them. To this end, each participant defines a region around his current location and merges it with the region of k - 1 other participants to obtain a larger region. Instead of transmitting all computed regions, only elected participants transmit their extended region. The tasks distributed by the campaign administrators to these elected participants are then redistributed between all participants according to the region they are able to cover. By doing so, the campaign administrators do not gain access to the individual participants’ location. Based on this approach, the same authors propose TAPAS, which aims at improving the quality of the collected sensor readings by optimizing the participants’ selection in proximity of a particular location of interest while still protecting their location privacy. In both cases, the privacy protection however fully depends on the participants’ trustworthiness and can hence be endangered as soon as the participants would, e.g., collude with the campaign administrators.

An alternative to PiRi and TAPAS is to use a central trusted entity to build the cloaked region based on the k nearest participants to a point of interest. In this case, the participants however provide their location to the trusted entity. They therefore need to trust this entity to efficiently protect their data against external attacks and also not to disclose it to unauthorized entities.

Instead of relying on either other participants or a trusted entity, the network provider can play the role of a broker between the participants and the application server. Following the same idea of privacy brokers, another proposed approach enables end users to directly distribute tasks to the participants. In this case, mobile cloud agents are responsible for managing the distribution of the tasks in a decentralized fashion. Again, the participants need to trust them to respect and apply their privacy preferences.

Ni et al.. proposed a privacy-preserving mobile crowdsensing system which considers the identity privacy of both data consumers and data providers. Proposed system employs a trusted authority and

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denotes the geographical region as a matrix. Apart from identity privacy, the system also achieves preservation on data privacy and location privacy. *(Wang et al., 2020)*

4.4.3.2.1.2.2 Sensing

Participants may be able to control ex ante the degree of granularity at which the sensor readings are collected depending on their individual privacy preferences. As enabler for this control, different interfaces allowing participants to choose between different degrees of granularity for the collection of location information, sound samples, pictures and acceleration data have among with picture-based warnings based on the participants' current privacy settings been proposed in the literature.

Additionally, the participants can define zones in which no sensor readings are either collected or reported to the application server. Setting such zones may however not be sufficient to efficiently protect the participants' privacy. For example, they may only contain the participant's home and hence indirectly reveal their identity. In order to prevent this issue, a solution was proposed which includes an underlying mechanism that automatically adapts the zone to cover at least k buildings. As a result, the so-called silent zones dynamically optimize the existing trade-off between privacy protection and data granularity based on the density of surrounding buildings.

4.4.3.2.1.2.3 Local processing and storage

After the collection of the sensor readings, local processing can be applied on the participants' phones to remove privacy-sensitive features. After processing, the remaining sensor readings may then be stored on either the participants' mobile phones or individual repositories. For example, participants can securely store their collected information on cloud servers. By encrypting them using proxy re-encryption and homomorphic encryption, the sensor readings are not accessible by untrusted cloud providers, but can be accessed by participatory campaigns selected by the participants.

4.4.3.2.1.2.4 Data Reporting

When reporting sensor readings to the application server, the following techniques can be applied to protect the participants' privacy:

4.4.3.2.1.2.4.1 Anonymity

To ensure the participants' anonymity, several solutions leverage the concept of mix networks or mix zones. The key idea is that the participants' contributions are mixed with others when sent to the application server to prevent the campaign administrators from identifying their original source. Multiple servers can ensure this function by mixing different contributions, rerouting them, and introducing delays. The participants themselves can also serve as routers and a multi-hop route is built between the participants, along which each participant only knows his predecessor and successor. When the sensor readings reach the tenth participant, they are uploaded to the application server.

An alternative is to leverage opportunistic encounters between participants to exchange collected sensor readings when being in physical proximity. This scheme called *path jumbling* however fully depends on the participants' trustworthiness and collaboration. To quantify the trust level of the participants and quarantine untrustworthy ones, *TrustMeter* approach has been introduced. Participants can leverage it associated with dedicated user interfaces detailed to set the minimum trust level required by other participants to be able to exchange sensor readings with them. Instead of exchanging full or partial sets of sensor readings, *SLICER* proposes to either exchange only one sensor reading at each encounter or select a subset of participants to share more sensor readings with and hence optimize the reporting process.

Christin et al.. addressed location privacy with a specific method that nodes exchange sensing data when they meet each other so that location information will be blurred to the adversary. The authors also presented a series of strategies and reporting strategies. The scheme emphasizes how to prevent privacy from being disclosed through the process of data reporting. *(Wang et al., 2020)*

Instead of considering individual sensor readings, the following mechanisms focus on the participants' full trajectories. The participants can conceal their own trajectories with those of other participants based on a trusted third party. The trusted third party can merge the sensor readings belonging to different participants to build new equivalent trajectories. Alternatively, the trusted third party maps the identities and the participants' trajectories entering and leaving predefined sensitive zones in *TrPF*. By doing so, the mixing function can be customized and optimized depending on the desired privacy protection.

To prevent the third party from linking the participants' identity to their location, the participants can first collaborate by relaying the other participants' sensor readings before uploading them to the third party. The third party then anonymizes the sensor readings and sends them back to the participants following the same route. Since the sensor readings have been previously anonymized, the participants can report them to the application server using their real identity.

Such centralized architectures however present a single point of failure, making them vulnerable to malfunctions and external attacks. *LOCATE* therefore adopts a distributed approach by leveraging a direct collaboration between the participants. In this case, not a third party needs to be trusted, but other participants. To mitigate this trust in other participants, two sets of the original participants' trajectories are built. The participants alternatively exchange trajectories from both sets and distribute the exchanges over time between different participants.

Yao et al.. proposed an anonymous data reporting protocol that includes two stages: slot reservation and message submission. The privacy countermeasure in the first stage is message shuffle to disguise a single data provider into a group of N members. On the data submission stage, the key idea is DC-Nets. *(Wang et al., 2020)*

4.4.3.2.1.2.4.2 Pseudonymity

To protect the participants' privacy, various applications replace the participants' real identity by a unique pseudonym. However, the provided protection is insufficient as the real identifies may be inferred based on the reported location information. The participants may have the possibility to mitigate this threat by dropping the collected sensor readings, if they estimate that they could endanger their anonymity. This however requires a manual intervention of the participants before each reporting. Moreover, it is assumed that the participants can correctly identify privacy threats by, e.g., taking into account their past contributions, which may not always be the case.

An alternative to unique pseudonyms is proposed in the *IncogniSense* framework. The key idea is to provide an anonymous reputation framework by using blind signature technology. The framework consists of two parts. The first one is to report data by using a periodic pseudonym. The second one is to transfer reputation score by virtue of reputation tokens. Besides, to prevent privacy disclosure risk resulting from reputation transfer, the authors adopted three reputation cloaking solutions. *(Wang et al., 2020)*

Building upon periodic pseudonyms, different alternatives have been introduced. For example, a trusted third party is responsible for building the pseudonyms' groups. Another alternative also based on blind signatures or a trusted third party adds an incentive mechanism on top of the reputation framework to reward contributing participants. The idea of rewarding (or penalizing) participants using pseudonyms is shared with other approaches as well.

4.4.3.2.1.2.4.3 Spatial Cloaking

Above solutions (subchapter 3.4.3.2.1.2.4.1 (Anonymity) and 3.4.3.2.1.2.4.2 (Pseudonymity)) protect the participants' privacy by breaking the link between their identity and contributions. By mixing the contributions between participants or utilizing different pseudonyms, most presented solutions preserve the original spatiotemporal information. Other methods alter the location information by providing it at a coarser degree of granularity and/or building groups of k participants sharing the same location. The

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degree of granularity has additional influence on the participants' location privacy than the number of participants sharing the same location.

Instead of selecting a predefined degree of granularity before the measurements (cf. subchapter 3.4.3.2.1.2.2 (Sensing)), dynamic solutions, (e.g. *ipShield*) can be applied. These solutions running on the participants' mobile phone consider the participants' current context and past contributions to compute the appropriate degree of granularity at which the location information can be released to the application server. As a result, end users will have access to this data with either the same (if the campaign administrators release the data as such) or a coarser degree of granularity (if the campaign administrators apply further processing).

Providing both coarse-grained information to the application server and fine-grained information to specific end users can be useful in certain application scenarios. This is possible with the scheme called P3S, which objective is to protect location privacy when providing fine-grained location service, namely. In the scheme, data providers generate two copies of location information. Then, they send the anonymized coarse-grained location information to server platform and encrypted fine-grained one to data consumers. *(Wang et al., 2020)*

Instead of adapting the degree of granularity to potential data recipients, *Vergara-Laurens et al.*. proposed a hybrid privacy preserving mechanism, which dynamically leverages the concepts of either spatial cloaking or aggregation (cf. subchapter 3.4.3.2.1.2.4.5 (Data Aggregation)) depending on the size of the monitored area. In essence, double encryption for data privacy protection is used to process small-size data.

4.4.3.2.1.2.4.4 Data Perturbation

The key principle of data perturbation is to hide the individual participants' contributions while allowing the application server to compute statistical trends over the whole participants' set. To hide the individual contributions, the first method consists in adding noise on the participants' sensor readings. As a result, the noise selection determines the participants' privacy protection.

Assuming that all participants share the same noise distribution, there is a risk that malicious participants may be able to reconstruct it based on their own data and hence breach the privacy of other participants. To mitigate this threat, the *PESP* scheme distributes different noise distributions to the participants and adapt them to the sensor readings already reported to the application server.

Instead of automatically adapting the individual noise distributions, *ALPS* adjusts the perturbation according to the participants' preferences. As a result, a tailored Gaussian perturbation is first applied followed by a smoothing function to remove potentially remaining insights about the participants and hence protect their privacy.

An alternative to using noise is to leverage the concept of negative surveys. In this case, the collected sensor readings are divided into different complementary categories. Instead of reporting their own sensor readings, the participants choose sensor readings from another category and report those to the application server. Using a perturbation matrix that maps the probability of perturbing a category to another, the application server is able to reconstruct the probability density functions of the original sensor readings without having access to them.

4.4.3.2.1.2.4.5 Data Aggregation

The idea behind data aggregation is also to break the link between the participants' identity and their contribution. In contrast to the mechanisms detailed in subchapter 3.4.3.2.1.2.4.1 (Anonymity), sensor readings from different participants are however merged together to build aggregates. The application server receiving the aggregates is hence unable to isolate individual sensor readings and link them to the collecting participants. Different methods can be applied to aggregate the data, ranging from centralized to distributed solutions. For example, *NoiseTubePrime* relies on a network of trusted brokers. The participants report their results on a map common to all participants and encrypted using the campaign administrators' public key to their respective broker. The brokers organized in a ring topology successively add the contribution of their participant until the aggregate map is completed.

Li et al.. presented scheme where participants not need to trust one or several aggregators (such as the brokers in NoiseTubePrime). The authors make use of additive homomorphic encryption combined with a new key management scheme to reduce both the communication and encryption overhead while still supporting sum and min aggregates. To better support the participants' dynamic (i.e., new participants joining or leaving), the original scheme has been extended by a novel ring-based interleaved grouping technique that diminishes the number of participants that need to renew their cryptographic keys.

Also not trusting the aggregator, *VPA+* adopts a hybrid solution, in which the participants first register their sensor readings to the aggregator before contributing them to the aggregate computed in a distributed fashion. Using a homomorphic MAC of the participants' sensor readings, the registration does however not reveal the original data but allows the aggregator to later verify which participants have contributed and hence guarantee the aggregate's integrity. Similarly, the participants collaborate to compute the sum aggregate without revealing the individual sensor readings.

Zhang et al.. employed Paillier homomorphic encryption for data privacy preservation and designed a data summation protocol. Zhang et al.. presented privacy-preserving data aggregation protocols, minimum and k-th minimum, with untrusted server platform. The key idea is probabilistic coding schemes besides a cipher system. *(Wang et al., 2020)*

Liu et al.. proposed a privacy preserving data sharing scheme for Location-Based Service (LBS) The scheme leverages k-nearest neighbors (KNN) to protect the location privacy of service provider. Besides, it employs Oblivious Transfer (OT) to hide queries of end users. As a result, attackers cannot analyze the content of queries to infer the location information of end users. CP-ABE helps protecting data privacy and enables end users to load the encrypted data ahead of time. Thereby, service provider only needs to transfer the decryption key to the end users, which greatly reduces communication overhead. *(Wang et al., 2020)*

Chen et al.. presented a privacy-preserving data aggregation scheme to address the weaknesses of k-anonymity based schemes. The intuition is that one node submits multiple data reports to the server platform with different pseudonyms. They also provided a mechanism to resist the Sybil attack. *(Wang et al., 2020)*

4.4.3.2.1.2.4.6 Hiding Selective Locations

For application scenarios, in which the temporal annotations of the sensor readings are irrelevant, the participants can explicitly choose the sensor readings corresponding to the locations they want to share with the application server. Their mobile phone then mixes them to modify their chronology and hence break the link between both spatial and temporal information. As a result, the application server can compute the application results based on the data voluntarily shared by the participants.

4.4.3.2.1.2.4.7 Storage and Access Control

The sensor readings reported to the application server can be either individually stored or directly processed on the application server to build, e.g., statistics or maps. The participants may thus only maintain control over their data in the former case. For this purpose, they may use dedicated access control and data sharing solutions, such as *SensorSafe* or *PDVLoc*. Using SensorSafe, the participants can manage several individual repositories using a broker and tailor the granularity at which the collected data are shared based on, e.g., its nature and context, the resolution required by potential end users, their identity or attributes, as well as the degree of trust of the participants in these end users. Following a similar model, PDVLoc allows participants to select potential data recipients as well as the corresponding degree of granularity at which the data is shared.

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4.4.3.2.1.2.5 Presentation

Participatory sensing results can be made available to end users in different forms. For example, end users may access a map aggregating all participants' results or be able to query and filter individual results based on, e.g., a region, sensor modality, or operating system of interest. As soon as end users are able to query participatory sensing results, the privacy of both participants and end users may be put at stake.

For this purpose, the participants can report only partial trajectories to the application server, which then optimizes the query answers by merging partial data collected by several participants. Instead of submitting only partial results, the participants encrypt their complete sensor readings and distribute multiple duplicates to other participants at regular and common time intervals in a scheme that guarantees query privacy with a tag (tags corresponding to the time interval at which they have been collected and exchanged) matching system, which indicates that the identity of the queried sensor is secure.

PEPPeR only focuses on end users' privacy and relies on tokens distributed by the application server to authorized end users. By using them, end users can directly query participants, who provide access to their sensor readings once they have verified the corresponding token with the application server. The verification process however does not disclose the identity of the end users to the application server and preserves hence their privacy.

Based on this work, Krontiris and Dimitriou proposed a sensing platform, in which data consumers can discover data providers within a specific region. Apart from the identity privacy of data consumers and data providers, they also took location privacy into consideration. To ensure the privacy of data providers, they introduce a Mobile object agent to represent a data provider so that the data consumer only interacts with the Mobile object agent, rather than that data provider. Therefore, privacy from data provider is ensured. *(Wang et al., 2020)*

PEPSI simultaneously protects the privacy of both participants and end users. It relies on a trusted third party responsible for their registration and authorization. During the campaign, the registered participants report their sensor readings encrypted to the application server, while the registered end users send their queries to the application server. Leveraging authorizations and tokens delivered by the trusted third party during the registration process, the application server blindly matches both sensor readings and queries. This means that both collected data and query content remain hidden from the application server.

In *PPSense* the authors add Access Point in the system. The key techniques are Cipher Policy Attribute-Based Encryption (CP-ABE) and Mix scheme. In CP-ABE, the access policy is embedded in the private key of a data consumer. Only when a data consumer fulfills access policy, can he/she decrypt the message. Server platform is composed of a data server and a management server. The former one is in charge of the broadcasting task and receiving data from data providers. While the latter one not only functions the authority of CP-ABE, but also manages identity-related information and the registration from data providers. The management server generates private keys for others. *(Wang et al., 2020)*

Recently, the drawbacks of a centralized Mobile Crowd Sensing system and the popularity of blockchain motivates researchers to build up a decentralized Mobile Crowd Sensing with blockchain, like *CrowdBC* and *MCS-Chain*. However, blockchain itself faces several problems in terms of privacy. Blockchain is an open and transparent system, attackers can also access the data on-chain, which presents a severe data privacy leakage problem. Besides, although blockchain achieves anonymity by allowing users to use public key rather than real identities, attackers can still link and trace user activities by analyzing on-chain data. This may cause crucial user identity leakage. Notably, existing blockchain-based MCS systems pay little attention to privacy preservation. *(Wang et al., 2020)*

4.4.3.2.2 Rules and Procedures for the Operation of Unmanned Aircraft Systems

Since 2018, the European aviation safety Basic Regulation **(**Regulation (EU) 2018/1139) applies to all civil unmanned aircraft, irrespective of their weight. It defines high-level rules and essential requirements and empower the European Commission to adopt detailed rules.[9]

In order to cope with the wide range of unmanned aircraft, the Commission and the European Union Aviation Safety Agency (EASA) have developed a regulatory framework superseding national regulations and making them not applicable anymore.

Commission Implementing Regulation (EU) 2019/947, which is applicable since 31 December 2020 in all EU Member States, caters for most types of civil drone operations and their levels of risk. It defines three categories of civil drone operations: the 'open', the 'specific' and the 'certified' category[10]:

The 'open' category addresses the lower-risk civil drone operations, where safety is ensured provided the civil drone operator complies with the relevant requirements for its intended operation. This category is subdivided into three subcategories, namely A1, A2 and A3. Operational risks in the 'open' category are considered low and, therefore, no operational authorisation is required before starting a flight.

The 'specific' category covers riskier civil drone operations, where safety is ensured by the drone operator by obtaining an operational authorisation from the national competent authority before starting the operation. To obtain the operational authorisation, the drone operator is required to conduct a risk assessment, which will determine the requirements necessary for the safe operation of the civil drone(s).

In the 'certified' category, the safety risk is considerably high; therefore, the certification of the drone operator and its drone, as well as the licensing of the remote pilot(s), is always required to ensure safety.

Commission Delegated Regulation (EU) 2019/945 defines the requirements applicable to the unmanned aircraft systems. Its Chapter II defines, in particular, a harmonization legislation (CE marking) defining the requirements that consumer drones must comply with in order to be used in the 'open' category of operations, i.e. without the need to obtain a prior authorisation from an aviation authority.[11]

EASA's publication *Easy Access Rules for Unmanned Aircraft Systems (Regulation (EU) 2019/947 and Regulation (EU) 2019/945)*[12] contains the rules and procedures for the operation of unmanned aircraft, displayed in a consolidated, easy-to-read format, with advanced navigation features through links and bookmarks. It covers Commission Implementing Regulation (EU) 2019/947, and the related acceptable means of compliance (AMC) and guidance material (GM), as well as Commission Delegated Regulation (EU) 2019/945 on unmanned aircraft systems (UAS) and on third-country operators of UAS.

4.4.3.2.2.1 Categories of Civil Drone Operations

As already mentioned in previous subchapter, according to Commission Implementing Regulation (EU) 2019/947, unmanned aircraft systems can be used in three categories of civil drone operations ('open', 'specific' and 'certified' category).

A drone can be operated in the "Open "category when it:

- bears one of the class identification labels 0, 1, 2, 3 or 4; or
- is privately built and its weight is less than 25 kg; or

[9] European Commission, https://ec.europa.eu/defence-industry-space/eu-aeronautics-industry/unmanned-aircraft_en, accessed 24 May 2022
[10] EASA, https://www.easa.europa.eu/domains/civil-drones, accessed 24 May 2022
[11] European Commission, https://ec.europa.eu/defence-industry-space/eu-aeronautics-industry/unmanned-aircraft_en, accessed 24 May 2022
[12] https://www.easa.europa.eu/document-library/easy-access-rules/easy-access-rules-unmanned-aircraft-systems-regulation-eu

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- it is purchased before 1 January 2023, with no class identification label as above;
- will not be operated directly over people, unless it bears a class identification label or is lighter than 250 g;
- will be maintained in visual line of sight or the remote pilot will be assisted by a UA observer;
- is flown at a height of no more than 120 metres;
- will not carry any dangerous goods and will not drop any material.

