SQAT

SOIL QUALITY ANALYSIS TOOL

Deliverable 2.2

Annual Use Case Report – Year 1

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Executive Summary

Farms are at the forefront of the data economy, propelled by digitalisation, robotics and smart algorithms. However, these advancements exacerbate societal pressures on soil health, demanding cleaner water, healthier soils, increased carbon storage and biodiversity. Current solutions are costly and unsuitable for farmers. With this in mind, the EU-funded SQAT project will develop a smart soil mapping service. Combining multi-level, multi-technology approaches, SQAT offers high-resolution soil property maps and tailored solutions for farmers. Using autonomous robot-mounted sensors and innovative in situ analysis tools, the SQAT system enhances productivity while reducing costs. Co-developing with SMEs, SQAT aims to commercialise its solutions, empowering farmers with variable-rate applications for liming, fertilisation, seeding, tillage, and carbon farming.

The use case plans are a key managerial and organisational tool for the project. To actualise and implement the project's co-creation approach, it is necessary to structure and order the work in each use case. We apply management best practices to identify and interlink specific objectives, related activities, expected results, and KPIs to measures success, for each use case. These are described separately for each of the seven use cases in SQAT, in: Belgium, Germany, Ireland, Netherlands, Serbia, Switzerland, and Ukraine.

The use case plans in turn will be used to track and evaluate the progress of each use case. They remain a flexible project management tool for the duration of the project and can be altered to address unforeseen issues or to seize upon new opportunities.

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Abbreviations

ABE	Association of Balkan Eco-Innovations
AGRILAB	Agrilab limited liability company
ATB	Leibniz Institute of Agricultural Engineering and Bioeconomy e.V.
BSI	Bare Soil Indices
EC	Electric Conductivity
EV ILVO	Eigen vermogen van het instituut voor landbouw-en visserijonderzoek
HSG-IMIT	Hahn-schickard-gesellschaft fur angewandte forschung ev
ILT-OST	Institute for Lab Automation and Mechatronics
MRV	Monitoring, reporting, and verification
NIR	Near Infrared
OFI	Officine innovazione s.r.l.
PG	"Poljoprivredno gazdinstvo" or agricultural holding in Serbian
TERRATMD	Terra controlling tmd d.o.o
VDBORNE	Van den borne projecten bv
VI	Vegetation Indices
WP	Work Package

1 Introduction

The Soil Quality Analysis Tool (SQAT) project aims to revolutionize soil management in European agriculture by leveraging advanced technologies for spatial soil property mapping and data-driven decision-making.

Agricultural intensification, larger machinery, and variable climatic conditions have increasingly degraded soil structure and fertility. This not only limits yields but also threatens long-term soil health and food security. While precision agriculture offers new opportunities for sustainable practices, its effectiveness hinges on reliable, high-resolution soil data. The SQAT project responds to this need by integrating satellite imagery, robotics, automated sampling, and field-level analytics into scalable solutions for farmers and advisors.

In its first year, SQAT has collaborated with stakeholders across seven diverse countries —Flanders, Germany, the Netherlands, Ireland/UK, Serbia, and Switzerland—to co-develop SQAT solutions in use cases to address pressing soil-linked challenges such as compaction, acidity, organic matter depletion, and field heterogeneity.

Each use case is different, in terms of pedoclimatic conditions, socio-economic context (including available machinery and legislation), which results in different needs for which soil properties mapping (through different applications) can offer a valuable solution. Specifically, the use cases showcase site-specific interventions highly relevant to their context including variable-rate liming, automatic soil sampling, improved subsoiling practices, carbon-smart dairy production, and regenerative approaches for crops and orchards. Across these applications, the use cases demonstrate the potential of SQAT to increase productivity, reduce environmental harm, and build climate resilience through smarter soil management.

The current document, as well as use case reports in successive years, follow up on the use case plans (Deliverable 2.1), which set out the activities, their timelines, the stakeholders involved, and the expected outcomes – quantified through Key Performance Indicators (KPIs). It reports on the progress of the use cases, referring to the expectations set out in the plans, as well as adding more pertinent details through narrative form. At the same time, it is an opportunity to reflect upon the plans and possible changes that may be required, due to a change of context or due to new opportunities, to make the best use of the use cases in the project and to facilitate post-project commercial exploitation. As such, the report contribute to monitoring expected progress as well as reflect upon the use cases and seek to further optimise them as a resource for project impact (where relevant).

The document will be updated annually to cover the previous 12-month period.

2 Use case 1 in Belgium: Prevention & remediation of soil compaction and acidity in Flemish soils

2.1 Brief context

In the past decades, working widths of agricultural machinery has increased to optimise labor efficiency. This causes an increase in weight (e.g., Keller and Or (2022) found a steady increase in wheel load of tractors (1.0 to 4.0 Mg) and of combine harvesters (1.5 to 12.0 Mg) in the past 60 years) and thus in the risk of soil compaction, especially with field operations conducted in late season, mainly for harvesting. The increase of soil pressure and field traffic in conditions with lower soil strength have a detrimental impact on the soil quality, down to the subsoil. Recent data suggest that between 23-43% of EU arable land is critically compacted (Brus and Van Den Akker, 2018).

For Flanders, a recent field study revealed that 27% of the arable soils were critically compacted in the upper subsoil (30-50cm; Lin et al., 2022). Since soil compaction cannot always be avoided, remediating through (deep) subsoiling is often needed. In current practice, remediation or decompaction is often performed through the use of subsoilers, equipped with several teeth to break through the compacted layers. In current practice, subsoiling is performed throughout the whole field, although significant variation, both spatially and in depth can occur.

To alleviate the compacted soil layer, avoid structure loss in non-compacted regions and optimize fuel efficiency, subsoiling should be performed only where needed and at the correct depth. Adequate and affordable detection methods for mapping soil compaction are lacking, EC and ECa scans can be related to soil compaction, but also to soil salinity, moisture level and texture and thus do not provide fully reliable soil compaction maps.

Manual penetrometer measurements are very time consuming and labour intensive. Automating these measurements using a robot platform, based on remote sensing data (e.g. Copernicus, UAV) overcome current barriers to variable-depth tillage based on precise spatial data.

2.2 Overall objective and specific aims updates

The overall objective is to apply the novel approach developed in SQAT to optimize (deep) subsoiling applications towards higher efficiency and sustainability in practice.

To deliver this objective, the specific aims are:

1. To develop an autonomous mapping of soil compaction with high spatial resolution as an input for variable depth tillage (subsoiling)
2. To test the device(s) at the ILVO farm comparing results with manual reference measurements
3. To test the device in practice at Belgian farmers' fields
4. To conduct demonstrations and practical workshops towards relevant stakeholders

2.3 Partners involved

The partners involved are shown in the table below.