(Article 4 and article 20 of the EU Regulation 2019/947; Annex part A and Article 5(1) of the EU Regulation 2019/947, Part1 to 5 Annex of the EU regulation 2019/945)

The ‘open’ category is in turn subdivided in three sub-categories – A1, A2, A3 -- which may be summarised as follows[13]:

- A1: fly over people but not over assemblies of people
- A2: fly close to people
- A3: fly far from people

In individual sub-categories unmanned aircraft systems with a specific class identification labels (0, 1, 2, 3 or 4) or with no class identification label (within the transitional period and privately built) can be flown. Each subcategory comes with its own set of requirements for remote pilot and unmanned aircraft system, flight altitudes, distances from people and objects, etc. Most remote pilots will have to take an online training course and an online theoretical exam. Open category requirements are summarized in Table 4.

[13] EASA, https://www.easa.europa.eu/domains/civil-drones/drones-regulatory-framework-background/open-category-civil-drones, accessed 25 May 2022

Table 6: Requirements and limitations applicable to different classes of drones and conducted operations. Source: EASA, https://www.easa.europa.eu/the-agency/faqs/open-category

UAS		Operation		Drone Operator/pilot		
Class	MTOM	Subcategory	Operational restrictions	Drone Operator registration	Remote pilot competence	Remote pilot minimum age
Privately built	< 250 g	A1 (can also fly in subcategory A3)	- may fly over uninvolved people (should be avoided when possible) - no fly over assemblies of people	No, unless camera / sensor on board **and** a drone is not a toy	- no training needed	No minimum age
0					- read user's manual	16*, no minimum age if drone is a toy
Legacy drones (art. 20)						16*
1	< 900 g		- No expected fly over uninvolved people (if happens, should be reduced) - no fly over assemblies of people	Yes	- read user's manual - complete online training - pass online theoretical exam	16*
2	< 4 kg	A2 (can also fly in subcategory A3)	- no fly over uninvolved people - keep horizontal distance of 30 m from uninvolved people (it can be reduced to 5 m if low speed function is activated)	Yes	- read user's manual - complete online training - pass online theoretical exam - conduct and declare a self-practical training - pass a written exam at the CAA (or at recognized entity)	16*
3	< 25 kg	A3	- fly away from people - fly outside of urban area (150 m distance)	Yes	- read user's manual - complete online training - pass online theoretical exam	16*
4						
Privately built						
Legacy drones (art. 20)						

* The minimum age can be lowered by the state to 12, in which case, this new threshold will be valid only in that state.

A drone can be operated in the 'in the 'specific' or the 'certified' category, when it does not meet the requirements laid out under the open category (Article 4 and Article 20 of EU Regulation 2019/947; Annex part A and Article 5(1) of EU Regulation 2019/947, Parts 1 to 5 Annex of EU Regulation 2019/945).

When operating under the 'specific' category, if the operations can be conducted within the limitation of a standard scenario (a predefined operation, described in an appendix to EU regulation 2019/947) and using an appropriate drone (class identification label C5 or C6), the drone operator only needs to submit a declaration to the National Aviation Authority and wait for the confirmation of receipt and completeness. For all other operations in the 'specific' category, an operational authorisation issued by the National Aviation Authority is needed.

The 'certified' category caters for the operations with the highest level of risk. In this category aircraft will always need to be certified (i.e. have a type certificate and a certificate of airworthiness) and operations will be conducted in any of the following conditions: over assemblies of people, involving the transport of people or the carriage of dangerous goods, that may result in high risk for third parties in case of accident. The UAS operator will need an air operator approval issued by the competent authority and the remote pilot is required to hold a pilot license.

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4.4.3.2.2.2 Geographical Zones

In accordance with Article 15 of the EU Regulation 2019/947 Member States determine drone geographical zones, which are areas where drones may not fly (e.g. national parks, city centres or near airports) or may fly only under certain conditions, or where they need a flight authorization. Flight authorizations are different from the operational authorization required for the specific category. It is therefore important to consult National Aviation Authorities to check where the drone can or cannot be flown. All states are required to publish maps identifying these geographical zones. In most of state, apps for mobile phones are available to easily identify where you can fly. The links to National Aviation Authorities are available at EASA's website (https://www.easa.europa.eu/domains/civil-drones/naa).

A flight authorisation is applicable to all operations in 'open' or 'specific' category and is issued by the authority/entity identified in the maps by the state. For example a state may want to restrict the flights over a natural park or a riskier area such as industrial area or over a prison etc. The state may then publish a geographical zone requiring that all drone operations conducted in these zones must have a flight authorisation issued by the authority managing the area (e.g the park authority or the owner of the industry etc..).[14]

Other types of geographical zones are those where one or more of the limitation of the open category are alleviated. For examples area where the state may authorise all drones to operate up to a height more than 120m or with drones heavier than 25kg or in BVLOS etc., without the need for an authorisation or a declaration.

4.4.3.2.2.3 Registration Requirements

Unless they are certified, drones do not need to be registered, but a drone operator/owner, must register himself. This can be done with the National Aviation Authority of the UAS operator's EU country of residence.

UAS operators shall register themselves:

a) when operating within the 'open' category any of the following unmanned aircraft:

i. with a MTOM of 250 g or more, or, which in the case of an impact can transfer to a human kinetic energy above 80 Joules;

ii. that is equipped with a sensor able to capture personal data, unless it is a toy (its documentation shows that it complies with 'toy' Directive 2009/48/EC).

b) when operating within the 'specific' category an unmanned aircraft of any mass.

(Article 14 of the EU Regulation 2019/947)

A drone is certified when it has a certificate of airworthiness (or a restricted certificate of airworthiness) issued by the National Aviation Authority. In this case, it requires a registration. A certified drone is needed only when the risk of the operation requires it. So certification is never needed for drones operated in the 'open' category.[15]

[14] EASA, https://www.easa.europa.eu/the-agency/faqs/drones-uas#category-once-in-the-air, accessed 25 May 2022
[15] EASA, https://www.easa.europa.eu/the-agency/faqs/drones-uas#category-registration-requirements accessed 25 May 2022

4.4.3.3 Maintaining Sensing Devices

Air monitoring technology, like most other forms of technology, requires careful care and maintenance to ensure proper functionality and reliable performance. These preventative actions are necessary in both the short- and long-term, and may vary with the specific monitoring technology being utilized. By properly caring for a monitoring device errors in data collection can be reduced, extend the shelf-life of the device extended, and money that would otherwise be spent on replacement parts and repair services can be saved.

Typical maintenance processes include regularly (*Williams et al., 2014*):

- Calibrating with pollutant standards and flow meters,
- Cleaning internal and external surfaces and components to prevent the buildup of bugs, dust, etc.,
- Replacing filters and consumables,
- Replacing the sensor when it has failed or reached its lifespan of service,
- Replacing rechargeable batteries,
- Reviewing (visually inspecting) data for odd patterns, a decrease in overall response, drift in the baseline, and other unusual features. Instrument problems tend to produce data that often look too regular and repeatable, or that change too abruptly, to be due to natural atmospheric phenomena,
- Inspecting sensor placement to ensure that no significant changes have occurred (e.g., tree growth, building changes, etc.).

4.5 INTERPRETING AND COMMUNICATING AIR QUALITY DATA

The way the results of sensor-based air quality data collections are presented to intended audience is critical to successfully achieving its objectives. There are many ways of visualizing the data, but generally, simply showing the collected measurements will not be sufficient, as the audience will want to know about all the steps that were taken to ensure data quality.

There are a number of complicating factors for understanding and interpreting LCS (and LCS network) data. These factors include for example, variable performance/lack of certification, interferences that affect sensor performance from weather conditions and/or other chemical compounds, no standardization of instrument siting, high-resolution data (e.g. data point every second) associated with a higher degree of uncertainty, and differing limitations depending on the sensor system. While LCS networks and combinations of LCS and reference- or regulatory-grade sensors are often designed or intended to offset some of the measurement error by providing an aggregation of more data points, there are also many factors that affect the efficacy of the configuration in doing so. All of these factors together mean that interpreting and communicating air quality data from LCS can have a lot of pitfalls and added complexity. To address some of the challenges and perceptions of LCSs, it’s crucial to communicate details about the data, including data collection, processing, and quality assurance. This enables those using and interpreting data to understand its strengths and limitations. Publishing the “good” and “bad” aspects of LCS data is a responsibility for anyone or any organization using LCS. And as with all scientific inquiry, describing limitations or uncertainty in a measurement is a strength, not a weakness. (*Peltier et al., 2021*)

While there are many ways and methods to publish and communicate data, the following framework developed by *Peltier et al. (2021)* offers some essential elements that need to be considered.

1. **Identify the purpose or objective for collecting the data.** Because LCS may be appropriate for one application and not another, it is crucial to identify and describe how LCS were used to meet the objectives.
2. **Describe data collection and processing.** One major challenge of LCS is that there are no standards for determining performance, data collection and processing, and reporting results.

Being open and transparent about how the data were collected and processed builds trust. When discussing LCSs (whether it is in a journal article, smartphone application, or elsewhere) it is recommended that information on the following topics is addressed or made easily accessible:

a) **Calibration/adjustments.** LCS data always require some level of calibration or adjustment. A description of efforts made to adjust data should be included.
b) **Maintenance and operations.** Describe how the LCSs were deployed, maintained, and operated.
c) **Quality control.** LCS will need an enhanced level of scrutiny and evaluation to ensure high quality data. Describe the steps taken.
d) **Uncertainty.** LCS data can have more uncertainty than traditional reference instruments. It is useful to disclose this uncertainty whenever possible.
e) **Limitations of the data and air sensors.** Clearly describe all of the known limitations with the LCS (e.g. interference issues) and the data produced.

3. **Document the metadata**. Clearly describe aspects of the LCS that allows others to gain confidence in the data and results. Include information about the placement and siting of the sensors, along with quality control indicators, time standards, and units.
4. **Interpretation of the data**. Interpreting LCS data can be more challenging due to its high time resolution, greater uncertainty, and increased complexity of obtaining machine-readable data for analysis for the average non-expert user. While there are many ways to communicate LCS data, here are a couple of suggestions. First, find methods to share the uncertainty along with the data. Second, when using an air index (e.g. Air Quality Index), it is necessary to understand the index, how it is formulated, and its associated thresholds. One common mistake is using high time resolution data (e.g. 5-second concentrations) and converting that to an air quality index number. Most air indexes are based on longer averaging period (e.g. 24-hours) and health effects and precautionary language corresponding to data with a longer averaging period.

Under *Task 3.4 – Final Assessment and Optimisation of the Sensing System* overall success of particular sensing solutions and the sensing system itself will be evaluated, which will include the assessment of accuracy of gathered data.

5 SENSING OF OTHER ENVIRONMENTAL PARAMETERS

5.1 SOIL SENSING

Soil sensing can facilitate the measurement and monitoring of the soil's physical and biochemical attributes (e.g. nutrients, water) to better understand their dynamics, their interactions with the environment while considering their large spatial heterogeneity. Using soil sensors allows innovative 'bottom-up' approaches that characterize local soil and environmental conditions in space and time, improving the efficiency of production to maximize yield and minimize environmental side effects. The sensed information can be used to build site-specific databases of relations between soil and plant condition and growth. Recent technological developments in sensing coupled with ongoing advances in information and communication technologies have given ground to a renewed interest in soil sensing and its use in different applications at different spatial scales. The new sensing methods can also be used to effectively monitor soil organic carbon and be central to the adoption of best practices that also allow carbon sequestration and a reduction of greenhouse gas (GHG) emissions. Thus, sensing can help us to better articulate the potential of soil to meet the world's needs for food, fiber, climate adaptation and environmental sustainability allowing the design and implementation of innovative management practices and policy aimed at sustainable development[2].

On-the-go or in-situ sensing technologies will pave the way for future soil nutrient monitoring which in the present state are somewhat limited by sample collection and preparation requirements, and may not always be economical. Currently, soil nutrient determination is largely performed in laboratory setting which is not only expensive (per sample) but also time and labour intensive leading to irregular testing and low adoption rate. Depending on the application, the need for easy to use, reliable and economical nutrient is immense. N, P and K are among the common externally supplemented nutrients making their efficient application in the field critical for both economic and environmental gains. Continuous progress is being made in various sensing methodologies as presented in the subchapters below, ranging from low-cost solutions to portable and real-time applications while improving sensor lifetimes, selectivity, sensitivity and accuracy.

5.2 TYPES OF SOIL SENSING METHODS DISCUSSED

I. Soil temperature is an important property that is essential for many soil processes and reactions that may include, but are not limited to, water and nutrient uptakes, microbial activities, nutrient cycling, root growth, and many other processes.

II. Within this chapter, soil moisture determination has been divided into four main sections describing soil moisture measurement metrics and laboratory-based testing, followed by in-situ, remote and proximal sensing techniques. The application, advantages and limitations for each of the mentioned technologies are discussed.

III. Soil pH affects the soil's physical, chemical, and biological properties and processes, and thus significantly influences plant growth.

IV. The nutrient monitoring methods are reviewed beginning with laboratory-based methods, ion-selective membrane based sensors, bio-sensors, and capillary electrophoresis-based systems for inorganic ion detection.

V. Methodologies for estimating carbon sequestration in agricultural soils.

5.2.1 SOIL TEMPERATURE SENSING

Soil temperature is often a significant factor, especially in agriculture and land treatment of organic wastes, because growth of biological systems is closely controlled by soil temperature. In addition, soil temperature influences the physical, chemical, and microbiological processes that take place in soil. These processes may control the transport and fate of contaminants in the subsurface environment[3].

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Within a limited range, the rates of chemical reactions and biological processes double for every 10°C increase in temperature (the so-called Q10 value, i.e., Q10 = 2). Water has a greater specific heat (i.e., the energy required to heat a mass by 1°C) than soil minerals. Thus, wet soil requires more energy to heat than dry soil. Soil temperature is also affected by ground cover. Vegetation and organic residues on the soil surface can moderate extremes in temperature by keeping soil cool in hot weather and insulating against heat loss in cold weather. They also play a role in moisture retention which in turn affects soil temperature. Soil colour also has an impact on soil temperature. Bare, dark-coloured soils warm more quickly than light-coloured soils, which can have an impact on planting dates, etc[4].

5.2.1.1 Conditions to be Considered when Measuring Soil Temperature

The standard depths for soil temperature measurements are 5, 10, 20, 50 and 100 cm below the surface; additional depths may be included. The site for such measurements should be a level plot of bare ground and typical of the surrounding soil for which information is required. If the surface is not representative of the general surroundings, its extent should not be less than 100 m^2.

When the ground is covered with snow, it is desirable to measure the temperature of the snow cover as well. Where snow is rare, the snow may be removed before taking the readings and then replaced.

When describing a site for soil temperature measurements, the soil type, soil cover and the degree and direction of the ground's slope should be recorded. Whenever possible, the physical soil constants, such as bulk density, thermal conductivity and the moisture content at field capacity, should be indicated. The level of the water table (if within 5m of the surface) and the soil structure should also be included.

At agricultural meteorological stations, the continuous recording of soil temperatures and air temperatures at different levels in the layer adjacent to the soil (from ground level up to about 10 m above the upper limit of prevailing vegetation) is also desirable[5].

5.2.1.2 Soil Temperature Measuring Devices

Soil temperature can be easily measured by using a thermometer. Some of the thermometers normally used in soil work include mercury or liquid in glass, bimetallic, bourdon, and electrical-resistance thermometers. The selection of the appropriate thermometer for an application is based on its size, availability, and accessibility to the measurement location, and the degree of precision required.

For precise temperature measurements, thermocouples are preferred because of their quick response to sudden changes in temperature and ease of automation. Soil temperature is influenced by solar radiation, daily and monthly fluctuations of air temperatures as well as vegetation, amount of precipitation, etc. For accurate measurements of soil temperature, measuring instruments should be protected from solar radiation, wind, and precipitation.

5.2.1.2.1 Mercury-in-glass Thermometer

Two forms of the mercury-in-glass thermometer are used for this purpose. For measurement at small depths, a thermometer with a right-angle bend in the stem is used. The bulb is inserted into a hole in the ground with the stem lying along the surface. A thermometer that has been fused into an outer protecting glass shield is used for measurement at greater depths. Wax is inserted between the bulb and the shield to increase the time constant. To obtain a measurement, the instrument is lowered into a steel tube that has been driven into the soil to the desired depth.

5.2.1.2.2 Bimetal Thermometers

Thermometers making use of the expansion of solid material are not directly used for body temperature measurement, however, bimetallic thermometers have a wide application range in physiological and clinical measurement, providing a threshold-temperature triggering switching processes or alarms. Two metal strips with different coefficients of linear thermal expansion are welded together. Such a bimetallic strip bends towards the metal with the lower coefficient, the so-called passive metal, if temperature increases. Bimetallic thermometers or switches are constructed either as a flat or as a u-shaped or as a helix-shaped strip.

Bimetal thermometers are simple to use, robust in design, and reasonably accurate in low and mid-range temperatures. They don't require any power and are used in many different applications such as food and beverage quality control, general lab use, asphalt/concrete testing, and soil and compost testing. Stem lengths range from 12cm to 120cm and they can be calibrated in the field.

5.2.1.2.3 Bourdon-tube Thermometers

The general arrangement is similar to that of the bimetallic type but its temperature-sensitive element is in the form of a curved metal tube of flat, elliptical section, filled with alcohol. The Bourdon tube is less sensitive than the bimetallic element and usually requires a multiplying level mechanism to give sufficient scale value.

5.2.1.2.4 Electrical-resistance Thermometers

The electrical resistance thermometer and resistance-temperature detectors (RTDs) are accurate methods of temperature measurement. The RTD relies on the change in resistance in the temperature-sensing material as an indicator of the thermal activity. Unlike thermistors, which are made of semiconductor materials and have a negative temperature–resistance relationship, the RTD has a positive temperature–resistance relationship, although the sensitivity is lower than that of a thermistor. RTD temperature–resistance characteristics may also be somewhat nonlinear. The RTD typically can be used over a higher temperature range than a thermistor, having temperature ranges of −250 to 1000°C. A constant-voltage bridge circuit, similar to that used with strain gages, is usually used for sensing the resistance change that occurs.

5.2.1.2.5 Thermocouples

A thermocouple is a sensor that measures temperature. It consists of two different types of metals, joined together at one end. When the junction of the two metals is heated or cooled, a voltage is created that can be correlated back to the temperature. A thermocouple is a simple, robust and cost-effective temperature sensor used in a wide range of temperature measurement processes.

Thermocouples are manufactured in a variety of styles, such as thermocouple probes, thermocouple probes with connectors, transition joint thermocouple probes, infrared thermocouples, bare wire thermocouple or even just thermocouple wire.

5.2.2 SOIL MOISTURE SENSING

Water and agriculture are inherently intertwined, where water is one of the key determinants in crop production, agricultural processes affect the hydrological cycle in terms of evapotranspiration, groundwater recharge and runoffs. Soil moisture is also directly related to the amount of irrigation and influences the yield of crops. Accordingly, a soil moisture sensor is an important tool for measuring soil moisture content[6].

Optimum availability of moisture in soil is essential for various biophysical processes like germination of seeds, plant growth, nutrient cycling as well as sustaining natural biodiversity in soil. The importance of soil moisture also makes it a key variable in agricultural monitoring and prediction software tools. Monitoring soil moisture provides key insights into not only the availability of water to crops, but also soil health and moisture retention which are important indicators of sustainable agroecosystem.

Several soil moisture sensing technologies have been developed with various goals in mind such as precision agriculture, landscape moisture statistic monitoring and long term global soil moisture mapping. Soil moisture sensing techniques range from large scale satellite-based remote sensing methods suitable for regional and global scales (100s of km2) to precision in-field sensors aimed towards plot and field scale (0.1 m2 to 10000 m2) measurements[7].

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The soil moisture sensing methodologies have been divided into five subsections:

- Soil moisture metrics and laboratory method
- In-situ soil moisture sensing methods
- Remote sensing methods for measuring soil moisture
- Proximal in-field soil moisture monitoring
- Other soil moisture sensing methods.

5.2.2.1 SOIL MOISTURE METRICS AND LABORATORY METHOD

Soil is a mixture comprising of minerals, organic matter, living organisms, water and gases. The mineral part of the soil can be divided into three size-based particles, sand (largest), silt and clay (smallest). The proportion of each of these types of particles gives the soil its characteristic texture, often based on which the soil type is defined.

Water in soil is present in two main forms: (i) bounded, adsorbed on the soil mineral particles and is unavailable to plants; (ii) unbounded, free existing water molecules which are available for absorption by roots, measured in the form of soil water tension/water potential. Depending on the type of soil, the ratio of the water present in bounded and unbounded form varies.

Soil moisture sensors can detect either total soil moisture content (SMC) or soil water tension/potential (SWP). The relationship between the SMC and SWP is described by the soil water characteristic curve which provides the amount water retained in a soil (SMC) under equilibrium at a given matric potential. The is highly nonlinear and is strongly affected by factors like soil texture, structure and organic matter.

5.2.2.1.1 The Drying/Weight Method

The method most commonly used for determining SMC in laboratories is the thermo-gravimetric method, where the fresh soil sample of known volume is weighed, then oven dried at 105◦C for 24 hours and re-weighed, and the difference between the weights provide the amount of the water present in the soil sample. This is also known as the drying method or weight method.

The drying method is the most commonly used technique for determining soil moisture content. Owing to its simplicity, ease of implementation, and sufficient accuracy, this method is the basic technique for determining soil moisture as well as the basis for the testing and comparison of other methods. However, it has significant disadvantages, i.e., it is time-consuming and laborious, takes a long measurement period, and is not suitable for the continuous dynamic monitoring of soil moisture at a fixed point[8].

Sampling is performed with an auger from the soil at a 0 to 30 cm depth. In perennial crops it is important to standardize where the samples are taken between the trees in the tree row. At least 6 sub samples per treatment should be extracted and mixed together to form a mixed sample on which the analysis will be performed. Soil water status in the field trials should be measured at least yearly during the period characterized by higher risk of water stress[9].

5.2.2.2 IN-SITU SOIL MOISTURE SENSING METHODS

In-situ soil moisture sensing methods refers to non-destructive point-based measurement approaches where the instrument is taken in the field and is in contact with the soil medium. These methods have unique potential to provide real time point-based high resolution moisture content data that is representative of plot to field scale areas and are particularly useful for agricultural applications as they are easier to calibrate, control time scale, can provide measurements at variable depths and in general, more accessible to farmers.

5.2.2.2.1 Tensiometer

A tensiometer is a device that mimics the operation of a plant’s root, measuring the ease with which a plant can absorb water up from the soil. It consists of a stem filled with distilled water, a porous ceramic tip at the bottom and a pressure/vacuum gauge on the top. It works by releasing or sucking water, to or from the soil through the ceramic tip depending on the water potential difference between the soil mixture and the stem. In dry soil conditions, the water inside the instrument tries to seep into nearby soil creating measurable tension (measured in kPa or centibar). The tension is recorded via a pressure gauge or a transducer that measures pressure.

A tensiometer directly measures the water available to the plants (unbounded water content) or the SWP, as opposed to other methods that use indirect soil properties like thermal or electrical, hence it is a highly accurate and a better indicator of water availability for plants than volumetric or gravimetric water content observations.

Tensiometers have various advantages such as they are not affected by soil temperature or salinity, as the dissolved salts can freely move in and out through the ceramic head and they do not require site-specific calibration based on the type of soil. Tensiometers provides accuracy of up to ±3% of the full scale measurement[10], costing between EUR100 to EUR300 (not including the electronics or data loggers)[11].

Some disadvantages associated with the device includes frequent maintenance, as the distilled water in the stem needs to be refilled every 2 to 4 weeks depending on the soil type and irrigation frequency, the device has to be removed during winter as freezing temperatures may harm the instrument, and extra care must be taken during deployment as any air pocket around the ceramic head will affect the accuracy of the measurement. Tensiometers and granular matrix sensors are among the most commonly used soil water sensors developed for commercial applications.

5.2.2.2.2 Gypsum Block/Granular Matrix Sensor

This sensing approach employs a porous material like a gypsum block or a granular matrix, consisting of gypsum wafers surrounded by porous granular filler material, with electrodes embedded inside. The sensor is buried in soil in the root zone and works on the principle of resistance change depending on the water penetration inside the material.

Gypsum has reasonable solubility in water and begins to dissolve as the moisture from the soil seeps inside the porous matrix/material. This mobilizes the ions inside the porous material reducing the resistance between the electrodes and vice versa.

This type of sensor is easy to manufacture, low-priced, and is one of the most prevalent type of sensor used in the field. However, there are some limitations to this method like poor accuracy with error ranging between 10% and 25% [10], slow response time, the gypsum tends to dissolve over time, problems in accuracy as the resistance of gypsum is affected by temperature, and the calibration may vary depending on soil type (or salinity)[12].

5.2.2.2.3 Thermal Probe/Heat Pulse Method

Thermal soil moisture sensing probes measures the temperature of a porous block buried in soil (often made of gypsum or ceramic) or the soil itself, before and after a small heat pulse is applied. The amount of heat dissipation is proportional to the thermal conductivity of the porous block or the soil, which in turn depends on the moisture content in soil.

The main components of the sensor include a heating element (like a thermister) and temperature sensor (such as a pn junction), which are embedded in the porous block (gypsum or ceramic) and buried into the soil, measuring SWP or directly buried in soil, measuring SMC. Several thermal probe/heat pulse sensors have been described in literature with single, dual and multi probe designs[13]. In a single-probe heat pulse (SPHP) soil moisture sensor based on a single npn bipolar junction transistor (BJT) the collector-base (CB) junction functiones as the heating element and the base-emitter (BE) junction serves as the temperature sensor. Dual probe heat pulse (DPHP) techniques involve separate heater and temperature sensing elements, one such sensor was described for SMC estimation where the heater probe was an insulated copper wire that is folded length-wise to pack into a short steel tube with a K-

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type or T-type thermocouple for the temperature probe. Alternatively, a multi-probe heat pulse sensor has also been reported where multiple temperature sensors are placed around the heater probe.

Thermal soil water sensors are also commercially available[14] and offer a relatively low-cost solution with accuracy between 5% to 10%, but require soil-type specific calibration, show variations in accuracy due ambient temperature and humidity changes, show slow response, and are energy intensive.

5.2.2.2.4 NEUTRON PROBE METHOD

The neutron probe (NP) method for SMC determination uses the characteristic property of hydrogen nuclei in water molecules to scatter and/or slow down neutrons. Based on the energy transfer, scatter cross-section and having the similar size as a neutron, hydrogen nucleus has greater thermalization (collision) effect with neutrons than any other element. High energy neutrons from a radioactive source, such as radium-beryllium or americium-beryllium slow down or change direction due to elastic collisions. The thermalized neutron density can easily be measured by a detector and if the capture cross-section of soil media remains fairly constant i.e. the chemical composition remains fairly constant except the variation due to water, the measurements from neutron probes can be calibrated to represent the SMC[15].

In the neutron probe soil moisture sensor, the general construction of the device consists of a radioactive neutron source and a detector connected through a cable. The high energy neutrons are released by the radioactive source that collide with hydrogen atom nuclei of water in soil and are captured by the detector.

Neutron probes are available commercially where, with good calibration based on soil make up (metal content and density) and proper installation (sampling region completely buried in soil and minimal air gaps around the probe), precision between 1% to 5% can be achieved[16].

Some advantages of NPs include high accuracy, and relatively less dependence on soil temperature and salinity. Some limitations of this method include radiation hazard, the requirement of a skilled operator to properly install and take measurements making the method labour as well as cost intensive.

5.2.2.2.5 TIME DOMAIN REFLECTOMETRY-BASED METHOD

The time domain reflectometry (TDR) is a well-known technique that was originally developed for detecting faults across transmission lines by observing the reflections from impedance mismatches and the time interval based on the velocity of the electromagnetic (EM) signal along the transmission line[17]
.

TDR-based SMC measurement works by determining the propagation velocity of EM signal in the soil and using it to calculate the permittivity/dielectric constant. Soil can be considered as a mixture of water, dry soil/matter and air, where water has a specifically high dielectric permittivity at room temperature as compared to air, and dry soil/matter, hence, the overall permittivity of the soil is highly dependent on its water content.

TDR-based SMC sensors consist of a transmission line made of parallel metallic probes completely buried in soil at the required depth. As the signal propagates, a part of an incident EM wave is reflected at the interface where the cable connects to the probe because of the impedance mismatch as the cable and the probe may have different characteristic impedance, the rest of the wave propagates through the probe to the tip buried in soil and is reflected back[18].

Overall, the TDR method for SMC determination has high accuracy of within 2% with respect to the standard thermogravimetric laboratory-based method and can also be used to measure bulk conductivity of soil. The stimulus EM signal used is a rectangular pulse waveform with frequency of the order of 1 GHz and the time resolution for the reflection intervals of the pulses is in the range of 10 ps[19]. Hence, sophisticated data analysis methods as well as circuits are required to record the reflection times accurately making the probes expensive. TDR soil sensors are also readily commercially available offering accuracy within ±2% can cost between EUR1500 to EUR7500 (including data reader) making it an expensive sensing method[20].

5.2.2.3 REMOTE SENSING METHODS FOR SOIL MOISTURE ESTIMATION

Several satellite-based remote sensing systems for soil moisture monitoring have been reported in literature[21] . In 2015, NASA launched its first Earth satellite designed to collect global observations of the vital soil moisture called the Soil Moisture Active Passive (SMAP) satellite. Remote sensing (RS) methods for SMC (RS-SMC) determination are particularly suitable for regional to global scale measurements and are based on either reflected or emitted electromagnetic (EM) energy from the soil surface.

The methods can be broadly classified into two main categories:

- Active methods where the reflected or scattered energy is recorded in response to incident energy.
- Passive methods where sensors (like radiometers) are used to detect the radiation emitted by the target al.so known as the brightness or the brightness temperature of the target.

Techniques have been developed for observing SMC remotely in the following EM spectral ranges: visible, infrared/thermal and microwave, where the soil moisture is determined based on the intensity variations of the radiation due to parameters like dielectric constant, temperature, and thermal properties. Secondary parameters such as vegetation cover, surface roughness and atmospheric effects also play an important role in successful RS-SMC retrieval. Vast amounts of RS-SMC data from various satellite missions has been observed and processes in literature[22], however will not be further discussed in this document due to their unsuitability for the aim of the project.

5.2.2.4 PROXIMAL IN-FIELD SOIL MOISTURE MONITORING

Proximal in-field soil moisture sensors refer to devices that are not in direct contact with the soil but are in proximity to the soil surface for non-point-based estimation. Such sensing systems consist of airborne as well as land-borne techniques for plot and field scale SMC measurements. The sensor measures a soil property directly or indirectly.

Data from proximal soil sensing technologies can be used to show how one or more soil properties vary over a portion of the landscape, to help estimate the range in property values for a particular soil series or map unit component, to refine the boundaries of soil map unit delineations, and to identify the location and extent of contrasting soil components within soil map unit delineations. Some of the methods can be used to document soil properties at specific locations (point data) when describing soil profiles.

The three geophysical methods most commonly used for soils and agriculture are ground-penetrating radar (GPR), electromagnetic induction (EMI), and electrical resistivity (ER).

5.2.2.4.1 Ground-Penetrating Radar (GPR)

Ground-penetrating radar is an impulse radar system. It transmits short pulses of very high and ultra-high frequency (from about 30 MHz to 1.2 GHz) electromagnetic energy into the soil and underlying strata from an antenna. When these pulses contact an interface between layers with contrasting dielectric permittivity, a portion of the energy is reflected back to a receiving antenna. The more abrupt and contrasting the difference in dielectric permittivity, the greater the amount of energy that is reflected back to the receiving antenna. The receiving antenna records the amplitude of the reflected energy as a function of time, and the variation in amplitude is displayed on a video screen and stored for playback and processing. Interpretation of GPR data is generally performed by noting the arrival time of a reflection from a subsurface interface and associating the reflection with a known or suspected soil interface. To interpret the depth to an interface, the velocity of the pulse through the soil must be determined or the interface depth must be obtained by ground-truth measurements.

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Ground-penetrating radar is most effective at sharp interfaces between materials of contrasting dielectric permittivity. Although influenced by bulk density and mineralogy, dielectric permittivity in soil is primarily controlled by water content. Thus, GPR is useful for imaging the interfaces between layers that contain different amounts of water. It is also very effective in determining the location of air-filled or water-filled voids (such as pipes) and metallic objects. GPR works best in coarse grained soils because electrically conductive materials (i.e., soils with high clay content and saline soils) weaken the signal.

A disadvantage of GPR is that resolution decreases with increasing depth of investigation and decreasing antenna frequency. Although higher frequency antennas provide higher resolution, they also provide lesser depth of investigation. Penetration depth is inversely proportional to the sounding frequency. In general, penetration with low-frequency antennas is less than 30 cm in saline soils and less than 1 m in wet, clayey soils. In dry, sandy and gravelly soils, however, GPR penetration can exceed 50 m with low-frequency antennas. Profiling depths as great as 10 m have been recorded in organic soil materials that have very low electrical conductivity[23].

The speed, field economy, high resolution, and continuous measurement of GPR are assets in soil investigations. Modern GPR systems are self-contained and portable and have integrated GPS and real-time data visualization capabilities, which allow greater mobility and more effective use.

5.2.2.4.1.1 GPR Systems on Unmanned Aerial Vehicles (UAVs)

Ground penetrating radar (GPR) systems mounted on unmanned aerial vehicles (UAVs) or drones have emerged as one such promising proximal SMC determination method. They present a drone-borne GPR sensor for soil moisture mapping using a lightweight vector network analyzer (VNA) combined with a hybrid horn-dipole antenna, a lightweight global positioning system (GPS), a computer system and a smartphone. Reflection coefficient or return loss is measured using the single port VNA in the 500 MHz to 700 MHz frequency range. The data processing was done in two main steps: (i) radar modelling, where the VNA-antenna-multi-layered medium (soil) were modelled as linear systems in series and parallel in the frequency domain, (ii) full-wave inversion for parameter retrieval, namely, an inverse problem was defined using weighted least-squares formulation[24].

UAV-based high resolution thermal and multi-spectral imagery coupled with image processing algorithms have also been applied for proximal SMC determination. These imaging techniques are similar to satellite-based remote sensing methods but provide higher spatial resolutions due to close proximity to surface. In a recent work, nine vegetative indices (VIs) related to water stress in maize at different growth stages were derived from UAV multi-spectral imagery and weather conditions, and were used to establish a crop water stress index (CWSI) inversion model, which was then compared with CSWI obtained from on-site ground-based SMC measurements[25].

The key advantages of UAV-based SMC sensors include ability to cover relatively larger areas, autonomous operation, potential to add other sensing technologies like imaging for weed detection and crop scouting, and the demand for drones in agriculture is predicted to increase rapidly[26].

Some limitations include complex data processing is required, accuracy in SMC estimates is lower than in-situ methods, uneven terrain may cause errors, environmental conditions like snow cover and rainfall may affect the measurement, and UAVs can present a significant cost.

5.2.2.4.2 Electromagnetic Induction

Electromagnetic induction (EMI)-based methods can also be identified as land-borne proximal SMC sensors. EMI sensors work by measuring apparent electrical conductivity of soil, which positively correlates to the water in soil as more ions gets mobilized with higher SMC, by inductive coupling. The sensing structure is composed of transmitter (Tx) and receiver (Rx) coils, where Tx coils are energized with alternating current (AC) and generate time-varying EM fields that induces circular eddy currents in the nearby conducting media (soil). Weak eddy currents in soil in turn generates secondary EM fields that induces AC current in Rx coils. The amplitude and phase difference between Tx and Rx currents is then used to determine soil properties[27].

EMI-based sensors are better suited to determine SMC in drier soils with higher electrical resistivities. However, the result from the sensors can vary depending on variable soil properties such as salinity and metallic ion content mandating soil-type specific calibration for sufficient accuracy, and generally requires special expertise for operation in the field.

Overall, EMI-based soil sensing is a relatively mature technique with numerous commercially available sensors, both handheld as well as vehicle mounted.

5.2.2.4.3 Electrical Resistivity (ER)

Soil electrical resistivity represents the capacity of soil materials to resist the flow of electrical current. Methods that calculate the apparent electrical resistivity use Ohm's law and the measured injected current, the measured potential difference, and a geometric factor. The geometric factor is a function of the electrode spacing or configuration Apparent resistivity is commonly expressed in units of ohm-meters. The apparent resistivity is a complex function of the composition and arrangement of solid soil constituents, porosity, pore-water saturation, pore-water conductivity, and temperature.

Electrical resistivity methods can be divided into those that inject currents into the ground through direct coupling and those that inject through capacitively induced coupling. Typically, both types of methods measure the apparent electrical resistivity, which is subsequently converted to its inverse, the apparent electrical conductivity of the soil[28].

5.2.2.4.3.1 Direct-Coupling ER

The traditional direct-coupling electrical resistivity method, also known as the galvanic source method, injects electrical current into the soil using an array of electrodes that are in contact with the ground. In a common four-electrode array, an electrical current is applied between two "current" electrodes and the voltage (the electric potential difference) is measured between two "potential" electrodes. For field surveys, current and potential electrodes are maintained at a fixed distance from each other. The array is moved along a survey line to successive measurement points. Horizontal and vertical resolution, depth of investigation, and signal-to-noise ratio vary with the configuration of the electrode array. The depth of investigation and volume of soil materials measured increase with increasing electrode spacing. Conversely, resolution decreases with increasing electrode spacing. Depending on the relative positioning of the potential and current electrodes, several different array configurations are possible[29].

Standard ER surveys, which require the repetitive insertion and removal of electrodes from the soil, are relatively labour-intensive and time-consuming. To reduce survey time, computer-controlled, multi-electrode systems with tens to hundreds of electrodes have been developed. These systems, however, have had limited use in soil studies.

5.2.2.4.3.2 Capacitively Induced Coupling

Capacitively induced coupling resistivity (CCR) systems use capacitive coupling rather than galvanic contact to introduce electric current into the ground. They measure voltage at the surface in order to determine apparent soil electrical resistivity. The capacitive coupling uses coaxial cables to form a large capacitor. The metal shield of the coaxial cable is one of the capacitor plates and the soil surface is the other. The outer insulation of the coaxial cable acts as the dielectric material separating the two plates. The system transmitter applies an alternating current (AC) to the coaxial cable side of the capacitor, which in turn generates AC in the soil on the other side of the capacitor. With regard to the receiver, a similar phenomenon occurs, except in reverse. The AC in the soil charges the receiver coaxial cable capacitor, and the measured capacitance is then used to determine the potential difference (voltage) generated by the flow of electric current within the soil.

Capacitively induced coupling resistivity systems are rarely used in soil studies. In the field, the lines are easily snared on obstacles and broken off. CCR systems work exceedingly well in high resistivity

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soils, where it is often difficult to transfer sufficient current into the ground with towed-electrode array systems. In highly conductive soils, however, these systems provide little signal penetration and the resulting data are noisy[30].

5.2.3 SOIL PH SENSING

Soil is very vital for all life on earth, because the soil supports plant life by providing nutrients and water to support plant roots. Knowing how much of soil pH (Potential of Hydrogen) is the most important to determine what type of plant is suitable for the soil. Measurement of soil acidity and soil pH value is also as a parameter for determine soil fertility[31].

The value of pH is the acidity level used to determine the acidity of a soil. The pH value is defined as the quantity logarithm of hydrogen (H+) ion activity. The ion activity of hydrogen is difficult to measure experimentally, so the activity coefficient value is based on theoretical measurements. Therefore, the pH scale value is a relative value. This is a relative standard value as a solution of the pH value which is determined based on the international agreements[32].

Soil acidity or alkalinity (pH) is extremely important because it has an effect on the decomposition of mineral rock into essential elements that plants can use. It also changes fertilizers from their form in the bag to a form that plants can easily uptake. Soil microorganisms that change organic nitrogen (amino acids) to the ammonium form of nitrogen to the nitrate form that plant can use also depends on the soil pH. Soil pH should be checked periodically and consistent testing will indicate whether your pH-control program is working.

The best pH for plants is typically between 5.5 and 6.5, though some plants may thrive in more acidic or more alkaline soils. Additionally, soil nutrients are tied strongly with pH of soil; in fact, pH control maximizes the efficiency of fertilizers by controlling nutrient bioavailability. Besides nutrients, pH of soil affects the presence of toxic elements, structure of certain soils, and the activity of soil bacteria. For example, aluminium can leach from soils with a pH below 5.0 and cause plant toxicity. Soils with heavy clay content may become excessively hard or sticky at non-neutral pH. Lastly, bacterial activity that assists in nutrient availability is optimized from pH 5.5 to 7.0.

5.2.3.1 Adjusting Soil pH

5.2.3.1.1 Raising pH

The ideal pH range for soil is from 6.0 to 6.5 because most plant nutrients are in their most available state. If a soil test indicates a pH below 6.5, the usual recommendation is for the application of ground limestone. In addition to having the ability to raise pH, limestone contains calcium. Some prefer dolomitic limestone because it contains both calcium and magnesium, however soils high in magnesium (serpentine) do not need more magnesium.