Table 1: SQAT partners involved in Use case 1 in Belgium, their main contact person, and their specific responsibilities.

Use case role	Organisation	Main contact	Specific responsibilities
Use case lead	EV ILVO	Tommy.dhose@ilvo.vlaanderen.be Valentijn.decauwer@ilvo.vlaanderen.be	Overall use case management, testing of the robotic solution in controlled conditions (ILVO testfarm), and in practice conditions (Belgian farmers' fields)
Support	Exobotic	rembrandt@exobotic.be	Testing of robotic platform

2.4 Description of key stakeholders' involvement and feedback

Table 2 provides an overview of relevant stakeholders. Farmers, agri consultants, and soil mapping companies were contacted last year for insights into the robot design and current soil sampling applications and procedures.

Table 2: End-users involved in Use case 1 in Belgium.

	Farmers	Agrifood companies	Agri consultants	Soil mapping company	Other
Involved	✓	✗	✓	✓	✓
Name and description	The EV ILVO testfarm, the Experimental platform for agroecology in Hansbeke, a selection of Belgian farmers		A selection of agri-consultant companies	Regional soil mapping companies	Machine manufacturers (e.g. tillage equipment)

2.5 Test locations

2.5.1 Justification for any changes or additions to test sites

No changes or additions to the test sites were made.

2.5.2 Test location description

Soil resistance measurements were performed with an automated and a hand-held penetrometer on an experimental field of ILVO in autumn 2024 to compare the two measuring devices. Measurements were conducted across various plots of an existing field experiment.

Table 3 Test location Belgium

Location name	ILVO experimental field: S15
Sampling area size	1,85 ha (only parts of the field were sampled)
Number of individual penetration resistance measurements	1120
Sampling depth	75 cm

2.6 Activities and Implementation Steps

2.6.1 Detailed description of activities carried out

Penetration resistance measurements were conducted in lab conditions and on an experimental field using the CIMAT robot and an automated penetrometer. Additionally, manual penetrometer measurements were performed to validate the automated device. For the measurements in lab conditions, soil was compacted in stainless steel cylinders to create soil compaction profiles in a controlled way. Measurements in the field were taken across plots of an existing field experiment and along spraying tracks within the same field. The different plots of the experimental field were initially screened in May 2024, and in December 2024, high-resolution measurements were conducted on selected plots and across spraying tracks. The results were published in a paper (https://doi.org/10.3390/s25061919).

2.6.2 Challenges encountered and how they were addressed

A single penetration resistance measurement provides information from only a small area of influence, meaning high-resolution penetrometer measurements are required. Therefore, the automation of soil resistance measurements is essential. Furthermore, a data layer fusion approach is preferred for accurate soil compaction mapping, rather than relying on a limited number of penetration resistance measurements. Although automated, the number of measurements is still limited due to operational and logistical costs. A smart sampling approach based on other data layers is necessary to optimize the sampling location selection.

2.7 Key Performance Indicators (KPIs)

2.7.1 Status of defined KPIs

The key performance indicators (KPIs) for the use case are shown in table 3. We have been working on KPI 3, with the first scientific paper on the automation of a soil mechanical resistance sensor published on 19 March 2025.

Table 4: Key performance indicators for use case 1 in Belgium.

KPI title	Target	Means of verification	Link to specific aims
1. Field demonstration events to engage stakeholders	2 events for stakeholders (farmers, researchers, agri-consultants, advisors)	At least 40 external participants	Iterative development requires stakeholder feedback, both from end-users as well as other stakeholders.
2. Promote	Promotion of the use case results	2 vulgarizing publications 12 social media posts	All of the above
3. Relevant scientific papers on thematic areas	1-2 draft scientific papers, can be combined with other use cases	Dissemination reporting	All of the above
4. More efficient soil compaction management	Positive economic balance for (deep) soiling applications	After scanning, field variability in soil compaction can be determined in a more optimal way compared to the SOTA. Furthermore, fields can be subsoiled in a more optimal way, resulting in a net higher profit for the farmer (input savings: fuel, time).	All of the above
5. Business model assessment	To have financial models that reflect the opportunity for SQAT SOC estimation	Cost analysis	

2.7.2 Assessment of progress toward meeting the KPIs

Since the use case implementation is in its early stages and technical developments are ongoing, further work is needed to meet the listed KPIs. However, we remain on schedule to achieve them.

2.8 Results and impact

2.8.1 Key results obtained

For further reading, we refer to the published paper on our soil mechanical resistance sensor (https://doi.org/10.3390/s25061919). Our findings show that the mechanical resistance sensor correlates well with a standard manually operated penetrometer, confirming the reliability of the measurements. Automating penetration resistance measurements is a crucial step toward efficient and effective soil compaction mapping. Moreover, by ensuring a constant insertion speed of the penetration cone, measurement variability was reduced, demonstrating the high repeatability of the developed sensor. Mapping soil compaction levels throughout the soil profile is an essential step toward precision subsoiling applications.

2.8.2 Contribution to the overall SQAT project goals

The development and validation of the mechanical resistance sensor serve as a foundation for a data fusion approach, providing qualitative, cost-effective, and high-resolution soil (compaction) data. By enabling high-resolution compaction mapping (in combination with other data layers), this novel technology can support new precision agriculture applications, such as precision subsoiling, thereby making farming more efficient and profitable.

2.9 Lessons learned and recommendations

Vertical penetrometers precisely locate compacted soil layers (e.g., plow pan). However, penetration resistance measurements showed high variability over very short distances, highlighting the need for numerous measurements. Another approach is data fusion, where vertical penetration resistance, combined with other data layers such as electrical conductivity, (historical) yield, soil type, topography, and machinery telemetry, provides an accurate and comprehensive view of the soil compaction state. In the future, it is crucial to determine the necessary spatial resolution, both laterally and vertically, for precision subsoiling, avoiding an unnecessarily high resolution.

2.10 Next steps and action plan

In the coming year, we will investigate the correlation between soil compaction and other data layers, such as electrical conductivity, (historical) yield, soil type, topography, and machinery telemetry, to provide a more holistic view of a field's soil compaction state. Additionally, we will develop and test a new automated vertical penetrometer.

3 Use case 2 in Germany: Variable-rate liming to improve resource efficiency and limit environmental damage

3.1 Brief context

Soil acidity is a key factor in soil fertility that concurrently influences several yield-relevant soil properties. For these reasons, farmers regularly apply lime to their fields to strive to obtain and maintain an optimal soil pH to improve crop growth. However, even in countries with intensive agricultural production, such as Germany, the soil pH of agricultural fields is often not within the optimum range. According to a recent national soil pH survey in Germany, only 35% of the arable soils and 24% of the grassland soils were in the optimum range, whereas the pH of approximately 42% of the mineral soils under arable farming and 57% of the grassland soils was too low. Apparently, lime management on farms in Germany is not sufficient. One reason is that most farmers do not manage soil heterogeneity at field scale. In Germany, the best management practice for lime requirement calculation is based on the empirical algorithm developed by the Association of German Agricultural Investigation and Research Institutions (VDLUFA). The procedure is based on 30 years of fertilization trials studying the correlation between soil pH and agricultural yield, brought into a simplified management structure. The approach involves two steps: (i) a soil sampling of one mixed soil sample that is composed of several sub-samples from either the whole field or from sub-plots of 3–5 ha of assumed soil homogeneity and (ii) a look-up table system that defines the target pH value for the management unit from the analysed soil texture, soil organic matter (SOM) content and calculates lime requirement from the mismatch between this target pH and the current pH value. However, the VDLUFA guidelines for liming are limited because they are based on relatively rough classifications of soil texture and SOM into five and four classes, respectively (Fig. 1). However, the algorithms that are needed in the context of the present-day requirements of precision farming should be continuous and stepless. Furthermore, site-specific and variable-rate liming (VRL), which is a precondition for optimizing soil acidity management, requires soil data at a very fine spatial scale. High-resolution maps can therefore help to assess internal field variations in soil properties and reduce the decision uncertainty caused by this unknown spatial variation.

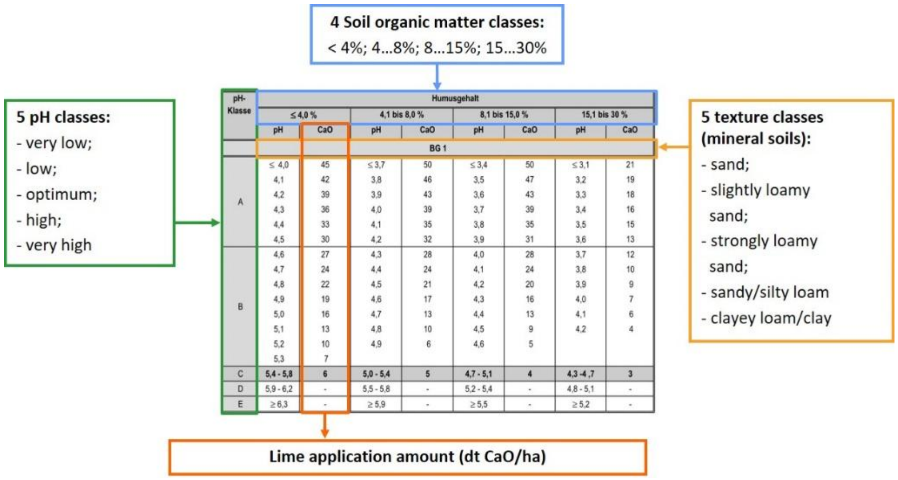


Figure 1 Look-up table system of the VDLUFA for lime requirement calculation in Germany

Consequently, SQAT will test autonomous sensor-based soil mapping for generating high-resolution lime requirement maps for variable-rate liming.

Since 2021, ATB is setting up the Leibniz Innovation Farm (InnoFarm) for Sustainable Bioeconomy together with 20 Leibniz institutes and 5 universities from all over Germany, developing and testing innovative concepts and technologies for a sustainable, circular bioeconomy on 940 ha of agricultural land. There are >3.000 visitors per year for trainings, field trips, seminars, etc. and there are long-standing ties with other farms and the research institutions in the region. The entire workflow of autonomous sensor mapping and lime requirement map generation is to be tested on farm scale at the InnoFarm, including the integration of our approach within the operating procedures and practical conditions of a real farm. For transfer of the project results to practitioners, we organise field days and practical workshops with farmers, service providers and agri-consultants.

With regards to the initial use case plan, no significant changes occurred during the reporting period that influenced the use case's implementation and outcomes.

3.2 Overall objective and specific aims updates

The overall objective is to test the developed SQAT for generating high-resolution lime requirement maps.

To deliver this objective, the specific aims are:

1. To develop autonomously sensor mapping and soil property map generation of soil pH, texture and soil organic matter in a high spatial resolution for lime requirement calculation.
2. To integrate the algorithm for stepless lime requirement calculation of Rühlmann et al. (2021, https://doi.org/10.3390/agronomy11040785) into the automated data pipeline of SQAT.
3. To test the SQAT on test fields of the Leibniz Innovation Farm and compare the soil mapping results with already existing sensor-based soil property maps
4. To conduct field days and practical workshops for transferring the results to farmers, service providers and agri-consultants

With regards to the initial use case plan, no updates or refinements are necessary.

3.3 Partners involved

The partners involved are shown in the table below.

Table 5. SQAT partners involved in Use case 2 in Germany, their main contact person, and their specific responsibilities.

Use case role	Organisation	Main contact	Specific responsibilities
Use case lead	ATB	Sebastian Vogel (svogel@atb-potsdam.de)	Overall management, testing of the robotic solution on the Leibniz Innovation Farm
Support	EV ILVO	Axel Willekens (Axel.Willekens@ilvo.vlaanderen.be)	Development of the robotic platform
Support	ILT-OST	Dejan Šeatović (dejan.seatovic@ost.ch)	Development of the robotic platform
Support	HahnS	Mohamed Bourouah (Mohamed.Bourouah@Hahn-Schickard.de)	Development of the lab-on-the-field module

With regards to the initial use case plan, there are no changes in the partnership structure or shifts in responsibilities.

3.4 Description of key stakeholders' involvement and feedback

We will also involve multiple other stakeholders as externals that will valuable to achieve the objectives of the use case, presently identified in the table below.

Table 6. End-users involved in Use case 2 in Germany.

	Farmers	Agrifood companies	Agri consultants	Soil mapping company	Other
Involved	✓	✗	✓	✗	✗
Name and description	Leibniz Innovation Farm (Gross-Kreutz, Germany); Landwirtschaft Philipp (Boossen, Germany)		LAB GmbH (Agricultural consulting of the agricultural associations Brandenburg)		

In cooperation with a regional agri consultant (LAB GmbH, Agricultural consulting of the agricultural associations Brandenburg), all agricultural land of the two partner farms (Leibniz Innovation Farm, Gross-Kreutz, Germany and Landwirtschaft Philipp, Boossen, Germany) was mapped with soil sensors (electrical conductivity, optical reflectance, pH and gamma ray). Sensor data and reference laboratory data were used to generate high-resolution soil property maps of soil pH value, soil texture and soil organic matter content in order to calculated high-resolution lime requirement and lime application maps. The latter can now be used for variable-rate lime fertilization.