Rock forming silicates are by far the most abundant mineral class on Earth and contain, to varying degrees and excluding N, all mineral elements essential for plant growth[33]. The release of elements through silicate weathering is one of the fundamental geochemical processes shaping the environment of the planet, and the primordial source of mineral nutrients in the soil[34]. Finely ground silicate rock powders (SRPs) - also called rock dust, stone meal, agrominerals or remineralizers - have therefore been proposed as slow-release fertilizers and soil amendment[35].

Swoboda et. al, 2022[36], based on the work of *Manning,2010*[37], made an overview of crop trials with SRPs and several trials report increased soil pH. In some cases, the pH effects were compared with lime. Mostly, the lime amendments had stronger effects on pH, although some studies suggest other benefits compared to liming, such as reduced nitrate leaching[38], a more versatile effects on nutrient supply[39] and soil biology[40], and less CO2 production when weathered[41].

Besides the potential of being a multi-nutrient fertilizer and soil amendment, other co-benefits might arise from the use of SRPs. Those involve potential effects on carbon sequestration, nitrous emissions and benefits of silicon for plants[42]. The weathering of silicate minerals naturally consumes CO2, which has regulated the global carbon cycle and thus the Earth's climate over several eons[43]. Enhanced weathering aims to accelerate the natural geological process of carbon sequestration by amending soils with crushed reactive calcium (Ca)- and magnesium (Mg)-bearing rocks such as basalt[44]. In *Task 6.2 - Establishing Active CO2 Uptake in Cities through NBS* pilot applications for nature-based negative emission techniques (NETs) in the Upsurge city NBS demonstrations will be performed by adding crushed silicate rock powder (basalt) to selected soils. Weathering and the associated CO2 uptake will be quantified according to standard assessment methods.

5.2.3.1.2 Lowering pH

Some soils are alkaline and have a pH above 6.5. Some fertilizers (ammonium sulfate, urea, and ammonium nitrate) create an acid reaction in the soil, so they aid in lowering or maintaining a specific pH. Certain acidifying organic materials such as pine needles or peat moss can lower soil pH gradually over many years.

In nature this takes thousands of years. For more rapid results in lowering pH, sulphur is used. Sulphuric acid forms when sulphur is added to the soil, the smaller the particles of sulphur, the faster the reaction. Lowering the pH is a slow process and will take 1-2 years to see a reaction.

5.2.3.2 Soil pH Sensing

5.2.3.2.1 Glass Electrode Method

The most common measurement method, discovered by Cremer in 1906, and is still found in many laboratories, is glass electrode based. The glass electrode produces fast, accurate and reliable readings, however, suffers from a number of drawbacks, such as complexity of construction, fragile materials involved and the need of frequent calibration. Because of these drawbacks, glass electrodes are not ideal candidates for miniaturization. Other approaches have been developed with miniaturization as their main design objective[45].

5.2.3.2.2 Ion Sensitive Field Effect Transistor (ISFET)

An ISFET is an alteration of the typical field impact transistor utilized as a part of numerous speaker circuits. In the ISFET, the metal door, which is ordinarily utilized as data, is supplanted by a particle touchy film, the deliberate arrangement, and a reference terminal. In this manner, an ISFET joins in one gadget the sensing surface and a sign enhancer which delivers a high current, low impedance yield and permits the utilization of associating links without exorbitant protecting[46].

Dissimilar to glass electrodes, where the pH-sensitive knob must be loaded with a support arrangement, the ISFET semiconductor innovation brings about a genuine strong state pH sensor. The entire microchip is implanted in plastic in such a route, to the point that just the gate surface is left open to be in contact with the sample. By supplanting the delicate glass globule with the implanted microchip, a powerful and without glass pH measuring gadget can be outlined. The last anode consolidates in one plastic lodging, the pH-sensitive ISFET device, reference terminal and a temperature sensor[47].

Materials like silicon oxide (SiO2), silicon nitride (Si3N4) and aluminium oxide are used in the pH sensing layer. Hydrogen ions will reside at the surface of the chemical layer in proportion to the pH. The positive charge of the hydrogen ions produces an electric field that influences the current between the source and drain. Therefore, if the pH value changes, the current through the transistor will change accordingly. To maintain the drain–source current at a constant value a control voltage has to be applied through the reference electrode. The change in the control voltage is a measure of the pH value of the sample[48].

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5.2.3.2.3 Conductimetric pH sensor

A polymer is a chemical compound constituting repeated structural units formed by the process of reacting monomer molecules to form polymer chains. This process is called polymerization. The main advantage of using polymers for sensor applications is their relative low cost and ease of fabrication. Most of sensing applications use polymers. This is because their physical properties (e.g. volume) or chemical properties (e.g. ion concentration and hence conductivity) will change when they react with external materials (e.g. nutrients, pH, temperature, humidity and soil moisture).The high application potential of conducting polymers (CP) in chemical and biological sensors is one of the main reasons for the intensive investigation and development of these materials. A standard conductimetric sensor consists of two identical electrodes, between which a sensing layer is deposited. In conductimetric, pH sensor poly-aniline (PANI) is chosen as the pH sensitive material to be deposited over the interdigitated electrode (IDE) structure. PANI is a conducting polymer and has shown its suitability as a pH sensing material in many applications[49]

5.2.4 SOIL NUTRIENT SENSING

For the majority of history, nutrient cycling had occurred naturally from soil to plants and animals, and then back to soil through decomposition of biomass. As humans went from hunter-gatherers to practicing agriculture and developing long term settlements, the natural soil nutrient cycling was altered through production and application of agrochemicals (chemical fertilizers, pesticides, herbicides, etc.). In the mid-20th century agriculture was further transformed by the green revolution that increased the crop production worldwide through selective breeding for developing and adopting high yielding crop varieties, especially cereal and novel cultivation practices. Ever since then, achieving sustainability through precision agriculture has been a goal for humanity.

In general, it has been established that there are 17 essential elements/nutrients that are critical for plant growth, and deficiency of any one of them can result in reduced yields. The non-mineral elements, carbon, hydrogen, and oxygen are available to the plant either from the atmosphere or in the form of natural biomass or water. The mineral elements that are required in relatively larger quantities for crop growth are categorized as primary macronutrients that includes nitrogen, phosphorus and potassium. The deficiencies in N, P and K may lead to significant yield losses and are therefore added exogenously to soil to meet the plant’s needs. Calcium, magnesium and sulphur are classified as secondary macronutrients as they are needed in relatively lesser amounts and are often present in sufficient quantities in soil. Plants also need other nutrients for healthy growth but only in trace amounts, these elements are classified as micronutrients. Micronutrients are largely present naturally in adequate amounts in soil and if required, are added to macronutrient doses in minute quantities. Excessive concentrations of micronutrients in soil can also lead to toxicity in plants[50].

Nutrient/fertilizer application is one of the largest expenses incurred in crop production not only in terms of direct capital but also in terms of its ultimate impact on the environment. Hence, precise monitoring of nutrients in soil enables better application efficiencies and enhanced sustainability in agriculture.

This section presents the methodologies employed towards detection of nutrients in soil, particularly primary macronutrients, and is divided into the following subsections:

- Laboratory-based methods
- Ion-selective membrane (ISM)-based electrochemical (EC) sensors
- Other biosensing methods
- Electrophoresis-based methods.

5.2.4.1 LABORATORY-BASED METHODS FOR SOIL NUTRIENT ANALYSIS

Standard soil testing procedures in laboratory setting consists of two main steps, (i) sampling, and (ii) nutrient extraction and quantification. Recommendations for soil sampling procedures vary with different laboratories. Generally, the top 15 cm of soil has the most root activity and fertilizer applications are generally restricted to this depth, however, in case of deep rooted crops such as wheat or for more detailed nutrient analysis, cores from 15 to 60 cm can be taken. A relation between the number of cores and coefficient of variation is as expected - the variation decreases with larger number of collected sample cores[51].

The collected soil samples are dried, ground and sieved prior to analysis to obtain a homogeneous mixture. To begin analysis, first the nutrients are extracted from the processed sample. The extractants are chemically separated from the sample to rapidly assess either total and/or available (or soluble) soil nutrient pools. Several nutrient specific extraction chemistries, often dependent on pH of the soil, have been developed over the years, such as N extraction using calcium sulphate, P and K extraction using Mehlich 3 method and more[52].

Laboratory- based methods provide accurate as well as precise measurements which are used as standard (or ground truth) for other sensing techniques but require several sample collection and preparation steps. Therefore, there exists a need for cost-effective and field accessible soil nutrient sensing technologies to enable continuous monitoring for precise fertilizer application as well as soil health analysis.

5.2.4.1.1 Colorimetry

Colorimetry used to one of the standard laboratory soil testing methods prior to using more sophisticated instruments. In this method, the changes in intensity of color or turbidity is recorded in response to reactions between the sample extractant and a prescribed reagent, which directly correlates with the concentration of a specific ion. Various colorimetric reagents have been developed for detecting different soil nutrients. The developed color is compared to a reference color strip according to which the concentration levels are determined[53].

Thus the accuracy of measurement is affected by the limited number of reference levels as well as human interpretation. However, in recent years, photometers and image processing has been applied for improved color analysis. A portable colorimetric analyzer based on smartphone camera for P determination in soil was presented in. Colorimetric test kits are also readily commercially available providing low-cost per test for soil analysis. In general, colorimetry-based methods require several sample preparation steps making the process labour as well as time intensive[54].

5.2.4.1.2 Spectometry

Compared to colorimetry, spectroscopy-based methods offer more precise and rapid analysis with relatively simpler soil preparation requirements. Spectroscopic techniques like visible (vis), ultraviolet (UV) and IR spectroscopy, X-ray fluorescence (XRF) spectroscopy, inductively coupled plasma spectroscopy, among others, have been employed for laboratory-based soil testing.

vis and UV spectrophotometers work on the principle of interaction of vis or UV light with the electron in the constituent atoms, where the electrons in orbitals can absorbs photons of specific energy (or wavelength) and are observed in the absorbance spectrum.

In IR spectroscopy, the test sample is irradiated with IR radiation and the frequencies corresponding to the vibrational modes of the atomic/molecular bonds are absorbed while the rest are reflected. The output spectrum is recorded using a spectrophotometer where different molecular bonds exhibit distinct vibrational modes which are characterized in the IR absorbance bands.

In inductively coupled plasma (ICP) optical emission spectroscopy (ICP-OES), the test samples are introduced inside the core of ICP argon plasma which generates temperature of about 8000◦ C making the thermally excited elements emit light at their characteristic optical wavelengths. The emitted light is

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scanned using a spectrometer and the amplitude at each wavelength is recorded is representative of the elemental concentration.

XRF spectroscopy works on the principle that when primary x-rays are targeted at a sample, secondary x-radiation (fluorescence) is emitted by the target. Electron bombardment at the target can also be used as a source of primary excitation. When excited, each element emits x-rays of characteristic wavelength (inversely related to the square of the atomic number of the element) and intensity, proportional to the amount of the element present[55].

5.2.4.2 ION-SELECTIVE MEMBRANE (ISM)-BASED ELECTROCHEMICAL METHODS

Sensors like ion selective electrodes (ISEs) and ion selective field-effect transistors (ISFETs) use ion selective membrane (ISM) for selectivity and are the most common electrochemical sensing methods studied and applied for the determination of inorganic ions in soil.

ISMs can be classified into 3 broad categories:

(i) glass membrane (primarily used for pH measurement),
(ii) inorganic salt crystal-based solid state membranes, and
(iii) polymer membranes containing ionophores.

A general procedure for fabricating ISMs includes pouring the prepared recipe in a glass mould, kept in an air permeable enclosure, until the solvent evaporates and the ISM is left behind for use. The detection principle of an ISE is based on a potentiometric electrochemical (EC) cell where instead of direct analyte redox reactions, selective binding of the analyte ion to a membrane generates an electric potential. An ISE sensor is composed of a complete galvanic cell with two electrodes, a working electrode (WE) and a reference electrode (RE), where an ISM specific to a particular analyte/ion is integrated with the WE, and the potential difference between the WE and the RE varies depending on the concentration/activity of the analyte in the test solution/electrolyte[56].

5.2.4.2.1 N DETECTION USING ISMs

Plants take majority of N from soil in the form of NO− 3, however NH+4 can be dominant in some acidic and/or anaerobic environments, and it has been widely accepted that co-provision of nitrate with ammonium may be ideal for plant growth. Among the inorganic forms of N, nitrate is the most mobile making it prone to leaching and therefore, requires frequent replenishment. The ideal concentration range of nitrates in soil is about 10 to 30 mg/kg or approximately 0.1 to 0.5 mM, which coincides with the detection range of most ISM-based devices[57].

N detection using ISEs and ISFETs has been explored for several decades and many recipes have been developed for nitrate ISMs.

5.2.4.2.2 P DETECTION USING ISMs

After N, P is the second most limiting primary macronutrient which is often supplemented in soil with external fertilizer application. It is absorbed by the plants largely in orthophosphate forms H2PO−4 or HPO2−4 present in soil. The fraction of these ions depend on the pH of the soil: For pH values above 7, HPO2−4 is dominant, whereas below pH 7, H2PO−4 is abundant. Therefore, majority of ISE sensors have been reported for detecting these forms of phosphates. In soil extractants typical concentration of plant soluble phosphates range from 9 mg/kg to 30 mg/kg or 90 µM to 300, which lies within the operation range of most of the ISM-based P sensing devices. The selectivity of an ionophore towards an ion is governed by the hydration energy of the ion which is a measure of the free energy of transfer from the solution to the membrane phase, resulting in the Hofmeister series (perchlorate > thiocyanate > iodide > nitrate > bromide > chloride > acetate > phosphates). Phosphates have high hydration energy and consequently lie at the lower end of the Hofmeister series, this makes developing phosphate selective ionophores challenging[58].

However, ISM-based sensors for P have been reported in literature and the developed approaches can be classified into two broad categories:

(i) polymer membrane-based electrodes containing organic ionophores, and
(ii) metal compound-based electrodes.

5.2.4.2.3 K DETECTION USING ISMs

The interest in K detection spans from monitoring its levels in human serum to determining its concentration in soil. K is the third critical nutrient for crop production, and although it is present in the soil in large quantities, the plant available K pool is small. Desired potassium ion levels in soil range from 50 mg/kg to 600 mg/kg or 1.25 mM to 15 mM[59].

Among the ISMs developed for K detection, valinomycin has been observed to be the most successful ionophore for potassium ion detection because of its high selectivity towards the ion[60] [99].

5.2.4.3 Other biosensing methods

Besides ISM-based EC devices, other biosensors have also been reported for detecting macronutrients in soil, particularly N and P. Some of the key recent biosensing methods include enzymatic biosensors, molecularly imprinted polymer (MIP), aptamers, and electro-catalysis-based detection methods.

5.2.4.3.1 N DETECTION

The reduction of NO−3 to NO−2 in the presence of the enzyme, nitrate reductase (niR) can be characterized using EC methods to develop nitrate sensors. Enzymes are protein molecules that act as biological catalysts for specific biochemical reactions, and can thus, be used for developing selective and sensitive biosensors.

In a recent work, a microfluidic impedimetric sensor for soil nitrate detection using graphene oxide (GO) and conductive nanofibers decorated with niR was reported. The sensor was characterized using electrochemical impedance spectroscopy (EIS) and had a wide range of operation[61].

In addition to enzyme-based approaches, MIP-based biosensing approaches such as described in have also been reported, where Isobutyl nitrate (IBN) (1 mmol) and 1-allyl-2-thiourea (AT) (4.0 mmol) were used as template molecule and functional monomer, respectively. These sensors operate on the principle of selective binding of the analyte ion to the previously manufactured MIP molecules via dipole interactions and hydrogen bonding[62].

Alternatively, the electro-reduction of nitrate to ammonium ion on copper-based electrodes (coated wire electrodes) has also been employed for nitrate detection. A composite of Cu nanoparticles, multi-wall carbon nanotubes (MWCNT) and reduced-GO (rGO) for simultaneous electrochemical detection of nitrite and nitrate was reported[63].

5.2.4.3.2 P DETECTION

An amperometric phosphate biosensor, based on a cobalt phthalocyanine screen-printed carbon electrode (CoPC-SPCE) employing enzyme pyruvate oxidase was reported in. The principle of operation consisted of the enzymatic reaction in the presence of inorganic phosphate where pyruvate was converted to acetylphosphate, CO2 and H2O2. The analytical response was then recorded by the electrocatalytic oxidation of the formed H2O2 with Co2+ to produce Co+[64].

Additionally, MIP-based sensors have also been developed for P detection where an interdigital capacitive biosensor using MIPs to detect phosphates in a hydroponic system was reported. MIPs were synthesized using functional monomers methacrylic acid (MAA) and N-allylthiourea, against the template molecules diphenyl phosphate, triethyl phosphate, and trimethyl phosphate. Selectivity of different MIPs were tested against nitrate and sulphate where a selective change in capacitance was observed for phosphate[65].

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Fluorescence-based sensors have also been reported for P detection, where in one such work, synthesized thioglycolic acid (TGA) capped cadmium telluride (CdTe) quantum dots (QDs) were used in ‘turn on’ photoinduced electron transfer (PET)-based inorganic phosphate sensing in aqueous solution[66].

5.2.4.3.3 K DETECTION

K detection using EC sensors using ISM devices has been studied extensively in literature. An aptamer-based sensor using the interaction of gold nano-particles (AuNPs) and a cationic dye for K detection was reported. Aptamers are single-stranded functional oligonucleotides (DNA or RNA) which have been proved to have receptor-like activity and can display affinity for specific chemical species. In the developed framework, in the presence of K+ ions, the aptamers dissociated from the surface of AuNPs (aptamer-modified AuNPs), and the free AuNPs and the cationic dye makes the solution green (due to aggregaton of AuNPs), therefore, the solution turns from orange to green as the concentration of K+ increases[67].

In another work, a graphene Hall effect biosensor was developed for K detection where a flexible single-stranded DNA with guanine-rich sequences (5’-GGTTGGTGTGGTTGG-3’) was immobilized on the graphene surface as a probe, which could fold into a tetraplex structure (guanine-quadruplexes) with K+ ions due to the formation of intramolecular hydrogen bonding in order to efficiently and selectively capture K+ ions[68].

A novel molecular K+ probe for colorimetric, fluorescent, and photoacoustic detection was reported, where the developed probe called NK2 is composed of 2-dicyanomethylene-3-cyano-4,5,5-trimethyl-2,5-dihydrofuran (TCF) as the chromophore and phenylazacrown-6-lariat ether (ACLE) as the K+ recognition unit. NK2 showed good response and high selectivity which was demonstrated by the absorbance spectrum, fluorescence spectrum, and photoacoustic measurements leading to a linear detection range of 5 mM to 200 mM[69].

5.2.4.4 Electrophoresis-based methods

Capillary electrophoresis (CE) works on the principle of physical separation of ions in a buffer solution traveling inside a capillary tube/microchannel under the effect of an electric field. A detector is located at the end of the tube or microchannel which records sequential crossing of the different types of ions.

Following one of the early prominent works on zone electrophoresis in open-tubular glass capillaries[70], CE has progressed into an established contemporary analytical technique for quick high resolution sequencing of bio-molecules as well as inorganic ions.

Most of the commercially available CE systems like are targeted towards bio-molecule detection costing $1000s and are limited to lab setting. However, recent advances have been made in the development of economical field-applicable CE systems for nutrient/inorganic ion monitoring in soil samples[71].

5.2.5 SOIL CARBON SEQUESTRATION MEASURING

The global carbon (C) cycle describes the deposition and release of C between soil, vegetation, atmosphere, oceans, rocks and fossil fuel emissions, which in part defines the quantity of atmospheric carbon dioxide (CO2).

Total C in soils is the sum of inorganic and organic C. Inorganic C is largely found in carbonate minerals (e.g. CaCO3), and is highest in soils that formed from calcareous parent materials under arid conditions. Approximately two-thirds of the C in soils in in organic form, referred to as SOC. Soil organic carbon consists of the cells of microorganisms, plant and animal residues at various stages of decomposition, humus synthesised from residues, and elemental forms of C such as charcoal, graphite and coal.

Soils contain one of the largest organic C stocks on the planet, with ca. 1500 Pg C (1 Pg ¼ 1015 g¼ 1 billion metric tonnes) to a depth of 1 m and 2400 Pg C to 2 m depth[72]. This carbon actively exchanges with the atmosphere via the processes of photosynthesis and respiration. As such a large and active C pool, small percentage changes in these stocks can greatly affect the amount of C as CO2 in the atmosphere and the C balance at a global scale.