3.5 Test locations

3.5.1 Justification for any changes or additions to test sites

With regards to the initial use case plan, no changes or additions were made to the test sites.

3.5.2 Test location description

Table 7 Test location Germany

Location name	Leibniz Innovation Farm
Sampling area size (ha)	~ 900 ha
Number of composite samples	390
Number of individual samples combined for composite sample	5
Sampling depth	0 – 30 cm
How sampling location was determined	Targeted sampling based on the sensor data layers (electrical conductivity, optical reflectance, pH and gamma ray)

The SQAT approach will be tested on selected arable fields of the Leibniz Innovation Farm that are characterized by a high spatial variability of the soil properties related to liming, i.e., pH value, soil texture and soil organic matter content.

The InnoFarm is being build at the Teaching and Research Institute for Animal Breeding and Animal Husbandry (LVAT e.V.) in Groß-Kreutz (Germany) and is a 940 ha large mixed farm consisting of 579.6 ha arable land and 347.8 ha permanent grassland (270 ha grassland with usage restrictions). The farm and land are predominantly owned by the federal state of Brandenburg and, with their different site conditions, represent typical arable and grassland sites in the state.

The soils of the region developed on morainic landscapes shaped by the Pleistocene glaciation processes as well as by fluvial processes in the river valley of the Havel River. The soils are predominantly sandy. Climatically, the test site is located in the transition zone of the humid oceanic and dry continental climates.

- Altitude: 33-55 m above sea level
- Average annual temperature: Approx. 9.2 °C
- Average rainfall: 500 mm
- Soil type: Light soils (S) – 70 % of the agricultural land; Boggy soils close to groundwater (meadows and pastures) – 30 % of the agricultural land
- Sloping land: 50 % of the agricultural land

3.6 Activities and Implementation Steps

3.6.1 Detailed description of activities carried out

As stated above the agricultural land of the Leibniz Innovation Farm (Gross-Kreutz, Germany) was mapped with soil sensors (electrical conductivity, optical reflectance, pH and gamma ray). Sensor data and reference laboratory data were used to generate high-resolution soil property maps of soil pH value, soil texture and soil organic matter content in order to calculated high-resolution lime requirement and lime application maps (Fig. 1). The latter can now be used for variable-rate lime fertilization. Those data will serve as the baseline for comparison with the soil property and lime requirement maps generated by the SQAT. The generation of this baseline dataset was a major milestone.

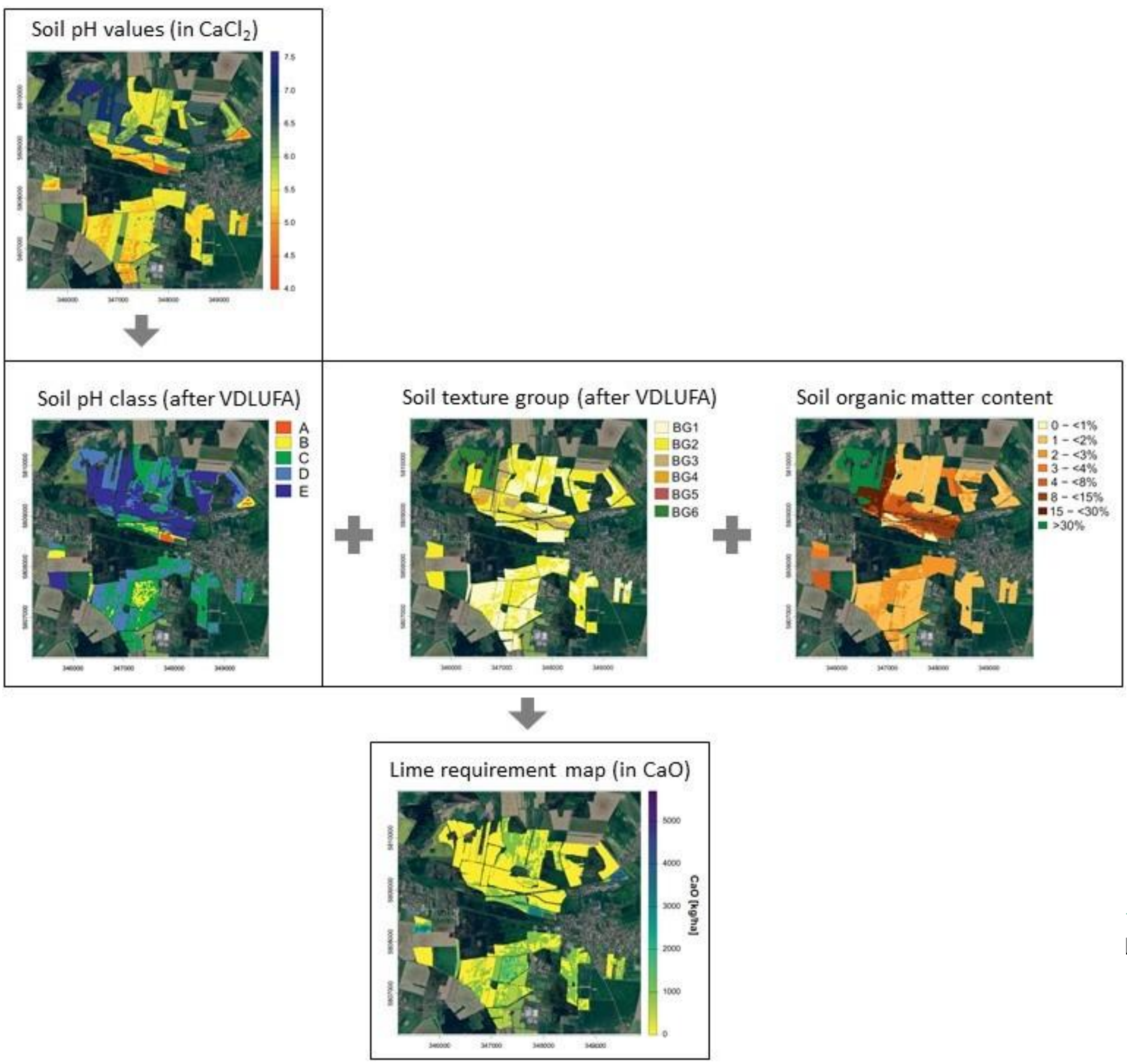


Figure 2 Results of the sensor-based soil property mapping and lime requirement calculation at the Leibniz Innovation Farm (Groß Kreutz, Germany).