Soil can be a potential source or sink of atmospheric CO2 and play a key role in climate regulation. SOC sequestration, which implies transforming atmospheric CO2 into long-lived C forms and storing it securely in soil, is one of the key cost-effective options for mitigating climate change with additional co-benefits of improving soil fertility and other ecosystem services. Maintaining or enhancing SOC stocks was recognized as part of Sustainable Development Goal 15 (ADG 15)[73].

Increases in SOC can be achieved through restoration of degraded soils and ecosystems, agroforestry, addition of biochar, adoption of perennial cropping systems, reforestation and afforestation (particularly with hardwood species), “enhanced weathering” (discussed in more detail in subchapter 4.1.4.1.1 (Raising pH)) and other forms of management that affect land cover and land use. Recorded SOC sequestration ranges from 0-150 kg C/ha in dry and warm climates to 100-1000 kg C/ha in humid and cool regions[74].

Depending on soil characteristics and climate type, soil and vegetation store very different quantities of C. A greater quantity of C is generally stored in the soil relative to vegetation, but surface vegetation often serves to preserve soil C; in areas where surface biomass is removed through, e.g., deforestation, a large fraction of soil organic C is typically lost over time due to subsequent degradation and leaching.[75]

There are several tools and approaches for modelling C storage and sequestration in above-ground vegetation. Here, the discussion is focused on current methods and approaches for quantifying SOC stock change and the associated removals of CO2 from the atmosphere and models as means to predict SOC stock changes.

5.2.5.1 Critical pre-estimation parameters for accurate assessment of SOC

For climate change research, an accurate and reliable measurement method is required to estimate C stock over time so that the impact of management practices can be monitored and verified. Prerequisites for accurate SOC stocks calculation are[76]:

- Clearly defined boundary lines and appropriate planning of experiments:

The SOC sequestration should be calculated within a defined and meaningful boundary line that provides a clear and important finding. SOC sequestration calculation should not consider carbon that originates from the land unit and not directly from the atmosphere. Hence, depending on the land unit, clearly defined and identified boundaries should be drawn for the plot area, field, farm, and landscape under study.

- Baseline establishment:

Determination of SOC in the initial soil before treatment is required for fixing it as a boundary line so that SOC change, steady state, retention and loss of SOC within the soil can be assessed. In some studies, however, the pre-treated plots as baseline were compared with different treated plots at the end of the experiment period, in order to determine the SOC change in the form of build-up or erosion from the soil in agriculture. As the baseline is related to the scope, objective and structure of the system, it invariably has to be fixed by researchers.

- Time line/time horizon:

Fixing a time line is essential for measuring the SOC sequestration after the treatments have been administered. Spatial variability and very slow rate of C changes are the key challenges for correct assessment of SOC change. Long-term field experiments lasting many years or decades are therefore suggested for detecting any change in SOC sequestration within various land and soil management options.

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- Sampling design and number:

The most widely used sampling designs to measure the C stock in soil are the systematic or random method or by convenience. To capture the variability present in soil, a combination of stratified as well as random sampling design can be used, by dividing the plots into possible homogenous sub-plots or strata followed by random sampling within these zones to get unbiased estimates of SOC. Sub-plotting or stratification can be done on the basis of salinity and clay content of soil through electromagnetic survey, yield map and remote sensing. A systematic grid sampling and nested sampling design have also been suggested so that estimates improve. The sampling design can be further improved by applying the concept of autocorrelation, variogram and range in the model-based approach to ensure that the target variables show auto correlation and the samples are collected at intervals less than the range obtained from the experimental semi variogram.

Along with sample design, sample numbers must be determined before samples are actually collected. Sample number should be adequate enough to estimate the mean of SOC with a greater confidence interval so that a reliable SOC change is detected and correct inferences are made.

- Sampling method:

Sampling methods often depend on the objective (i.e., short-or long-term storage change). Several sampling methods used for SOC change measurement are: digging open pits, core sampling with a punch core, core drill method, etc.

The core sampling method is more efficient than pit sampling because it consumes less time, thus making possible to collect more samples with greater accuracy, particularly in spatially heterogeneous sites. There is an acceptable trade-off between increased sample numbers and soil compaction caused by coring. On the other hand, soil structure and horizon development is better revealed by excavating the pit than coring. It makes it possible to measure the mass, which is required for bulk density determination and enhance the estimated accuracy that coring cannot do. Re-sampling at a later date from the same point is not possible in pit sampling as it involves site disturbance, which affects the precision of estimation. Taking an additional augar sample close to the pit or a core barrel sampler attachment technique have been suggested to solve this problem.

- Sampling depth:

SOC variation over the soil depth is uneven and long-term SOC accumulation can occur in deeper soil layers up to a depth of 100. Usually, SOC measurements are done in the top 30 cm depth, a recommended sampling depth according to the Intergovernmental Panel of Climate Change's recommendation[77], however nearly all SOC sampling protocols (e.g., GRACE net) recently advised to take samples from a minimum depth of 100 cm. It should be noted though that the subsoil carbon accumulation depends on soil type.

Samples can be collected either by fixed depth or horizon-wise. Sampling by fixed depth interval is an inexpensive, simple and a preferred method for stock estimation at the regional scale, whereas horizon sampling is preferred in pedogenesis studies. To capture the profile variations, raster sampling, fine grid sampling on soil monoliths and fuzzy c-means sampling methods can also be used. Undoubtedly, for stock estimation or SOC sequestration analyzes, deeper sampling is an ideal option, but there is a trade-off between accuracy versus cost and labour resources.

- Bulk density corrections:

The SOC stock for a given depth is calculated from SOC concentration, bulk density (BD) and soil depth.

Despite several methods being available for correcting SOC data that arise due to concomitant variation of BD with SOC over the depth in response to soil management change, comprehensive evaluations of these methods are still lacking. To overcome this problem, the equivalent soil mass (mass-depth) approach in place of linear depth is suggested, where equivalent soil mass is defined as "the reference soil mass per unit area chosen in a layer" and equivalent C mass is "C mass stored in an equivalent soil mass".

The material coordinate system that compares collective C density on a temporal scale on the basis of initial sampled cumulative mineral mass, is suitable for agricultural soil subject to frequent disturbances However, it cannot detect SOC change in an individual layer, requires unreasonably larger sample numbers for a meaningful comparison at lower layer, and is prone to error magnification due to integration of SOC stock.

5.2.5.2 Ex-situ methods

Several ex-situ methods are available to determine SOC and total organic carbon (TOC) in soils: wet digestion, loss-on-ignition technique and dry combustion (DC) in an elemental analyzer. Ex-situ methods, i.e. dry combustion, have long been regarded as the 'gold standard'. However, conventional sampling of soil and their subsequent chemical analysis is expensive and time consuming and not sufficiently sensitive to identify small SOC changes over time. Several in situ analytic methods promise to increase the accuracy and reduce the time and cost of conventional field soil sampling and laboratory analyzes. Some other ex-situ methods are discussed in subchapter 4.2.5.4.1.1 (Measurement in laboratory).

5.2.5.2.1 Wet digestion

This process involves the oxidation of organic matter by an acid mixture and measuring the evolved CO2 by gravimetric, titrimetric, or manometric methods.

Wet combustion involves oxidizing soil organic matter to CO2 with a solution containing potassium dichromate (K2Cr2O7), sulfuric acid (H2SO4) and phosphoric acid (H3PO4), following the reaction: $2Cr2O7^{-2} + 3C^{0} + 16H^{+} = 4Cr^{3}– + 3CO2 + 8H2O$. This reaction generates a temperature of 210°C and is sufficient to oxidize carbonaceous matter. The excess $Cr2O7^{-2}$ (not used in oxidation) is titrated with $Fe\ (NH4)_2(SO4)_2{\cdot}6H2O$, and reduced $Cr2O7^{-2}$ is assumed to be equivalent to the sample's SOC content. Calculations for SOC content are based on the fact that C present in soil has an average valence of zero. The wet combustion method has undergone a number of modifications related to the type and concentration of the acids used and whether external heat is applied or not.[78]

The most popular is the Walkley-Black" (WB) method[79] because it is easy, rapid and involves minimal equipment. However, this method oxidizes only the active SOC in the sample, and this is deemed to be its major drawback. A correction factor of 1.33 (based on 76% organic C recovery) is often used to compensate for the partial oxidation. The correction factor depends on soil types, matrices, depths, textural class, horizons and SOC fractions. Therefore, the correction factors have to be determined by conducting experiments with soil types existing in different areas.

Interferences by chloride (Cl^-), ferrous iron (Fe^{2+}), higher oxides of manganese (Mn^{2+} and Mn^{4+}) and coal particles also entail incorrect estimations of SOC content[80].

Despite still being widely used globally to measure SOC concentration, the wet digestion method has limitations due to variable recovery percentage. Development of site-specific correction factors or using exogenous heat during digestion to accurately estimate SOC when applying the WB method is therefore recommended[81].

5.2.5.2.2 Dry combustion

Incinerating SOC and thermal decomposing carbonate minerals generate CO2 that is measured by (1) dry combustion followed by measuring the difference in mass loss-on-ignition (LOI); and (2) dry oxidation of SOC, then collecting and determining the evolved CO2 with automated instruments. Both methods involve oxidizing the SOC at a high temperature. The LOI method involves heating the sample in a muffle furnace between 200–500˚C, whereas dry oxidation via automated analyzer is carried out between 950–1150˚C.

5.2.5.2.2.1 Loss-on-ignition method (LOI)

In this method, the soil organic matter is assessed by measuring the weight loss from a dry soil sample (oven-dried at 105˚C) after high-temperature ignition of the carbonaceous compounds in a muffle furnace. Following assumptions underlie this method: (i) LOI is due only to the combustion of soil organic matter, and, (ii) the C content of soil organic matter is constant. The concentration of SOC can be computed from the LOI-SOC relationship, where SOC is determined by an autoanalyzer or by the multiplication factor of 0.58, assuming that soil organic matter comprises 58% of the SOC. However, these relationships and conversion factors vary with the soil type, the nature of SOC, soil depth and soil horizons. The LOI does not generally represent soil organic matter because LOI can decompose inorganic constituents without igniting the entire soil organic matter pool. Temperature and the duration of ignition are critical to prevent the loss of CO2 from carbonates and the structural water from clay minerals and amorphous materials (volcanic soils), the oxidation of Fe^{2+}, and the decomposition of hydrated salts[82].

Sample size is another source of variation in LOI measurements. A single regression equation cannot be used universally due to problems involving accuracy[83], so knowledge about the nature of the soil and the correction factor is essential before analysis can commence[84].Clay content in soil plays an important role in determining the nature of the LOI-SOC relationship[85]. Predictive potential of the regression equation can be improved by applying bivariate function of LOI and clay content[86].

The TOC content measured using this method by some researchers has produced ambiguous results. Natural soil inorganic carbon (SIC) and SOC cannot be precisely segregated by this method due to overlapping of the combustion and decomposition temperatures. For an improved segregation of SIC and SOC with diverse temperatures, it was thus recommended using the CO2 and the H2O signals. The idea is that, if SOC is combusted, the CO2 and the H2O signals appear at the same time, whereas for SIC, only a CO2 signal is recorded.[87]

While the LOI is a simple, rapid, and inexpensive technique of determining SOC content, the LOI-SOC regression equation must be determined for particular soil type and depth. Finally, consistency should be assured for ignition temperatures, exposure times, and the samples' size and information on these three parameters included at the time of publishing the research[88].

5.2.5.2.2.2 Dry combustion in an elemental analyzer

The content of total soil C (TC) is determined by dry combustion using an elemental analyzer (EA), and TC in a typical non-calcareous soil becomes SOC. In a calcareous soil, SOC can be measured by subtracting the inorganic carbon determined with a modified pressure calcimeter[89] from the TC determined by an EA. Alternatively, it can be measured by removing SIC from samples through HCl pre-treatment to eliminate SIC before measurement, where the TC becomes SOC[90]. At a high concentration of SIC in soil, the estimation error will be probably very large and may need a correction factor[91]. It was reported that when carbonate content is high, it can be measured, and subtracted from TC to calculate the SOC by the difference from the dry combustion[92].

In the Scheibler method, samples are treated with HCl and the soil's carbonate content is calculated from the amount of CO2 released in a volumetric analysis[93]. In the case of acid pretreatment, adequate care must be taken to eliminate acids by centrifugation[94], and filtration and drying. Caughey et al..[95] recommended a temperature of 40 °C; a temperature higher than this will lead to considerable loss of volatile organic carbon (VOC). Special attention must be paid to sample weight and size, the latter should be adequate enough to create a detectable signal and generate representative data within its combustibility limit[96].

Dry combustion analysis using EA is the most correct method for measuring the soil C content. The elemental analyzers are more accurate and advantageous as all forms of carbon are decomposed in this method, there is minimal sample requirement and it requires only a short time for analysis. Nonetheless the initial purchase of the required equipment is expensive as are the maintenance costs.

5.2.5.3 Soil organic carbon fractionation

For sequestration to happen, the soil carbon needs to be stable, non-labile and resist loss in a reasonable time frame when changes in management occur[97], temperature changes[98] and there is small C input[99]. The stable part of the SOC persists in the soil for a longer period[100] and plays a significant role in climate change science. Soil organic matter can be: (1) physically stabilized, or protected from decomposition, through microaggregation, or (2) intimate association with silt and clay particles, and (3) can be biochemically stabilized through the formation of recalcitrant SOM compounds[101].

The SOC has generally been categorized into different pools - labile, stable, refractory and inert -based on their biological stability.

Accurate identification and estimation of the various SOC pools are crucial for mechanistic understanding and modeling of soil organic matter decomposition and stabilization processes[102]. Several physico-chemical methods are available to separate SOC fractions of different stabilities[103]:

- *physical fractionation methods* include particle size, density and aggregate separation (by using dry and wet sieving, slaking, dispersion (ultrasonic vibration in water), sedimentation and density separation. Physical method is generally time-consuming and involves many pre-treatments. As this approach alone cannot resolve the exact nature of the bonding between organic and mineral compounds, it cannot alone perform a satisfactory recovery of the stable SOC fraction.
- *wet chemical methods* involving the principle of solubility and mineralogy separation depending on the nature and degree of interactions between organic and mineral phases of soil. Among these methods, chemical oxidation is regarded as the most efficient at preferentially removing the young SOC inputs, simulating the microbial degradation that happens in nature. Neither fractionation method alone can accurately differentiate SOC fractions with distinct turnover time and stabilization processes, but the methods in combination can precisely isolate various fractions from the soils with different mineralogy, which will lead to a better understanding of SOC pools and their stabilization processes. Developments in the mid-infrared (MIR) spectroscopic measurement combined with partial least-squares regression is a promising method for predicting various stabilized soil C fractions.

5.2.5.4 Spectroscopic methods

The spectroscopic method could be a comparatively rapid and less time-consuming technique for measuring and monitoring SOC. Traditionally, employing these methods was confined to the laboratory, but subsequently some of these are increasingly applied for in-situ measurements and air-borne monitoring using platforms such as UAV, aircraft and satellites.

5.2.5.4.1 Visible and near-infrared (VNIR) and mid-MIR spectroscopy

5.2.5.4.1.1 Measurement in laboratory

Infrared reflectance spectroscopy is a rapid technique for measuring soil C based on the diffusely reflected radiation of illuminated soil[104]. Visible near-infrared (VNIR), shortwave infrared (SWIR) mid-infrared (MIR) diffuse reflectance spectroscopic (DRS) methods have been developed to estimate SOC. The VNIR (400–1100 nm), SWIR (1100–2500 nm) and MIR (2500–25,000 nm) spectra can be taken either in the laboratory or in the field.

MIR spectroscopy can also predict SOC and TC, often with more accuracy than VNIR spectroscopy. The diffuse reflectance spectroscopy can also accurately estimate TOC and particulate organic C (POC, <53 mm organic C fraction) while charcoal-C fraction can be estimated employing photo-oxidation and

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nuclear magnetic resonance[105]. Currently, several bench-top spectroradiometers covering a wide spectral range, and measurement resolution with different measurement principles are available. Nevertheless, there are several issues associated with laboratory spectroscopy, these being spectral configuration, detector performance, optical characteristics, calibration quality, sample homogeneity, reference method and measurement condition[106]. Other uses of laboratory spectroscopy include the development of calibration models in larger contexts (i.e. aerial and satellite) reflectance measurements[107].

5.2.5.4.1.2 Measurement in field

Both the VNIR and MIR portable instruments can be used for on-site analysis of SOC in the field, however for field conditions, appropriate correction methods are required in order to remove the effects of soil water on the spectra[108]. The VNIR is better than MIR spectroscopy at predicting in-situ estimation of SOC because strong water absorption in the MIR may blur or mask the absorption of SOC, which in turn will lead to inaccurate calibration and validation[109]. The surface roughness and spatial averaging of data (on the basis of speed and time of movement) also introduces error in SOC estimation in mobile devices for in-situ estimation of SOC[110]. Under such situations, these devices may not capture field level SOC variations[111]. Nevertheless, prediction using portable spectroscopy can match laboratory results through appropriate spectral pre-processing and implementing suitable methods to model SOC from VNIR-MIR spectra[112].

5.2.5.4.1.3 Aerial measurement

Only a few studies have been conducted for the prediction/estimation of SOC contents, where reflective spectroscopy using air-borne (aircraft or UAV) or satellite platform can be exploited. This is because of complexities involved in the acquisition of reflectance data. These attempts yielded varying level of success; the accuracy of prediction can be further enhanced at the regional level by following stringent appropriate calibration and validation procedures when using hyperspectral as well as multispectral data[113]. Strict scanning protocols, appropriate selection of spectral processing and models that correspond with soil data obtained from reference method is required for accurate prediction of SOC from the VNIR and MIR spectra[114].

5.2.5.4.2 Laser-induced breakdown spectroscopy (LIBS)

Laser-induced breakdown spectroscopy (LIBS) is based on atomic emission; the soil's C content is determined by analyzing the unique spectral signature of C (at 247.8 or 193 nm, or both). A laser beam at a specific wavelength, e.g., 1064 nm, is focused on each sample with a lens of 50 mm focal length to form microplasma that emits light that is characteristic of the sample's elemental composition[115]. The emitted light is spectrally resolved using a grated-intensified photodiode array detector. Intact soil cores or discrete, pressed samples are used for analysis; spectra are collected along a soil core or from each discrete sample. The spatial variability of C in soil profiles is accounted for by the ability to analyze and average multiple spots. Several researchers have reported a very good correlation between LIBS and conventional dry combustion that determined total SOC[116]. Different calibration models can now analyze the LIBS data and improve the prediction efficiency.

The presence of Fe and Si[117] and soil texture[118] and other chemical compositions affect the level of detection thus need signal correction to reduce the interference and improve estimation. By using LIBS the total carbon, organic carbon and inorganic carbon in soils of intact core without any pre-treatment can be discriminated in the 245–925 nm spectral range using LASSO and MRCE calibrations[119]. Unlike reflectance spectroscopy, the LIBS method can accurately determine soil bulk density and subsequently enable estimation of the SOC stock[120]. The LIBS can successfully estimate the humification degree of bulk organic matter in whole soil and its accuracy and precision are comparable to conventional methods such as electron spin resonance, nuclear magnetic resonance, and fluorescence spectroscopies[121]. However, further research is needed to mitigate limitations at the field level: soil structure, mineralogy, inorganic C (carbonates) content, moisture; and at the instrument level: plasma formation and interaction with the surroundings[122]. These issues must be dealt with order to ensure LIBS is widely accepted for SOC analysis.

5.2.5.4.3 Inelastic neutron scattering (INS)

The INS system is based on inelastic neutron scattering of neutrons from SOC nuclei and measuring gamma rays' response by gamma ray spectroscopy[123].

It can be used in-situ, and examine large volumes of soil and up to a depth of 30 cm[124]. It can also be run in scanning mode that helps in determining the mean carbon content of a large area in a short time[125].