3.6.2 Challenges encountered and how they were addressed

No challenges were encountered in 2024.

3.7 Key Performance Indicators (KPIs)

The key performance indicators (KPIs) for the use case are the following:

Table 8 KPIs Germany

KPI title	Target	Means of verification	Link to specific aims
1. Leverage on field demonstration events to engage customers	1-2 events stakeholders (farmers and agricultural consultants)	At least 50 external participants	
2. Judicious use of printed materials for promotion	Preparation of fact sheets to stakeholders	Distribution of fact sheets to stakeholders at workshops and online via farmers networks, 1-2 practical articles in farmers magazines	
3. Relevant scientific papers published on thematic areas	1-2 scientific papers published		
4. More efficient soil acidity management	Positive economic balance concerning use of resources and/or yield development, harmonization of soil pH value	After the liming cycle of 3 years, all parts of the field are in an optimal pH value	

3.7.1 Status of defined KPIs

1. Leverage on field demonstration events to engage customers

- No activity yet

2. Judicious use of printed materials for promotion:

- The ATB has only recently published together with colleagues from the Eberswalde University for Sustainable Development and the Leibniz Institute of Vegetable and Ornamental Crops an open access textbook for farmers and agricultural service providers on sensor-based mapping of soil properties for site-specific liming:

https://link.springer.com/book/10.1007/978-3-662-69174-8

- Additionally, 11 fact sheets on precision liming were generated covering specific topics like:
    1. Need and benefits of site-specific liming
    2. Guidelines for precise liming
    3. Determination of soil texture using mobile soil sensors
    4. Determination of the soil pH value using mobile soil sensors
    5. Determination of the soil organic content using mobile soil sensors
    6. Reference sampling and sampling strategy
    7. Stepless determination of the lime requirement
    8. Base neutralizing capacity - a direct determination of lime and acidification requirement
    9. Generation of application maps for liming
    10. Economic effects of site-specific liming
    11. Zoning for site-specific soil management

    Those fact sheets are in German and will additionally be translated into English to also be available for farmers and service providers outside of Germany.

3. Relevant scientific papers published on thematic areas

- **VOGEL, S.**; GEBBERS, M.; SCHRÖTER, I.; SCHWANGHART, W.; BÖNECKE, E.; RÜHLMANN, J.; KRAMER, E.; GEBBERS, R. (2025): Towards site-independent calibration of in situ soil pH sensor data: Relevance of spatial and temporal proximity, sample size and data spread for calibration model performance. Geoderma. (April 2025): p. 117261. Online: https://www.sciencedirect.com/science/article/pii/S0016706125000990
- TAVAKOLI, H.; CORREA REYES, J.; **VOGEL, S.**; OERTEL, M.; ZIMNE, M.; HEISIG, M.; HARDER, A.; WRUCK, R.; PÄTZOLD, S.; LEENEN, M.; GEBBERS, R. (2024): The RapidMapper: State-of-the-art in mobile proximal soil sensing based on a novel multi-sensor platform. Computers and Electronics in Agriculture. (November): p. 109443. Online: https://www.sciencedirect.com/science/article/pii/S0168169924008342
- SCHMIDINGER, J.; BARKOV, V.; TAVAKOLI, H.; CORREA REYES, J.; OSTERMANN, M.; ATZMÜLLER, M.; GEBBERS, R.; **VOGEL, S.** (2024): Which and how many soil sensors are ideal to predict key soil properties: A case study with seven sensors. Geoderma. (October): p. 117017. Online: https://doi.org/10.1016/j.geoderma.2024.117017
- **VOGEL, S.**; EMMERICH, K.; SCHRÖTER, I.; BÖNECKE, E.; SCHWANGHART, W.; RÜHLMANN, J.; KRAMER, E.; GEBBERS, R. (2024): The effect of soil moisture content and soil texture on fast in situ pH measurements with two types of robust ion-selective electrodes. Soil. (1): p. 321-333. Online: https://doi.org/10.5194/soil-10-321-2024
- SCHMIDINGER, J.; SCHRÖTER, I.; BÖNECKE, E.; GEBBERS, R.; RÜHLMANN, J.; KRAMER, E.; MULDER, V.; HEUVELINK, G.; **VOGEL, S.** (2024): Effect of training sample size, sampling design and prediction model on soil mapping with proximal sensing data for precision liming. Precision Agriculture. : p. 1-27. Online: https://doi.org/10.1007/s11119-024-10122-3

4. More efficient soil acidity management

- No activity yet

3.7.2 Assessment of progress toward meeting the KPIs

1. Leverage on field demonstration events to engage customers

- Field demonstration event will be carried out later in the project when the SQAT was developed and tested.

2. Judicious use of printed materials for promotion:

- KPI achieved

3. Relevant scientific papers published on thematic areas

- KPI achieved

4. More efficient soil acidity management

- We are currently working on a comprehensive economic assessment of sensor-based soil property mapping for site-specific liming. This will end up in a scientific publication, which will also serve as the basis for an additional publication in a farmers' magazine.

3.8 Results and impact

3.8.1 Key results obtained

Own field trials have shown that site specific liming is able to reach the optimum pH value and decrease the pH variability of fields showing a high variability of soil properties. From soil acidity and soil structural aspects, this is the foundation of a fertile soil in order to enable optimum growing conditions for crops. If this will also result in an increase of yield finally depends on the other yield-limiting factors (e.g. water).

We conducted an initial economic assessment of sensor-based lime requirement estimation on a farm of approximately 930 ha in the East of Germany. We compared the conventional way to estimate lime requirement by using low-resolution soil texture data with high-resolution soil texture data from proximal soil sensing. Besides soil texture also the soil pH and soil organic matter (SOM) content is needed for lime requirement calculation. Soil texture and SOM determine the target pH value and the difference between actual pH and this target pH determine the amount of lime needed. Already by using the low-resolution soil texture data to determine the target pH, we found that only on 40% of agricultural land, the soil texture was classified correctly. 50% of land was overestimated (texture too fine) and 10% were underestimated (texture too coarse). This means that, already due to the overestimation of the soil texture also the lime requirement of 50% of agricultural land (465 ha) were overestimated and the farmer applied approximately 97 tons of CaO too much in every liming cycle of 3 to 4 years. Apart from the cost of that unnecessary amount of lime, this oversupply with lime resulted in a soil pH value being too high, which additionally causes decrease of crop yield. Thus, we estimated a loss of grain yield for the farmer of approximately 280 tons in every liming cycle of 3 to 4 years. This initial calculation emphasizes the importance to used high-resolution soil property data on pH, texture and SOM to correctly calculate the lime requirement and to do site-specific liming.