For wider application of this technique, INS needs further improvement and specifically, this means system optimization, calibration in wider area and soil type and cheaper models to reduce errors.[126]

5.2.5.5 Measurements of carbon sequestration by eddy covariance technique

Recent decades have seen the development, refinement and deployment of flux measurement systems, based on principles of micrometeorology, in all kinds of terrestrial ecosystems[127]. The most widely used technique, eddy covariance (EC), relies on very frequent and highly accurate measurements of CO2 concentrations and air movements, that can be used to estimate the net gas exchange between the atmosphere and the land surface, as a result of photosynthesis (CO2 uptake) and ecosystem respiration (CO2 release). Gas fluxes, emission and exchange rates are carefully characterized from single-point in situ measurements using permanent or mobile towers, or moving platforms such as automobiles, helicopters, airplanes, etc[128]. When combined with measurements of harvested and exported biomass, and assuming other C losses (e.g. erosion, leaching) are negligible, EC can provide an integrated estimate of net ecosystem C stock changes and valuable information on its temporal dynamics.

EC measurement is a practical[129] tool for measuring net ecosystem exchange over annual cycles and can evaluate several crop rotations[130]. However, EC and other micrometeorological methods are (at present at least) restricted to the research environment. This is so as the techniques involve sophisticated and expensive instruments that require highly trained technical staff to manage and maintain them and to process and analyze the data. They also require several assumptions including relatively homogeneous study plots and level topography that are not always possible in manipulative field experiments or privately managed working lands. While these types of measurements are very useful for developing and validating ecosystem C models, they are not practical for routine deployment for C offset projects or in extensive farm/ranch-based measurement and monitoring networks. Rather, to meet such needs, soil sampling and measurement of SOC stock change is typically the most feasible field quantification approach.[131]

5.2.5.6 Life cycle analysis (LCA) for measurement of C sequestration in soil

Soil carbon sequestration, a climate change mitigation option for agriculture, can either increase or decrease as a result of land management change (LMC; i.e. changes in crop management practices which do not involve a permanent change in land cover; e.g. crop selection, rotations with high-biomass crops, shifting from annual to perennial crops or vice versa, change in bare fallow area, reducing or avoiding biomass burning, reducing tillage, crop residue management, nutrient and water management, use of organic fertilizers, and management of organic soils and degraded land) and land use change (LUC; i.e. change in the use or management of land by humans, which may lead to a change in land cover and is often divided into direct LUC (i.e. change in land management within the product system being assessed) and indirect LUC (i.e. change in the use or management of land which is a consequence of the production, use or disposal of raw materials, intermediate products and final products or wastes in the product system, but which does not take place at the location of the activities that cause the change)). To estimate all greenhouse gas (GHG) exchanges associated with various agricultural systems, life cycle assessments (LCAs) are frequently undertaken. To date LCA practitioners have not had a well-defined procedure to account for soil C in their assessments and as a consequence it is often not included.[132]

Soil carbon plays a vital role in other ecosystem services and should be included in life cycle assessment[133]. Soil carbon storage can be addressed either for delayed emissions impact category of

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LCA, or for the C foot printing (CF) framework[134].Despite the lack of consensus on how the impacts of land management and LUCs on SOC stocks would be best quantified within LCA, recommendations have been given for example by UNEP-SETAC. Their guidelines[135] are largely based on the framework of *Mila i Canals et al.., 2007*[136]. In this approach, the assessment is based on a comparison of the SOC stock level during production to a reference land use situation, which is defined as the constant SOC stock level in a biome-dependent natural state. The IPCC (The Intergovernmental Panel on Climate Change[137]) gives three optional approaches in estimating SOC changes in national greenhouse gas inventories: the 'Tier 1' approach corresponds to the simplest default methods; Tier 2 employs country-specific static parameters, where certain land-use types relate to some default SOC stock values. The most complex and recommended Tier 3 methods apply detailed measurements and/or modelling.

Goglio et al.., 2015[138] reviewed different methods to account for SOC in agricultural LCA, including measurements and dynamic crop-climate—soil models, simple carbon models and emission factors. They concluded that the selection of the method should be consistent with the objectives and scale of the LCA. Additionally, data availability affects the selection of the method. In their ranking of the preference of SOC accounting methods, models were preferred to measurements.

5.2.5.7 Model-based estimates of soil C stock changes

Models provide a means to predict SOC stock changes, taking into account the integrated effects of different management practices, as well as impacts of varying soil and climate conditions. Broadly speaking, there are two types of models used to predict SOC stock changes[139]:

1. *EMPIRICAL MODELS*

   Empirical models are based on statistical relationships estimated directly from sets of field experiment observations. The most widely known and used empirical-based model for predicting SOC stock changes is the model developed for the IIPCC national GHG inventory guidelines. The so-called Tier 1 method was developed to provide an easy way for countries (especially developing countries) to estimate national-scale SOC stock changes as a function of changes in land-use and management practices. The model uses a broad classification of climate and soil types to derive reference SOC stocks for native ('unmanaged') ecosystems, based on many thousands of measured soil pedons. Then, a set of scaling factors, estimated from statistical estimates of extensive field data sets, are applied to represent management impacts on stocks (i.e. land-use type, relative C input level, soil management). SOC stock changes are then computed for the stratified (i.e. climate x soil x management) land area being considered, as a function of observed land-use and management changes over a given time period. Constraints for the IPCC method include the lack of field experiment data for many climates, soil types and management combinations. The very broad climate, soil and management classes (and the high degree of aggregation of global data sets) from which the model was developed were intended to support national-scale inventory and reporting, whereas for more local application such as for C offset projects, additional data from regional and local field studies would be needed to re-estimate model parameters.

2. *PROCESS-BASED MODELS*

   In process-based models the model algorithms are based on more general scientific understanding, derived from laboratory and field-based experiments, as well as a variety of field-based observations of SOC distribution along climatic, vegetation, topographic and geological gradients. Empirical models are, by definition, restricted to making inferences within the range of conditions represented by the observations used to build the model, whereas process-based models are (in theory at least) more suitable for extrapolation and representation of conditions that might not be well represented in the observational data. Process-based models generally take the form of computer simulation models that employ sets of differential equations to describe the time and space dynamics of SOM. Most of the models that are currently used to support GHG inventory and/ or project-scale quantification were originally developed for research purposes, to analyze the behaviour of SOM as a function of environmental and edaphic variables (e.g. temperature, moisture, pH, aeration, soil texture) and land-use and management practices (e.g. vegetation type and productivity, crop rotation, tillage, nutrient management, irrigation, residue management). These types of models attempt to integrate these various factors, and knowledge about the intrinsic controls on decomposition and organic matter stabilization, into generalized models of SOC (and often soil nitrogen) dynamics and this comprehensive approach makes process-based models attractive as predictive tools to support SOC quantification at multiple scales. Examples of widely used process-based models that simulate SOC dynamics include DNDC, ROTHC, APSIM, DAYCENT, DSSAT, ECOSYS, EPIC, SOCRATES,…

While still primarily used to support basic research, process-based models are increasingly being utilized at local to national scales for soil C and soil GHG inventory purposes. To further develop the capabilities of process-based models for soil C accounting purposes, a better integration of models with supporting measurements is (e.g., networks of soil C monitoring sites, flux measurement networks and existing long-term field experiments) is needed. Continued efforts to evaluate the capabilities of process-based models to predict soil C changes and GHG emissions, including model intercomparison experiments, are needed as well.

5.3 WATER-RELATED SENSING

5.3.1 PRECIPITATION SENSING

Precipitation sensing is discussed within the *subchapter 4.4 – Automated Weather Stations.*

5.3.2 WATER LEVEL SENSING

Nowadays, the management of water is of paramount importance for modern societies due to the high water-availability requirements. The application of water management schemes requires the installation of water level data-acquisition systems[140].

Water level is one of the most commonly measured parameters, as accurate level data are essential for many applications. Climate change, pollution monitoring, and industrial water usage are broad reasons for monitoring water levels. Level is perceived as one of the most straightforward water parameters. In general, it is the level of water in a body of water, in groundwater, in a tank, etc. Not only are there very different water level applications and technologies used to measure it.

Establishing a baseline of water level is crucial for ponds, lakes, and reservoirs, as these data indicate when the volume of water is unusually low or high. Monitoring the water level in lakes and reservoirs is especially important, as they often serve as the source of drinking and irrigation water in many communities. In addition, these surface water bodies can generate electricity via a dam, help control floods, serve as a place for recreation, and as a habitat for wildlife.

5.3.2.1 Gage Height

Gage height is used to describe the water level of a river or stream. Level measurements in these applications are often collected at streamgage stations. Gage height changes due to precipitation or lack thereof, snowmelt, and water management decisions. A common reason to gather gage height data is to establish a baseline profile. These data are helpful to engineers that are designing structures such as bridges or levees. Additionally, ecologists can use baseline data when studying aquatic habitats and environmental impacts. Real-time gage height data can indicate when river levels are beginning to exceed the baseline, providing the local community an early warning of dangerous flood conditions.

Gage height is the most fundamental measurement captured at a streamgage station, a crucial piece of infrastructure for the long-term monitoring of surface water flows. These stations are often located in

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remote locations and provide end-users with reliable real-time data for decision making. Modern streamgaging stations often feature a water level instrument and a datalogger. The datalogger will contain an internal radio or cellular modem to transmit data to a database.

Gage height data can be used as the starting point for calculating discharge, although the method for doing so can vary from site to site. Often, a calibrated structure is already in place that controls water flow, such as a flume or weir. Flumes are specifically shaped structures – some are even prefabricated – that water flows through. A weir, sometimes called a low head dam, is often made from concrete or steel that stretches across an open channel.3 If a flume or weir is present, water level data is used to calculate discharge. Besides a water level sensor, discharge instrument (if necessary), and a datalogger, modern streamgaging stations are often equipped with instruments that measure water quality. For researchers aiming to obtain a comprehensive perspective on environmental phenomena, collecting water quality and level/discharge data is crucial to understanding what environmental and man-made influences impact a body of water

5.3.2.2 Measuring Water Levels

There are two main types of water level indicators – contact and non-contact. Contact sensors are placed in the water when measuring water level. In contrast, non-contact sensors use a measurement method (e.g., emission of microwave impulses or ultrasonic sound waves) that does not require any instrument components to be placed in the water.

5.3.2.2.1 Contact Water Level Sensors

These types of sensors have been around the longest. There is a wide range of contact sensors – from incredibly simple to high-tech – and some are designed for specific applications.

5.3.2.2.1.1 Crest Stage Gages[141]

A crest-stage gage is a simple way to measure water level, most often in streams and rivers. These gages consist of a metal pipe, wood staff, and a cork that's been crushed up. Unlike modern level sensors, the crest-stage gage can only record the maximum water level. They are typically 'reset' before a high-water event occurs and checked by a technician after the event is over or when the water level has stopped rising. Water enters through holes in the bottom of the pipe. It rises in the pipe, with the cork floating on top. Once the level stops rising, the cork sticks to the wood staff, and it stays there while the water recedes. Besides only being useful during high-water events, there are several potential issues with the design of a crest-stage gage:

- The holes in the bottom of the metal pipe can become clogged.
- Ants can build nests on the cork, thus preventing it from rising once a flood occurs.
- The cork can get washed out of the vent hole.

5.3.2.2.1.2 Staff Gages[142]

A staff gage provides a visual indication of the current water level. It looks like a ruler and is attached to a static structure, such as a bridge. The gage can be installed vertically or flush with the streambank on an incline, as this helps prevent damage. Staff gages are one of the most common reference sensors used when calibrating electronic level sensors. Staff gages are appropriate for water level measurement in nearly any application (e.g., rivers, reservoirs, wetlands). They do have limitations, as there's no way to monitor staff gages remotely – someone has to be on-site collecting data.

5.3.2.2.1.3 Wire-Weight Gages[143]

There are different types of wire-weight gages, but they all operate similarly. Wire-weight gages are placed over a body of water and are often attached to a bridge handrail. They consist of a drum wound with a cable that has a weight at the end. The technician lowers the weight to the surface of the water using a crank. A counter is part of the gage, and it is what determines how far the weight has been lowered. Once the technician has recorded a reading, they crank the cable back up from the water's surface. Like staff gages, wire-weight gages are often used as a reference when calibrating electronic level sensors

Wire-weight gages have a simple design, but they can be challenging to use. In turbulent conditions, multiple readings will be needed to determine the water level. If the water is still, it can be difficult to tell when the weight is touching the water. Like crest-stage and staff gages, wire-weight gages require a technician to visit the site and record measurements. used as a reference when calibrating electronic level sensors.

5.3.2.2.1.4 Electric Water Level Meters - Sounders

Electric water level meters – referred to as sounders – are frequently used in groundwater to measure level. These instruments are essentially tape measures with a probe on the end. Once the sensor contacts the water, it completes a circuit, causing an indicator to beep and an LED to glow. The water level depth can then be read on the tape.

Sounders are easy to use and relatively inexpensive. However, like the devices already mentioned, they require a technician to visit the site to take the measurement; these are not meant to collect continuous data.

5.3.2.2.1.5 Float Switches

Float switch – sometimes referred to as a level switch – indicates when the water level has risen or fallen to a specific point. These level sensors are most commonly used inside tanks at wastewater facilities and often trigger pumps or alarms. Because they are often deployed in harsh environments, float switches are constructed with rugged materials such as polypropylene. All float switches operate on the same basic principle – any change in position causes the sensor to activate.

5.3.2.2.1.6 Shaft Encoders

Shaft encoders are used to measure level in a stilling well as part of a streamgage station, hydro-meteorological site, or flood warning system. However, they are also sometimes used in groundwater wells.

Stilling wells are large vertical structures with a hollow center – many look like a giant tube – and are often installed along a riverbank. Water enters through pipes at the bottom of the well; this allows the water level in the well to be the same as that of the river. This design protects instrumentation inside the well and mitigates the impact of wind and turbulence on water level.

Shaft encoders are simple, accurate, reliable, and inexpensive. However, they must be installed inside a stilling well. Not only is a stilling well expensive and time-consuming to install, but they also have maintenance requirements and can be unsafe for those that need to service them.

5.3.2.2.1.7 Submersible Pressure Transducers

Submersible pressure transducers measure level by calculating the pressure exerted on them from the water column above – the more water above the sensor, the greater the pressure. Pressure is then converted to meters. Another source of pressure picked up by the sensor is the pressure exerted by the atmosphere upon the water's surface. Therefore, barometric pressure is a significant variable to consider when using pressure transducers. In general, there are two types of submersible pressure transducers – absolute and differential – that differ in how they handle barometric pressure compensation.

Differential pressure transducers are vented to the air via a vent tube, allowing the overall measurement to be compensated for barometric pressure. These are excellent options for challenging environments like wastewater sludge, lift/pump station sewage level, wet wells, and slurry tanks.

In contrast, absolute pressure transducers are not vented, so the pressure reading from the transducer reflects both the barometric pressure and the pressure attributed to the water column above it. Data can be adjusted to remove the influence of barometric pressure if an external barometric pressure sensor is

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used, but this requires additional steps. This also decreases the overall accuracy, as the error attributed to both the water level sensor and barometric pressure sensor are present in the final measurement.

Submersible pressure transducers can be used in a variety of applications, although they are most often used in groundwater. They are typically used in conjunction with a datalogger and a telemetry device when continuously monitoring water levels.

Submersible pressure transducers are easy to use. However, the sensing portion of the instrument – electronics included – is placed in the water, so they have a shorter lifespan than some other sensors (e.g., Bubbler). Also, pressure transducers can become clogged or damaged by debris in the water column are not the best choice when the water is turbulent.

5.3.2.2.1.8 Bubblers

Bubblers feature pressure sensors that are not placed in the water. However, they are still considered contact sensors, as part of the instrument – the orifice line (e.g., a plastic tube) – is placed in the stream.

They operate by continuously forcing air from the instrument housing through the orifice line. A pressure sensor in the instrument housing records the pressure required to push the air out of the line, while an onboard barometer automatically compensates measurements for barometric pressure.

Bubblers are accurate and can be used in a variety of applications, although they are most often used in surface water. The sensor is not placed in the water column, thus reducing the risk of premature sensor failure and damage to the sensor from debris. Therefore, bubblers tend to last longer than submersible pressure transducers. There are very few drawbacks to bubblers, one of which is the potential for the orifice line to become clogged.

5.3.2.2.1.9 Acoustic Sensors

Acoustic Sensors use an acoustic beam to measure water level. The beam sends a short pulse and waits for a reflection from the water's surface. The instrument converts the reflection time to level based on the speed of sound in the water at the site; this depends on temperature (measured with an integrated sensor) and salinity (user-defined).

While the beam is the primary measurement method, an onboard pressure sensor serves as a secondary measurement in the event valid data from the acoustic beam cannot be collected. The pressure sensor is not vented to the atmosphere; therefore, it must be calibrated for changes in atmospheric conditions.

The main advantage is they measure velocity in addition to level and are ideal for monitoring flows in canals, culverts, pipes, and natural streams.

The primary disadvantage to acoustic instruments is cost; these are the most expensive type of level instruments. Also, they are susceptible to fouling covering the sensing surfaces and can be complex to maintain. Thus for the purpose of measuring level alone, acoustic sensors might not be the best choice. But if level is the secondary aim and flow is a priority, these sensors can't be beat.

5.3.2.2.2 Non-Contact Water Level Sensors

Non-contact sensors have an advantage over contact sensors in some applications. They can be used when water may not always be present – bubblers can also be used in such an application – or when the sensor cannot be placed in the water due to other hazards. This also makes non-contact sensors safer for those that maintain them. Another advantage is there's no concern of sensor damage due to debris and flood conditions. It is for these reasons that many professionals prefer non-contact sensors.

It should be noted that non-contact sensors are susceptible to vandalism and damage from wind/severe weather events. They also need to be calibrated to measure the water level accurately and to eliminate interferences.

5.3.2.2.2.1 Radar Sensors

Radar water level sensors "downward-looking" measuring systems that operate based on the time-of-flight method (ToF). They are typically attached to structures like bridges. Microwave impulses are emitted by an antenna, reflected off the target (water surface), and received by the radar system. Radars are popular because they provide stable, long-term monitoring with high accuracy and a low cost to service and operate. As previously mentioned, non-contact sensors need to be configured to eliminate interferences.

5.3.2.2.2.2 Ultrasonic Sensors

Ultrasonic sensors are similar to radars, as both sensors are typically installed above the water's surface. However, ultrasonic sensors use ultrasonic sound waves – these require a medium to pass through, unlike microwaves – to determine the distance from the face of the sensor to the surface of the water by timing how long it takes the signal to return.

Ultrasonic sensors used for above-ground applications senda out a soundwave, this signal spreads outward with a beam angle, and objects in the path of the beam will interfere with the signal return. This type of sensor is suitable for various applications, including measuring river, lake, and tank levels and measuring open channel flow in larger flumes.

5.3.3 INFILTRATION CAPACITY

Infiltration is the act of water moving from the land surface into the soil. Usually, the infiltration is considered occurring in response to rainfall, where water is applied over the whole land surface. In that case, infiltration is important because it is one of the deciding factors in how much rainfall becomes available to plants and groundwater, versus running off over the land surface and potentially causing erosion and flooding.

Infiltration is also important for applications like irrigation – where furrows or drips might apply water to one part of the surface and not others, in order to more efficiently provide water to crops.

Infiltration is extremely important for stormwater green infrastructure, like rain gardens and bioretention cells, because we are explicitly designing them to be able to infiltrate water from impervious surfaces like parking lots and roof tops. For green infrastructure, the engineered soil properties are carefully designed to promote just the right amount of infiltration, but the performance of the green infrastructure can also be affected by the infiltration capacity of the surrounding native soils and sub-soil[144].

5.3.3.1 Infiltration Rate and Infiltration Capacity

Typically, we talk about infiltration as a rate: how fast is water entering the soil. But a lot of soils can soak lower precipitation quantities of water in giving an infiltration rate that is equal to rainfall rate. So, just talking about infiltration rate might not be helpful.

Contrary, the infiltration capacity tells us the maximum rate at which water can enter a soil. However, infiltration capacity changes over the course of a rain storm (or irrigation event), so it cannot just be measured at any random point of time and assume the data captured reflects a value that applies at other times.

After a long enough period of time, the infiltration capacity starts to asymptotically approach a constant value. This is called steady-state rate the equilibrium infiltration capacity, which conveniently and logically is approximately equal to the saturated hydraulic conductivity. Quantifying the soil infiltration capacity (soil infiltrability) is very important for determining components of the hydrological modelling, irrigation design and many other natural or manmade processes.

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5.3.3.2 Measuring Infiltration Capacity

5.3.3.2.1 Single Ring Infiltrometer

A single-ring infiltrometer involves driving a ring into the soil and supplying water in the ring either at constant head or falling head condition. Constant head refers to condition where the amount of water in the ring is always held constant. Because infiltration capacity is the maximum infiltration rate, and if infiltration rate exceeds the infiltration capacity, runoff will be the consequence, therefore maintaining constant head means the rate of water supplied corresponds to the infiltration capacity. The supplying of water is done with a Mariotte's bottle. Falling head refers to condition where water is supplied in the ring, and the water is allowed to drop with time. The operator records how much water goes into the soil for a given time period. The rate of which water goes into the soil is related to the soil's hydraulic conductivity. Infiltration capacity measurements with a single ring infiltrometer is considered less accurate than with double ring infiltrometer.

5.3.3.2.2 Double Ring Infiltrometer

Double ring infiltrometer devices consist of two concentric rings (30 cm and 45-60 cm in diameter) pounded slightly into the soil and filled with water. The water from the outer ring helps wet the soil and infiltrates both vertically and laterally into the dry soil. The infiltration rate is measured in the inner ring, where infiltration and percolation are happening only vertically, thanks to the water from the outer ring doing the lateral movement. Water levels are maintained at the same depths in both rings. The outer ring reduces the boundary effects for the measurement of vertical infiltration in the inner ring.

Tests can be conducted in two ways: falling head and constant head. In a falling head test, water is added to the rings and the water level declines over time as infiltration occurs. In high infiltration capacity soils, it may be necessary to add water several times before steady state is achieved. Falling head tests require less equipment than constant head tests, but the calculations are more complicated. In constant head tests, a device called a Mariotte bottle is added to the infiltrometer. A Mariotte bottle releases water so that a constant level (or head) is maintained inside the rings. This simplifies the calculations considerably.

5.3.3.2.3 Guelph Permeameter

The Guelph permeameter works on a similar principle as the infiltrometer, but water coming out of it sets up a wet bulb of a specific known shape, from which you can calculate equilibrium infiltration capacity. With a Guelph permeameter, the measurements are made at two different specified heads (usually 5 and 10 cm), and in each case allow infiltration to occur until a steady rate is reached. Then steady rates and chosen head values are inserted into an equation to get a number for saturated hydraulic conductivity. Guelph permeameter enables fairly easily to get vertical profiles of hydraulic conductivity or get the measurement at single specified depth below the surface (this would be useful for green infrastructure design, for example).

5.3.4 WATER QUALITY DATA MONITORING

Monitoring the qualitative status of freshwaters is an important goal of the international community, as stated in the Sustainable Development Goal (SDGs) indicator 6.3.2 on good ambient water quality. Monitoring data are, however, lacking in many countries, allegedly because of capacity challenges of less-developed countries[145]. Water quality monitoring programs are developed to meet goals including attaining regulatory compliance, evaluating long-term environmental changes, or quantifying the impact of an emergency event[146].

The quality of water resources in urban areas has undergone degradation due to the discharge of domestic and industrial wastewaters and urbanization among other factors. Despite the legal instruments that aim to preserve water bodies, other mechanisms should be implemented, such as monitoring networks and reporting results. Another challenge is the interpretation of the results that may support decision making on the actions that must be taken to preserve the water quality[147].

The proposed Upsurge sensing systems that will be implemented in 5 demonstration cities will not include water quality data gathering, however inclusion of such data from other official monitoring and measurement sources should be included in the overall environmental assessment and determining the rate of achieving the Key Performance Indicators proposed.

5.3.5 WATER CONSUMPTION DATA

Water shortages are increasingly making news headlines around the world with cities — such as Cape Town, South Africa, and Cairo, Egypt — already facing or expected to face severe shortages in water supply. With many major rivers and lakes scattered across its territory, Europe might appear unaffected by water shortages or water stress. This is not at all the case. In fact, water stress is a problem that affects millions around the world, including over 100 million people in Europe.

Similar to many regions in the rest of the world, worries over water stress and scarcity are increasing in Europe too, amid an increased risk of droughts due to climate change. About 88.2 % of Europe's freshwater use (drinking and other uses) comes from rivers and groundwater, while the rest comes from Reservoirs (10.3 %) and Lakes (1,5 %), which makes these sources extremely vulnerable to threats posed by over-exploitation, pollution and climate change.

Like any other vital resource or living organism, water can come under pressure, especially when demand for it exceeds supply or poor quality restricts its use. Climate conditions and water demand are the two key factors that drive water stress. Such pressure on water causes a deterioration of freshwater resources in terms of quantity (overexploitation or drought) and quality (pollution and eutrophication).

Despite the relative abundance of freshwater resources in parts of Europe, water availability and socio-economic activity are unevenly distributed, leading to major differences in levels of water stress over seasons and regions. Water demand across Europe has steadily increased over the past 50 years, partly due to population growth. This has led to an overall decrease in renewable water resources per capita by 24 % across Europe. This decrease is particularly evident in southern Europe, caused mainly by lower precipitation levels, according to an EEA indicator. For instance, in the summer of 2015, renewable freshwater resources (such as groundwater, lakes, rivers or reservoirs) were 20 % less than in the same period in 2014 because of a 10 % net drop in precipitation. More people moving to cities and towns has also impacted demand, especially in densely populated areas.

The EEA estimates that around one third of the EU territory is exposed to water stress conditions, either permanently or temporarily. Countries such as Greece, Portugal and Spain have already seen severe droughts during the summer months, but water scarcity is also becoming an issue in northern regions, including parts of the United Kingdom and Germany. Agricultural areas with intensive irrigation, islands in southern Europe popular with tourists and large urban agglomerations are deemed to be the biggest water stress hotspots. Water shortages are expected to become more frequent because of climate change[148].

The proposed Upsurge sensing systems that will be implemented in 5 demonstration cities will not include water consumption data gathering, however inclusion of such data from other official monitoring and measurement sources should be included, if sensible, in the overall environmental assessment and determining the rate of achieving the Key Performance Indicators proposed.

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5.4 URBAN HEAT ISLAND (UHI)

5.4.1 DEFINITION OF UHI

The Urban Heat Island (UHI) phenomenon is one example of local climate change. This effect is characterized by the heating of urban zones in comparison to its non-urbanized surroundings. The effect is most relevant at night when urban surfaces, with higher heat capacities than rural surfaces, release energy that has been stored during the daytime with less efficiency than do the rural areas. Among the local impacts of the UHI phenomenon, those who stand out are the influence on the energy consumption, mainly in hot climate regions where the use of air-conditioning is increasing. Moreover, higher urban temperatures can increase the amount of urban smog that is formed, raising the level of air pollution. Finally, one of the most important impacts is the influence on human health.

UHI is the difference between the temperature in a certain urban location and that at a given reference point in a nonurban location (e.g., an upwind rural location). Obviously, the choice of urban and reference points or a collection of points can affect the magnitude and the characteristics of a reported UHI.

Keeping the urban scale in mind, there can be a surface temperature heat island and an air temperature heat island. The latter can be further broken down using various scales and criteria, but some common classifications include canopy-layer heat islands and the more generic boundary-layer heat islands. The former generally occur below effective roof level (quite qualitatively) and the latter extend up to the boundaries of the urban heat plume[149].

5.4.2 CAUSES OF UHIS

Heat islands form as a result of several factors[150]:

- Reduced Natural Landscapes in Urban Areas. Trees, vegetation, and water bodies tend to cool the air by providing shade, transpiring water from plant leaves, and evaporating surface water, respectively. Hard, dry surfaces in urban areas – such as roofs, sidewalks, roads, buildings, and parking lots provide less shade and moisture than natural landscapes and therefore contribute to higher temperatures.
- Urban Material Properties. Conventional human-made materials used in urban environments such as pavements or roofing tend to reflect less solar energy, and absorb and emit more of the sun's heat compared to trees, vegetation, and other natural surfaces. Often, heat islands build throughout the day and become more pronounced after sunset due to the slow release of heat from urban materials.
- Urban Geometry. The dimensions and spacing of buildings within a city influence wind flow and urban materials' ability to absorb and release solar energy. In heavily developed areas, surfaces and structures obstructed by neighbouring buildings become large thermal masses that cannot release their heat readily. Cities with many narrow streets and tall buildings become urban canyons, which can block natural wind flow that would bring cooling effects.
- Heat Generated from Human Activities. Vehicles, air-conditioning units, buildings, and industrial facilities all emit heat into the urban environment. These sources of human-generated, or anthropogenic, waste heat can contribute to heat island effects.
- Weather and Geography. Calm and clear weather conditions result in more severe heat islands by maximizing the amount of solar energy reaching urban surfaces and minimizing the amount of heat that can be carried away. Conversely, strong winds and cloud cover suppress heat island formation. Geographic features can also impact the heat island effect. For example, nearby mountains can block wind from reaching a city, or create wind patterns that pass through a city.

5.4.3 TYPES OF UHIS WITH SENSING APPROACHES

Surface and atmospheric urban heat islands types differ in the ways they are formed, the techniques used to identify and measure them, their impacts, and to some degree, the methods available to mitigate them.

5.4.3.1 Surface UHIs

Surface urban heat islands are typically present day and night, but tend to be strongest during the day when the sun is shining. On average, the difference in daytime surface temperatures between developed and rural areas is up to 10 to 15°C; the difference in night-time surface temperatures is typically smaller, at 5 to 10°C. The magnitude of surface urban heat islands varies with seasons, due to changes in the sun's intensity as well as ground cover and weather. As a result of such variation, surface urban heat islands are typically largest in the summer[151].

To identify urban heat islands, scientists use direct and indirect methods, numerical modelling, and estimates based on empirical models. Researchers often use remote sensing, an indirect measurement technique, to estimate surface temperatures. They use the data collected to produce thermal images.

5.4.3.1.1 Define the Objectives

The first and most critical step is to define the objectives trying to be achieved. There are many reasons to undertake a heat island assessment, but the two most common are:

- <u>Understanding energy implications:</u> Higher urban temperatures drive demand for air conditioning, leading to higher energy bills during the warmer months of the year. Analyzing how temperatures in an urban area differ from those in the surrounding region will help quantify the energy impacts.
- <u>Understanding public health risks:</u> Heat islands can contribute to poor air quality, magnify the impacts of extreme heat events, and put people's health at higher risk. Identifying hot spots within a city can help focus interventions where they are most needed during heat waves.

5.4.3.1.2 Determine the Geographic Coverage

After clarifying the objectives, the determination of geographic coverage of data collection effort, the kind of data needed (air vs. surface temperatures, or both), and finding useful sources of existing temperature data is needed.

Assessments focused primarily on energy-related impacts of heat islands typically compare the temperature in the overall urban area with the temperature in the surrounding rural area to determine how much additional energy demand is caused by the urban heat island.

Assessments focused on health-related impacts of heat islands typically focus on assessing the differences in air temperatures among different locations within the city (i.e., identifying hot spots), and / or reference locations selected outside the urban area.

5.4.3.1.3 Types of Temperature Data

5.4.3.1.3.1 Air temperatures

Air temperatures are important for assessing heat islands are those found within the urban canopy, from ground level to the tops of trees and buildings. They are most useful for a study whose goal is to mitigate public health risks since they are the best indicators of conditions actually experienced by people.

Air temperatures can be measured directly using standard weather stations and other monitoring instruments and/or mobile traverses (cars with sensors that record temperatures along a fixed line). However, because monitoring networks and traverses typically cover just a portion of the city's area, they may not provide a representative picture of citywide temperatures. Urban climate models can be used in conjunction with observed data to estimate temperatures in places where no field data are available.

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5.4.3.1.3.2 Surface temperatures

Surface temperatures represent heat energy given off by the land, buildings, and other surfaces. Technologies that measure temperatures of surfaces, such as instruments mounted on satellites and airplanes, can provide better geographic coverage than those used for recording air temperatures. They can reveal temperature differences at very fine scales: for example, between roofs, pavements, and grassy areas. A combination of satellite data for surface temperatures and data from monitoring stations or traverses for air temperatures offers the most complete picture of a city's heat island.

5.4.3.1.4 Measuring Surface Temperatures

5.4.3.1.4.1 Satellites

Satellites provide extensive geographic coverage, but cannot portray the finer details of hot spots within neighbourhoods. Trees or tall buildings may prevent satellites from accurately capturing the temperatures of surfaces at ground level. Data are collected only during the times when a satellite passes over a city, and are available only for clear weather conditions.

5.4.3.1.4.2 Aircraft-Borne Instruments

Surface temperature data from aircraft-borne instruments offer higher resolution than those from satellites, since airplanes fly at lower altitudes, but aircraft data are more expensive and provide irregular coverage.

5.4.3.1.4.3 Ground-Based Thermal Sensing

Ground-based thermal sensing (e.g., using hand-held instruments that are pointed at surfaces to measure their temperature) can be used to get surface temperature data for specific urban features (e.g., parking lots versus city parks) or different surface types, such as light-colored roofs versus dark roofs.

Non-contact infrared measurement is proposed since it is often the better alternative for this as compared with tactile methods. An infrared thermometer (IRT) measures temperature by sensing the infrared radiation (light) coming from a surface. This instrument is sensitive to infrared radiation at wavelengths in the 8-14 μm range. With the IRT (that, when necessary, is wrapped in a thermal glove or has been placed outdoors for at least 30 minutes prior to data collection), surface temperature measurements can be taken of a wide variety of surfaces in a non-contact way.

5.4.3.2 Atmospheric Urban Heat Islands

Warmer air in urban areas compared to cooler air in nearby rural surroundings defines atmospheric urban heat islands. Atmospheric urban heat islands are often weak during the late morning and throughout the day and become more pronounced after sunset due to the slow release of heat from urban infrastructure. The timing of this peak, however, depends on the properties of urban and rural surfaces, the season, and prevailing weather conditions. Experts often divide these heat islands into two different types: Canopy layer UHI and Boundary layer UHI.

5.4.3.2.1 Canopy Layer UHIs

Urban canopy-layer heat islands (UCL) urban heat islands exist in the layer of air where people live, from the ground to below the tops of trees and roofs. UCL are the most commonly observed of the two types and are often the ones referred to in discussions of urban heat islands.

It describes the warmth of a near-surface air layer that extends from the ground to the mean height of the buildings and vegetation. It is the most commonly measured layer of the atmosphere in cities for air temperatures because it is easily accessed by ground-based instruments that are either fixed or mobile (e.g., on vehicles).

UCL are typically the largest at night during weather conditions in which winds are calm and skies are clear. Heat island intensities under such conditions are typically a few degrees Celsius in large parts of most cities and may exceed 10°C for the most densely developed parts of a large city. They are smaller and sometimes may even slightly negative (representing an urban "cool island") during clear daytime conditions; together, these indicate a strong temporal variability of the heat island over the course of a day under calm, clear weather conditions. When averaged over all weather conditions, the heat island magnitude in the UCL is typically 1°C - 3°C.

The spatial structure of the heat island shows a pattern of isotherms - isolines of equal temperature - that follow the border of the city with a relatively tight spacing when winds are calm, and hence the topographic analogy with an island. The spatial temperature gradient, the change of temperature over space, is typically large near the edge of the "island," forming the so-called cliff in response to the large relative change in surface characteristics in the region of rural-to-urban transition. Within the urban area, temperatures in the UCL are strongly controlled by the local characteristics of the urban surface. They may show substantial spatial variability (on the order of several °C) when weather conditions are favourable. The highest night-time temperatures, the peak of the heat island, are usually associated with the area of most intense urban development, and some warmer air is often transported horizontally downwind of the city.

5.4.3.2.1.1 Measuring Canopy Layer UHIs

Air temperature measurements using direct techniques (thermocouples and thermistors) are relatively simple. Often simple urban-rural station pairs are used to assess the UHI effect, but they may miss the location of the UHI peak as opposed to car traverses that provide a more complete sample of the full diversity of urban morphologies and land uses. More recently, networks with a large number of stations to provide better spatial resolution have been employed, benefiting from advances made in sensor miniaturization and data transmission technology. Careful siting and exposure are essential to obtain meaningful observations. The characteristics of the surface and atmosphere within the source determine the measured temperature.

To monitor the thermal environment of the canopy layer, the sensors must be exposed so that their microscale surroundings are representative of the local-scale environment representative of the selected neighbourhood. The sensor location must be surrounded by "typical" conditions for urban terrain. Ideally, the site should be located in an open space, where the surrounding n height-to-width ratio is representative of the local environment, away from trees buildings or other obstructions. Care should be taken to standardize practice across all sites used in a network regarding radiation shields, ventilation, height (2 – 5m is acceptable given that the air in canyons is usually well mixed) and to ensure that sensors are properly calibrated against each other. Locations in urban parks, over open grass areas, or on rooftops should be avoided since they are not representative of the urban canopy.[152]

Either individual air temperature sensors are proposed installed in line with the conditions as set forth in the previous paragraph, or temperature measurements could be taken from existing weather stations, however their placement with regard to the conditions should be pre-assessed.

5.4.3.2.2 Boundary layer UHIs

Above the UCL, the urban boundary-layer heat island represents an urban-scale warming through the depth of the urban boundary layer (up to 1-2 km during daytime with clear skies and a few 10s to 100s of meters at night) that has a smaller magnitude and is much less spatially and temporally variable than that of the underlying UCL heat island. The heat island magnitude here is positive both day and night.

The warmed boundary-layer air above the city is often transported downwind by the mean wind leading to a plume of warmer air above downwind non-rural areas.

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5.4.3.2.2.1 Measuring Boundary layer UHIs

Measurements of the urban boundary-layer heat island are relatively rare as access to this layer is difficult. Thermometers must be mounted on tall towers, balloons, or aircraft; or temperatures can be observed by remote sensing techniques using ground-based instruments.

5.5 AUTOMATED WEATHER STATIONS (AWS)

Meteorological (and related environmental and geophysical) observations are made for a variety of reasons. They are used for the real-time preparation of weather analyzes, forecasts and severe weather warnings, for the study of climate, for local weather dependent operations (for example, local aerodrome flying operations, construction work on land and at sea), for hydrology and agricultural meteorology, and for research in meteorology and climatology[153].

An automated weather station (AWS) is an automatic version of a traditional weather station. They can be single-site or part of a weather network. Automatic weather stations are the worldwide standard for climate and boundary-layer meteorology.

Surface weather observations are widely expanding for multiple reasons: availability of new technologies, enhanced data transmission features, transition from manual to automatic equipment, early warning for critical climate risks. One of the main objective is to rehabilitate/increase the density of existing network, by providing data from new sites and from sites that are difficult to access and inhospitable. Despite the increasing number of AWS's deployed, many remote sites are still not covered by surface observations[154].

An AWS consists of sensors, which automatically collect and transmit weather data. If these AWSs are deployed in larger numbers, the reliability and accuracy of their data is improved, hence accurate weather predictions.

5.5.1 TYPICAL AWS COMPOSITION

A typical weather station consists of a data logger and sensors mounted on a metal tripod. The system typically runs on battery power or a combination of solar power and a rechargeable battery. Key components of a weather station include:

- Data logger
- Sensors
- Cables
- Tripod or other mounting system
- Grounding
- Securing equipment such as guy wires

5.5.1.1 Positioning

Some researchers need data on general weather conditions for an area. In these applications, researchers should place their weather stations in open, unobstructed locations. Buildings and trees can affect temperature, relative humidity, rainfall, wind speed, and wind direction. For this reason, weather stations should also be at a distance of at least ten times the height of nearby trees and buildings away from these obstructions.

In many cases, researchers use weather stations to measure microclimates. For instance, a researcher might measure microclimates to learn how elevation affects temperature in a given area, while another may study how the absence of a tree canopy affects a microclimate. Although meteorological guidelines are helpful for setting up weather stations that measure general weather conditions, these guidelines may not apply for measuring microclimates. In these cases, researchers choose sites specific to their study and usually use multiple stations on various sites or move individual weather stations during the course of their research.

5.5.1.2 Data Logger

The data logger is the central unit within the weather station. Its primary components are a microprocessor, data input channels, battery, and a weatherproof enclosure. Data loggers record and store data collected from sensors at pre-set intervals. Researchers retrieve this data by offloading it to a PC or a data "shuttle" transfer device, or by accessing it remotely via cellular, WiFi, or other types of remote communications.

Researchers should consider the number of data input channels a data logger provides before purchasing. This number determines how many sensors can be added to the weather station.

Next, researchers should consider how weatherproof the housing is. Good weatherproofing ensures electronic components stay dry and function properly in wet or otherwise harsh outdoor environmental conditions.

5.5.1.3 Sensors

AWS use special instruments to measure the surface weather observations. Some parts of a weather station include a thermometer to measure temperature and a barometer to measure atmospheric pressure.