3.8.2 Contribution to the overall SQAT project goals

The expected results of the use case are:

1. More efficient soil acidity management:
    a. optimum pH values within fields
    b. positive economic balance concerning use of resources and/or yield development
        i. increases yields
        ii. reduced sensor mapping costs through autonomous mapping with robot
        iii. reduced number of reference lab analysis through lab-on-the-field module
2. Increasing acceptance and implementation of variable-rate liming in practical agriculture

3.9 Lessons learned and recommendations

From our initial economic assessment of sensor-based lime requirement estimation on farm level, we have learned that it is not most important what the service of sensor-based soil mapping costs, even though it is always the first question coming from the farmers. Even more important is to known how much money the farmers have lost by applying too much lime and how much yield potential they have consequently not exploited over the past years by using a bad data basis for lime requirement estimation. Even if the soil mapping service costs e.g. 100€/ha, when the farmer can gain 200€/ha by doing site-specific liming, the additional effort and expense is justified. When we have more robust data from the comprehensive economic assessment that is currently under way, this should be the way to promote the SQAT to the farmers.

3.10 Next steps and action plan

As soon as the soil mapping robot, which includes the NIR module, is developed, it will at first be tested on test sites of the ATB and at second on test fields of the Leibniz Innovation Farm. The quality of the data will be compared with the already existing soil sensor data. This will be the basis for several iteration loops for optimizing the SQAT.

4 Use case 3 in Ireland: Milk supply chain sustainability programme through Regenerative Agriculture practices

4.1 Brief context

The use case discussed here focuses on enhancing the sustainability of the milk supply chain through the implementation of regenerative agriculture practices. Within dairy supply chains, it is widely acknowledged that more than 85% of the carbon emissions associated with dairy products fall under Scope 3 emissions, which are related to the production level, including on-farm activities. This significant contribution to the overall carbon footprint emphasises the crucial need to reduce emissions at the farm level to effectively lower the total emissions of dairy products.

In the Irish context, a target has been set for a 25% reduction in agricultural emissions by 2030, with an even more ambitious target of 50% reduction by 2050. These targets are essential for Ireland's climate action plan, aligning with broader European sustainability goals. The national agricultural research body, Teagasc, has developed a set of guidelines designed to help Irish farmers achieve emissions reductions, which are rooted in sound scientific principles and practical strategies. However, despite their value, these guidelines are not fully equipped to help farmers meet the more aggressive longer-term targets set for 2050.

One of the critical gaps identified in the current strategy is the exclusion of Soil Organic Carbon (SOC) from emissions reduction targets. The challenge here lies in the complex and expensive nature of accurately measuring SOC. SOC is a significant factor in soil health and carbon sequestration, yet the difficulties in reliably quantifying it on a large scale have hindered its inclusion in official emission reduction calculations. This creates an opportunity for innovation. The SQAT (Sustainable Quality Assessment Tool) represents a promising avenue to explore how emerging technologies can assist the industry in measuring SOC effectively. By developing innovative solutions for SOC measurement, there is potential to support farmers in their efforts to meet both the short-term and long-term emissions targets.

The dairy industry has been specifically selected for this use case due to its stable supply chain and its overall economic value to Ireland. Dairy farming plays a pivotal role in Ireland's agricultural sector and contributes significantly to the national economy. As such, improving the sustainability of this sector could have a profound impact not only on emissions reduction but also on the economic resilience of the industry.

4.1.1 Significant Developments in the Reporting Period

During the recent reporting period, several noteworthy developments have occurred that directly impact the goals of this use case:

1. Carbon Farming Certification Framework (CFCF). A major development in the agricultural sustainability landscape is the introduction of the Carbon Farming Certification Framework (CFCF), which is being rolled out across the European Union. The primary aim of this framework is to establish a standardised, transparent, and reliable certification system for carbon farming

practices. This framework is proving invaluable in providing companies and farmers with greater clarity and certainty around the methodologies used to measure Soil Organic Carbon (SOC) and other carbon farming metrics. As more farmers engage with this framework, it will likely become a critical tool in ensuring consistency and credibility in measuring agricultural emissions reductions across the EU.

2. Advancements in Machine Learning for SOC Estimation. Another significant development is the increasing popularity of Machine Learning (ML) models for estimating Soil Organic Carbon. These models leverage vast datasets and sophisticated algorithms to predict SOC levels across large agricultural landscapes, offering a more efficient and scalable solution compared to traditional methods. While these models are still in the early stages of implementation, they hold great promise in transforming how SOC is measured. It is important to note, however, that while ML models reduce the amount of in-field validation sampling required, they still necessitate a degree of field-based verification to ensure accuracy. This approach is proving to be a promising alternative to traditional methodologies that typically require more intensive and costly sampling efforts. As ML models become more refined and validated, they could play a key role in helping farmers achieve the emissions reduction targets set for 2030 and 2050.

These developments highlight a growing commitment to integrating advanced technologies and innovative solutions into the dairy industry's sustainability efforts. By focusing on these technologies, the dairy sector has a unique opportunity to enhance its environmental footprint while simultaneously contributing to Ireland's ambitious climate goals.

4.2 Overall objective and specific aims updates

The overall objective is to replace standard approaches with the SQAT solution to potentially bring

down costs while maintaining or increasing accuracy of SOC estimation.

To deliver this objective, the specific aims are:

1. To develop an autonomous system to collect infield SOC and bulk density data across farms
2. To determine optimal sampling / data collection resolution based on pre sampling techniques (vegetation indices or soil scanning)
3. Conduct in field validation exercises to validate SQAT techniques to traditional soil sampling.