Depending on the provider and model, there are several components that make up a station. Each component enables the weather station to measure and transmit different atmospheric data. Within this subchapter 12 types of most common weather sensors are presented. AWS could also include some soil sensors (e.g. moisture), which are discussed in detail in subchapter 4.1.

5.5.1.3.1 Thermometer and Hygrometer

In outdoor weather monitoring, temperature and humidity sensors are one of the most basic measurement elements. The temperature and humidity measurement module itself is neither dust-proof nor water-proof, so it is usually placed in a waterproof and dust-proof solar radiation shield. It can not only protect the sensor from a harsh environment but also ensure good air permeability. This kind of meteorological temperature and humidity sensor can effectively measure the temperature and relative humidity in the atmosphere and is an outdoor temperature and humidity sensor with the highest usage rate and the best effect.

5.5.1.3.2 Anemometer

Anemometers measure wind speed and direction by the amount of wind pressure against a surface, such as a cup or a propeller, or by using sonic pulses. A mechanical anemometer contains a wheel with cups or a propeller at the end of the spokes of the wheel. One of them contains a magnet. Each time the magnet passes a switch, it makes a recording. This can give an extremely accurate reading of the wind speed. There are several types of anemometers.

A sonic anemometer, for example, uses disturbances and sound waves to calculate wind speed. It has no moving parts and relies on sonic pulse technology to measure both wind speed and direction. There are also Laser Doppler anemometers, plate and tube anemometers, wire anemometers, vane anemometers, and other designs. The Davis mechanical anemometer has sealed, stainless steel ball bearings that give it a long life under continuous use. It is rugged, but it is also accurate enough to measure the lightest breeze or change in wind speed.

5.5.1.3.3 Rain Gauge

The next important and easy-to-understand piece of any automatic weather sensor is a rain gauge. Rain gauges measure the liquid-equivalent precipitation. A rain gauge looks like a bucket or wide, vertical cylinder. Weather stations that have rain gauges can tell you how much rain or snow has fallen in a given time period. The rain gauges can provide the following information: daily rainfall, total daily rainfall average, weekly rainfall, total weekly rainfall average, yearly rainfall, total yearly rainfall average.

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5.5.1.3.4 Barometer

The atmospheric pressure sensor is a detection device that can feel the information of the air pressure, and can transform the detected information into an electrical signal or other required forms of information output according to a certain rule, usually composed of sensitive components and conversion components. It can be applied to air pressure and altitude measurement and is usually a supporting product of automatic weather station.

5.5.1.3.5 Solar radiation sensor

The total solar radiation sensor is an important ground meteorological observation instrument, and it is also an indispensable equipment in the field of solar energy resource survey and photovoltaic power station operation monitoring. At present, the photoelectric total solar radiation sensor and the pyroelectric total solar radiation sensor are commonly used.

The solar radiation sensor is equipped with a specially treated transparent dust cover outside the sensing element. Its light transmittance is as high as 95%. The transparent double glass cover has good sensitivity. The surface is specially treated to prevent dust adsorption and reduce outdoor dust. Adsorption can also effectively prevent environmental factors from interfering with internal components.

5.5.1.3.6 Sunlight sensor

The sunlight sensor is a device that detects the intensity of light. The working principle is to convert the illuminance into a voltage or current value. The light sensor has a high-sensitivity photosensitive detector that can monitor artificial light and natural light and has a wide range of applications. Light sensors include a solar radiation shield type used outdoors and a wall-mounted type used indoors. In meteorological monitoring, the most commonly used solar illumination ranges are 0-10W and 0-20W.

5.5.1.3.7 UV sensor

The ultraviolet sensor can use the photosensitive element to convert the ultraviolet signal into a measurable electrical signal through the photovoltaic mode and the light guide mode. When ultraviolet rays are irradiated on the ultraviolet sensor, more than 98% of the ultraviolet rays are transmitted through the see-through window made of high-quality light-transmitting materials, and irradiated on the measuring device that is sensitive to ultraviolet rays with a wavelength of 240~370nm.

5.5.1.3.8 Noise sensor

The noise sensor is a high-precision sound measuring instrument that can measure the sound size and noise intensity in real time. Its monitoring range is as high as 30dB~120dB, and the measurement frequency is also relatively wide between 20~12.5KHz. In order to facilitate the installation and use in different places, the noise sensor is divided into wall-mounted and solar radiation shields. For example, the solar radiation shield noise sensor can be selected when used in outdoor weather or construction sites. Its main feature is waterproof, rain, and snow have no effect on it.

5.5.1.3.9 Negative oxygen ions sensor

In the natural ecosystem, forests and wetlands are important places for generating negative oxygen ions in the air. Its concentration level is one of the indicators of urban air quality evaluation, and it is called “air vitamin”. The negative oxygen ion sensor is a special instrument for measuring gas ions in the atmosphere. It can measure the concentration of air ions, distinguish the positive and negative polarities of ions, and can distinguish the size of the measured ions according to the difference of ion mobility. Generally, a capacitive collector is used to collect the charge carried by air ions, and the current formed by these charges is measured by a micro-amperometer. The negative oxygen ion detector used in the process of weather monitoring is usually multi-functional, not only can monitor the number of negative oxygen ions, but also monitor temperature and humidity, formaldehyde, PM2.5 and TVOC and other environmental elements at the same time.

5.5.1.3.10 Evaporation sensor

Evaporation sensor is a sensor used to perceive the change of water surface evaporation, which can observe the change law of water surface evaporation in different time periods. The evaporation capacity sensor adopts the pressure measurement principle, which measures the evaporation capacity by measuring the change in the weight of the liquid in the evaporating dish, and then calculating the height of the page. This evaporation sensor can adapt to water surface evaporation measurement in various environments, and is not affected by liquid freezing. It overcomes the shortcomings of inaccurate measurement when the liquid level is measured by the ultrasonic principle.

5.5.1.3.11 Leaf wetness sensor

The leaf wetness sensor can accurately measure the leaf surface humidity, and can monitor the trace moisture or ice crystal residues on the leaf surface. The shape of the sensor adopts the design of imitating the blade, which truly simulates the characteristics so it can more accurately reflect the condition of the leaf surface. It measures the amount of water or ice by imitating the change in the dielectric constant of the upper surface of the blade medium. Low power consumption, long-term uninterrupted monitoring can be carried out. It is easy to install and can be hung on the greenhouse or used on the mast of the weather station.

6 BEEOMONITORING – NATURE-BASED SENSING SOLUTION

6.1 Introduction

BeeOmonitoring is a tool for measuring biodiversity and pollution through the analysis of pollen collected by bees, which act as natural drones and bioindicators. Many actors in different sectors use bee biomonitoring: water producers and catchment protection, actors in sustainable real estate and land use planning, food and beverage, industrial sector (recycling, incinerators, biopharmaceuticals, production and transformation, quarries, etc.), smart cities, energy, committed companies, etc. It is the only tool that allows the collection of qualitative and quantitative data on:

- the number and type of plant species present and their deficiency and impact on the whole ecosystem (biodiversity measurement tool);
- the type, concentration and impact of industrial and agricultural pollution (pollution measurement tool);
- over large areas, at low cost and on a continuous basis.

The measurements collected allow targeted action to be taken, if necessary, by collaborating or communicating with the local community and evaluating the impact of the measures taken, with scientific indicators and figures. Through the analysis of samples can identify, source and assess the level of pollutants (25 heavy metals, 523 pesticides, nitrates, PAH, dioxins, GMO, radio-activity) and take stock of biodiversity. BeeOmonitoring makes it possible to:

(i) monitor industrial and agricultural pollution;
(ii) assess the quality/diversity of plants;
(iii) make targeted improvement decisions; and
(iv) involve local communities to enhance biodiversity. No other method can monitor so many pollutants and provide biodiversity metrics as efficiently.

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6.2 Objectives of the BeeOmonitoring approach in the Upsurge Sensing System

Within Upsurge Sensing System, bee-based sensing solution will be deployed by distributing sampling equipment to local beekeepers with instructions on how to collect the pollen so it can be used for testing. Sample analysis of their pollen will identify the presence of pollutants, a reverse-engineering process their origin, their concentration and their impact on the environment and health. This data will be analyzed to provide quantitative and qualitative indicators of biodiversity and pollution in the respective locations. BeeOmonitoring will be included into the Upsurge Sensing System with the following objectives:

Objective I:

- To monitor pollutants & identification of their origin at 5 Upsurge demonstrations sites in Belfast, Breda, Budapest, Maribor and Katowice.
- To quantify the impact or enable definition of the absence of local impact on e.g. biodiversity.
- To assess the impact of the improvement by Upsurge demos - correction actions.
- To preserve the sites and corresponding nature-based solutions implemented against locally emitted pollutants.
- Assessing the impact on human health, including the benchmarking aspects.

Objective II:

- To monitor plant diversity and their nutritional value at 5 Upsurge demonstrations sites in Belfast, Breda, Budapest, Maribor and Katowice.
- To categorise the sites with identification of specific species (invasive, exceptional).
- To assess the specific and periodic nutritional deficiency of the ecosystem.
- To assess the impact by Upsurge demos - correction actions.

Objective III:

- To report and interpret the data and recommendations to improve the situation at 5 Upsurge demonstrations sites in Belfast, Breda, Budapest, Maribor and Katowice.
- To report on quantitative and qualitative indicators
- To elaborate on comparisons / benchmarking (sites, periods, regulatory standards / thresholds)
- To give site- and solution-specific recommendations.

Objective IV:

- To determine priorities, improvement actions and stakeholders (also through Place Labs and their corresponding Competence Groups).
- Prioritisations based on the risks identified / improvement actions recommended.
- To propose sustainable and effective targeted improvement actions.
- To involve and raise awareness of local stakeholders at each Upsurge demo site through improving relationships

6.3 Specific Properties of the Beeomonitoring Approach

6.3.1 Sensing Range, Viability and Representativeness of Results

The impact on the environment is not limited to a specific site and conversely, the environment is also impacting the site (e.g. some pesticides monitored on site can come from farmers established nearby).

Bees act like environmental drones. They collect samples daily on 8 billion plants on average and cover an area of approx. 80 ha (200 acres) to 700 ha (1.800 acres) according to the bees used. Bees go up to 1,5 km on average to feed themselves. 1,5km of radius equals 700ha of surface. In cities, more specifically, they cover on average 1138 meters (*Steffan-Dewenter and Kuhn, 2003; Waddington et al.., 1994*).

Bees will search for food and visit plants as long as they have not met the objectives in terms of amino acids and proteins and diversity. In other words, they will cover the surface required to have the ideal food diversity which strongly limits the risk of having them focusing on only one zone.

A feasibility assessment is done before placing bees based on the information relating to the surroundings found amongst others on google map pro +. If it appears that there is a lack of food, this will be communicated and additional actions can be taken (e.g. plantation).

BeeOmonitoring does not have a direct impact on the survival rate of bee colonies, as the cause of bee decline is a combination of lack of food, pesticides, pollution, and environmental influences. The pollen is monitored, which is in direct contact with air pollution. Bees have a filtration system similarly as humans do. If the concentration of pollutant emissions are above lethal doses 50 (LD 50) - doses above which more than 50% of bees will die - there is a risk for bees. If under LD 50, there is generally no problem. If above LD 50, solutions can be found to reduce the pollution level.

Generally, the pollen is analyzed because the pollen is directly in contact with the environmental elements whereas the nectar, for example is altered by other elements (such as enzymes, saliva). However, nectar can also be monitored and it can make sense for certain pollutants. Nectar is less representative of the environment because bees will concentrate only on the most productive sources vs. pollen where they will cover a large zone and take many samples.

Mostly, the pollution found in the pollen comes from the air. However, it depends of the pollutants. Some elements of the pollutants are mobile and can be absorbed, others are fixed and will remain in the soil. Some pesticides are systemic and can migrate in the plant. Others do not migrate.

The concentration of the pollutants in the pollen are not the same as in the soil because of the filtration and absorption system, but Beeomonitoring is a great complementary study to soil pollution. Most of the time soil pollution is limited to a site - Beeomonitoring can monitor the impact beyond the site.

The results of Beeomonitoring are liaised the food MRL (maximum residue level for humans). To have an indication linked to human health and to benchmark for heavy metals, a comparison with the food for which the highest MRL is accepted (e.g. mussels for lead). For pesticides, the MRL used is linked to products of a bee colony. So, if it is above the allowed threshold, the pollen or honey cannot be sold. These results do not mean that the same pollution level will be found in the fruits or vegetables, but it is an indication that there is a risk if it is above the reference MRL used in the Beeomonitoring.

An internal protocol is used based on DNA for the determination of the biodiversity results.

6.3.2 PERIODICITY

To have a global yearly view, one year of sampling and testing is needed. However, specific information related to a concerned period will already be available beforehand in the intermediary reports. Generally, BeeOmonitoring is performed for at least three years, where the first year presents the first assessment based on which improvement measures can be taken and monitored the second and third year. If there is an issue (e.g. lack of biodiversity, high concentrations of pollutants, etc.) identified in relation to a specific period, improvement measures can generally be taken directly after delivery of the intermediary results linked to that period. As the environment can change from one year to another, three years enable one to have a valid view of the environment on a medium to long term.

Depending on the pre-determined approach number of samplings can vary. Generally, four samples per year are acquired, so every two months from +/- April till October. Results are then published directly via the dashboard four times per year, within one to two months after the end of the concerned period. The full report is provided in January of the following year.

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6.4 Testing Protocol

6.4.1 Kick-Off

Once the project is set, the kick-off meeting happens with the project manager from BeeOdiversity, the partner and the beekeeper(s) in charge of the sample collection. During this kick-off meeting, the entire process is explained to the partner and beekeepers and all operational aspects are discussed.

6.4.2 Sample Kits

A sampling kit containing all the necessary equipment to collect pollen and to record data from the hives for the year is send from BeeOdiversity to the partner. This kit contains:

- 2 sampling devices (International Registration No. DM/217500)
  - Boxes (traps)
  - Baskets
  - Entrances
- 1 general calendar of the beekeeping season
- 1 field protocol
- 16 labelled sample bags (2 per period and per hive)
- 8 labeled sending bags (1 per period and per hive)
- 8 backup pots already labelled (1 per period and per hive)
- 1 cutter if there is not enough pollen in the basket. In this case, it is necessary to take some bee bread containing pollen by cutting it with a cutter.
- 1 plasticized card to easily encode population, brood, nectar and pollen data + 1 pen to write on

6.4.3 Field Protocol

In order to ensure the quality of the results and be able to compare results among sites, it is crucial that the samples are correctly collected, and during the same periods.

6.4.3.1 Beehive installation

The beehives have to be:

- Placed at a legal distance from buildings and public roads.
- Placed on a support foot or on an adequate support in order to be 20 centimeters away from the ground.
- Oriented to the south-east if possible, to benefit from the sunlight.
- In an open area. The vegetation growing under the beehive needs to be removed regularly so that bees' activities are not hindered and to favor pollen sample ventilation.
- Strapped to the support and/or ballasted to avoid overturn by wind.

6.4.3.2 Installation of the pollen traps

The traps can be installed at any moment during the year. However, for a complete monitoring season, we make sure traps are installed before or on March 15. For the installation of the traps, the steps are:

1. Remove the beehive entries (Nicot) or the two metallic entry flaps (Dadant).
2. Remove the alighting boards (Dadant) (if the bottom boards are equipped with it).
3. Secure with two screws each pollen trap at the entry of the hives ensuring that they are attached to the hive and that no entry is possible at the back of the traps.
4. Remove the punctured grid from the traps for 48 hours (for the bees to acclimatize).
5. Put back the grid in the traps after removing the possible dead bees from the bottom boards.
6. Ensure the sample harvest baskets are set up.

The devices need to always stay on the hives. They were designed not to affect bees (*International Registration No. DM/217500*). The traps can be removed for the wintering, after the sample collection.

6.4.3.3 Periods of sample collection

The samples are collected every day by the bees, and we group these samples into 4 periods that are analyzed in the laboratory. We ask our partners to collect the pollen contained in each trap at least two times per period, thus 8 times per year. A text message is sent at the beginning of each collection period to the person in charge. A calendar is integrated in the kit and allows to find the main steps of the project. Here are the 8 sample collection dates.

<u>Period 1: mid-April until end of May</u>

P1.1.: between the 01/5 and the 07/05, (conservation in freezer)

P1.2.: between the 25/05 and the 31/05, Shipping of samples 1.1. & 1.2.

<u>Period 2: beginning of June until mid-July</u>

P2.1.: between the 14/06 and the 20/06, (conservation in freezer)

P2.2.: between the 09/07 and the 15/07, Shipping of samples 2.1. & 2.2.

<u>Period 3: mid-July until end of August</u>

P3.1.: between the 01/08 and the 07/08, (conservation in freezer)

P3.2.: between the 25/08 and the 31/08, Shipping of samples 3.1. & 3.2.

<u>Period 4: beginning of September until mid-October</u>

P4.1.: between the 14/09 and the 20/09, (conservation in freezer)

P4.2.: between the 09/10 and the 15/10, Shipping of samples 4.1. & 4.2.

6.4.3.4 Samples collection

The steps of taking the samples for each beehive for each period are the following:

1. Clean the bottom of the beehives and the traps to avoid that vegetation and humidity interfere with the sample collection.
2. Take the freezer bag with the right number (example: P1.1 with the N° of the beehive in the site for the first collection).
3. Collect the pollen from the basket and transfer it in the freezer bag with the label corresponding to the collection period and the number of the beehive, write down the date.
4. When visiting the hive, take measurements on all the frames of the hive (population, brood, pollen, nectar, etc.).
5. Encode the results in the BeeoApp as you go.
6. Remove the possible dead bees from the bottom board that are behind the punctured grid of the pollen trap.
7. Ensure the sample collecting baskets are clean and well set up.
8. Place the freezer bag in the freezer while awaiting the shipping.

6.4.3.5 Encoding the data into the BeeoApp

The BeeoApp is a smartphone application created by BeeOdiversity that encodes data relating to hives (population, brood, pollen, and nectar). It replaces the beekeeping logbook for hives. The application allows us to follow the evolution of the colonies during the year. These data are important and will be put in parallel with the environmental data that we will obtain with the analysis of pollen: plant diversity and/or pollution. They will, for example, make it possible to detect pollen and nectar deficiencies in the environment. Steps:

1. Install the BeeoApp.
2. Follow the schedule provided with the type of visit to be made.
3. Encode the visits in the BeeoApp.

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6.4.3.6 Preparation of sample shipping

1. Place the entire pollen collection of the period in one freezer bag ("Shipping bag P1.1 & P1.2", for example).
2. Mix the bag correctly by shaking it for 2 to 3 minutes.
3. Extract a backup pot (supplied in the kit) of pollen (the one with the label corresponding to the shipping: "Back-up P1.1 & P1.2.", for example).
4. Store the backup pot in your freezer and send us only the bag in which you mixed the pollen (the backup pot will be useful to redo analyzes if needed: loss of sample by the transporter, need for additional analyzes, etc.).
5. By the end of the year, you can dispose the backup pots. They will not be useful for the project anymore.

6.4.4 ANALYZES PROTOCOL

Once the pollen samples are received by BeeOdiversity, the internal process followed by BeeOdiversity team is the following:

1. Storage. All samples are kept refrigerated in the freezers.
2. Homogenization. The received pollen is homogenized in order to make sure that each sample analyzed is representative of the whole period under analysis.
3. Laboratory analyzes. According to the asked analyzes, different quantities of pollen are required:
    - The biodiversity analyzes require 2 grams of pollen.
    - The pesticides analyzes require 10 grams of pollen.
    - The heavy metal analyzes require 2 grams of pollen.
    - The PAH analyzes require 10 grams of pollen.
    - The phosphorus analyzes require 2 grams of pollen.
    - The benzene analyzes require 10 grams of pollen.
    - The PCBs, dioxines and furanes analyzes require 1.5 grams of pollen.
    - The styrene analyzes require 5 grams of pollen.
    - The nutritious quality analyzes require 5 grams of pollen.
    - The nitrates analyzes require 20 grams of pollen.

    A back up of around 30 grams of pollen is kept in case an analysis should be renewed.
4. Results management. Once the results are out, we review them internally to check their accurateness. This is done in comparison with all of our sites and our historic.
5. Reporting. Through the year, the results are put online on a customer friendly platform showing the results with various graphics we created. The partner is warned by email when his intermediary reports are available. By the end of the year, a final report gathering all results is written with specific recommendations for the partner based on what has been analyzed on the site.

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