4.3 Partners involved

4.3.1.1 Use Case Lead - Senus

Stephen Coen
Email: stephen.coen@senus.com

- ***Responsibilities**: Overall management, testing, and validation of the robotic solution on pasture-based dairy farms in Ireland, the UK, and Western Europe.*

4.3.1.2 Support - EV ILVO

Axel Willekens
Email: Axel.Willekens@ilvo.vlaanderen.be

***Responsibilities**: Development of the robotic platform.*

4.3.1.3 Support - ILT-OST

Dejan Šeatović
Email: dejan.seatovic@ost.ch

- ***Responsibilities**: Development of the robotic platform.*

4.3.1.4 Support - HahnS

Mohamed Bourouah
Email: Mohamed.Bourouah@Hahn-Schickard.de

- ***Responsibilities**: Development of the lab-on-the-field module.*

4.3.1.5 Use Case Lead - ATB

Sebastian Vogel
Email: svogel@atb-potsdam.de

- ***Responsibilities***: *Generation of soil maps to determine sampling resolution.*

4.4 Description of key stakeholders' involvement and feedback

Customer engagements during the period

Stakeholder	Description	feedback / insights
Loamin	Loamin is a UK based company specialising in SOC machine learning modelling.	● The organization has actively begun collaborating with multiple companies, assisting them in estimating Soil Organic Carbon (SOC) levels with greater accuracy and efficiency. Their expertise in SOC estimation is proving valuable in helping businesses understand carbon sequestration potential and implement sustainable land management practices. ● Their approach to SOC estimation is most effective when combined with in-field data collection. While remote sensing and modeling techniques provide a strong foundation for estimation, integrating real-world soil samples enhances the precision and reliability of the results. By incorporating ground-truth data, they can refine their models, reducing uncertainty and improving the overall accuracy of SOC assessments. ● One of the most significant advantages of their modeling system is cost-effectiveness. The process can estimate SOC at a price point of less than €1 per hectare, making it an affordable and scalable solution for large agricultural areas. This affordability makes it accessible to a wide range of stakeholders, from small-scale farmers to large agribusinesses looking to implement climate-smart agricultural practices. ● Furthermore, their modeling capabilities extend back to 2018, allowing users to analyze historical SOC trends and monitor changes over time. This retrospective analysis is particularly beneficial for evaluating the impact of different land management strategies, regenerative farming practices,

		and environmental policies over the past several years. ● However, it is important to note that the current methodology is limited to the top 30 cm of soil. While this depth is sufficient for most agricultural and carbon accounting purposes, deeper SOC sequestration insights would require additional technological advancements or supplementary measurement techniques. ● Another key advantage is their seamless compatibility with squat-style platforms, making integration with existing field technology straightforward. This adaptability ensures that the modeling system can be efficiently deployed alongside various agricultural robotics and data collection tools, further enhancing the practicality and ease of implementation for users. ● By offering a cost-efficient, scalable, and adaptable solution for SOC estimation, this approach is positioning itself as a valuable tool in the transition toward sustainable and climate-resilient agriculture.
Climate KIc	Climate KIC are a consultancy firm working with the Irish government on creating a framework for carbon farming	● Soil Organic Carbon (SOC) estimation will play a pivotal role in helping Ireland achieve its national and EU-mandated climate targets. As agriculture remains one of the largest contributors to Ireland's greenhouse gas (GHG) emissions, accurately measuring and managing SOC levels is essential for implementing sustainable land-use practices. By understanding SOC dynamics, policymakers, farmers, and industry stakeholders can make data-driven decisions to enhance carbon sequestration, reduce emissions, and contribute to Ireland's ambitious climate action goals for 2030 and 2050. ● One of the key industries recognising the importance of SOC estimation is the dairy sector. Milk processors in Ireland have

		expressed strong interest in piloting new and innovative technologies that can facilitate more efficient and accurate SOC estimation. As part of their broader sustainability initiatives, these companies are looking for solutions that can help quantify carbon sequestration on dairy farms, assess soil health, and ensure compliance with evolving environmental regulations. By adopting advanced SOC estimation methods, milk processors aim to support farmers in their transition toward regenerative agricultural practices, ultimately improving the sustainability of the dairy supply chain. ● Recognising the urgent need for carbon farming initiatives, the European Union (EU) has allocated significant financial resources to mobilize carbon farming projects across member states. These funds are designed to support research, development, and implementation of innovative technologies that enhance soil carbon sequestration. Farmers, agribusinesses, and researchers in Ireland have a unique opportunity to leverage these EU funding streams to accelerate the adoption of SOC estimation tools, develop scalable solutions, and contribute to long-term carbon neutrality goals. ● By integrating advanced SOC measurement technologies into farming systems, Ireland can position itself as a leader in sustainable agriculture while ensuring compliance with both national and European climate policies. With strong industry interest, financial support from the EU, and a clear pathway toward emissions reduction, SOC estimation is set to become a cornerstone of Ireland's agricultural sustainability strategy.
Base Ireland	Base Ireland are a regenerative farming group with strong interest in SOC estimation	● The farming members within this network have been dedicated stewards of their land, effectively managing soil health for many years. Through responsible agricultural practices, they have maintained soil fertility,

		minimised degradation, and optimised land productivity. Their commitment to soil conservation has ensured that their farms remain resilient, productive, and environmentally sustainable over time. ● Despite their strong focus on soil health, one of the major challenges is the lack of financial incentives or regulatory requirements to actively measure Soil Organic Carbon (SOC). Unlike other environmental metrics, such as nitrogen levels or water usage, SOC measurement is not yet fully integrated into farm sustainability programs in a way that provides direct economic benefits to farmers. Without clear financial rewards, subsidies, or carbon credit schemes, there is little motivation for farmers to invest in regular SOC monitoring, even though it is crucial for long-term soil health and climate mitigation efforts. ● While SOC plays a critical role in carbon sequestration and emissions reduction, for most farmers, it is primarily linked to optimizing soil health and enhancing agricultural production. Higher SOC levels improve soil structure, water retention, and nutrient availability, leading to better crop yields and healthier pastures for livestock. This connection between SOC and farm productivity underscores its practical importance beyond just environmental impact. By improving SOC levels, farmers can boost resilience against climate variability, reduce dependency on synthetic fertilizers, and create more sustainable farming systems. ● Moving forward, greater awareness, financial incentives, and accessible measurement technologies will be key in encouraging more widespread SOC monitoring. Recognizing SOC's dual role—both in enhancing farm productivity and in supporting climate goals—will be essential in shaping future agricultural policies and industry standards.
Teagasc	National research and	Ireland recognizes the critical role of soil organic

	advisory service for agriculture in Ireland	carbon (SOC) in climate change mitigation and sustainable land management. To enhance SOC estimation accuracy, the Soil Organic Carbon and Land Use Mapping (SOLUM) project developed the Land Use and Soil Inventory for Ireland (LUSII), integrating soil and land use data to provide robust SOC stock estimates and inform tiered reporting activities. Recent research by Teagasc emphasises the importance of precise SOC stock measurements in Irish grassland soils, highlighting that inaccurate bulk density assessments can lead to SOC overestimations by 18-388%. Additionally, Ireland participates in international initiatives like the CarboSeq project, aiming to estimate feasible SOC sequestration potential across Europe by considering biophysical, technical, and economic constraints. These efforts underscore Ireland's commitment to advancing SOC estimation methodologies to support climate action and sustainable agriculture

4.5 Test locations

4.5.1 Justification for any changes or additions to test sites

No test location changes in this period

4.5.2 Test location description

Test locations will be chosen when the SQAT system is ready for infield testing.

The use case will involve multiple farm locations to test various activities and methodologies related to soil organic carbon (SOC) sequestration and sustainable soil management. These farms will serve as pilot sites for assessing SOC measurement techniques, validating methodologies, and understanding the practical implications of different agricultural practices on SOC dynamics. The selection of test locations will be guided by several key criteria to ensure scientific rigor, representativeness, and applicability to real-world farming conditions. The essential selection criteria are as follows:

1. Farm Type and Production System – The primary focus will be on pasture-based dairy and beef farms, as these represent the dominant agricultural systems in Ireland. However, arable farms may also be included in the trials to assess how different land-use practices influence SOC

sequestration potential and measurement accuracy. This diversity will provide insights into the variability of SOC dynamics across different farming systems.

2. Participation in Sustainable Soil Management and SOC Programs – To ensure alignment with existing sustainability efforts, selected farms must be actively engaged in a Sustainable Soil Management program and be part of an agri-corporate-led SOC initiative. This requirement will facilitate collaboration with ongoing research and industry-led sustainability commitments, ensuring that the use case contributes to broader environmental and agricultural policy objectives.

3. Implementation of Traditional Soil Sampling Methods – Farms must have a history of traditional soil sampling practices, such as bulk density assessments, core sampling, and loss-on-ignition (LOI) testing. This will allow for cross-validation between traditional laboratory-based soil carbon estimation techniques and emerging measurement methods (e.g., remote sensing, spectroscopy, or predictive modelling). By comparing these methodologies, the use case will generate insights into the reliability, scalability, and cost-effectiveness of different SOC assessment approaches.

4. Geographic and Soil Variability – The test farms must be strategically selected to represent a range of soil types, textures, and topographies. This diversity is essential to ensuring that findings are broadly applicable across different environmental conditions. By capturing variations in soil composition, drainage properties, and elevation, the study will provide a more comprehensive understanding of how SOC behaves in different landscapes. Additionally, this variability will help refine SOC estimation models and ensure that SOC sequestration strategies are tailored to specific farming environments.

4.6 Activities and Implementation Steps

4.6.1 Detailed description of activities carried out

Customer engagement

The main activity to date has been the engagement of customers or end users. This helps us understand this use case, the main drivers and stakeholders (see stakeholder feedback)

Assessment of SOC MRV methodologies

The main Measurement, Reporting, and Verification (MRV) approaches for estimating soil organic carbon (SOC) include direct soil sampling and laboratory analysis, remote sensing, modeling, and hybrid approaches. Direct soil sampling involves collecting soil cores from the field and analyzing them for carbon content using laboratory methods such as dry combustion or loss-on-ignition. Remote sensing techniques, including satellite imagery, LiDAR, and hyperspectral imaging, provide spatial estimates of SOC based on vegetation, land use, and soil reflectance properties. Process-based models, such as CENTURY or RothC, simulate SOC dynamics using climate, soil type, and management practices as inputs. Hybrid approaches combine field measurements with remote sensing and modeling to improve accuracy and scalability. A robust MRV system integrates these methods with transparent data collection, standardised protocols, and independent verification to ensure reliability in SOC estimation for carbon markets, sustainable land management, and climate change mitigation efforts.

SOC standards assessment

The main standards for soil organic carbon (SOC) estimation include the Intergovernmental Panel on Climate Change (IPCC) Guidelines, which provide Tier-based methodologies for SOC stock calculations in national greenhouse gas inventories. The ISO 14235 standard outlines chemical analysis methods using dry combustion to determine organic carbon content. The Walkley-Black method, a widely used wet oxidation technique, estimates SOC but may require correction factors for accuracy. The Loss-on-Ignition (LOI) method offers a simpler approach by measuring weight loss after combustion, though it is less precise. The U.S. Department of Agriculture (USDA) and Food and Agriculture Organization (FAO) protocols provide standardised field and laboratory procedures for SOC assessment. Emerging remote sensing and spectroscopy-based methods, guided by the Global Soil Partnership (GSP) and FAO's Global Soil Laboratory Network (GLOSOLAN), are increasingly used for large-scale monitoring. These standards help ensure consistency, comparability, and accuracy in SOC estimation across different regions and applications.

The Verra standard for soil organic carbon (SOC) falls under the Verified Carbon Standard (VCS), specifically the VM0042 Methodology for Improved Agricultural Land Management (IALM). This methodology provides a framework for quantifying, monitoring, and verifying SOC sequestration and greenhouse gas (GHG) reductions resulting from improved agricultural practices. It covers activities like reduced tillage, cover cropping, agroforestry, and improved grazing management. The Verra standard requires rigorous measurement, reporting, and verification (MRV) protocols, often combining direct soil sampling with modeling approaches such as the DayCent or RothC models. Projects validated under Verra can generate carbon credits, which can be sold in voluntary carbon markets. This standard ensures credibility, transparency, and environmental integrity in soil carbon sequestration initiatives.

Assessment of soil stratification approaches

For protocols such as Verra's VM0042 which uses stratified sampling to generate a design-based estimate (i.e. one that is based on the soil sample data alone), we leverage an approach developed by de Gruijter et al. (2015). This approach uses predictions of the soil outcome of interest (i.e. soil carbon stock or pH), alongside the prediction uncertainty, to devise an optimal stratification scheme. Furthermore, with this information, it is possible to estimate the sample size required to achieve a given level of performance. Simulation studies and field trials that have examined the performance of this approach have shown that sample sizes can be reduced by 50% compared to random sampling (de Gruijter et al., 2018). Another study exploring the implementation of this approach at national scale (across France) showed that this approach outperformed other common methods of stratification based on predictors and reduced sampling by 95% compared to random (McBratney et al. 2016).

de Gruijter, J. J., Minasny, B., & McBratney, A. B. (2015). Optimizing stratification and allocation for design-based estimation of spatial means using predictions with error. Journal of Survey Statistics and Methodology, 3(1), 19-42.

de Gruijter, J. J., McBratney, A. B., Minasny, B., Wheeler, I., Malone, B. P., & Stockmann, U. (2018). Farm-scale soil carbon auditing. Pedometrics, 693-720.

McBratney, A. B, Saby N, de Gruijter J. J, Minasny B (2016)Designing soil monitoring schemes for large areas based on digital soil mapping products. Available. at https://projects.au.dk/fileadmin/1_McBratney_ospats_DSM_Aarhus.pdf

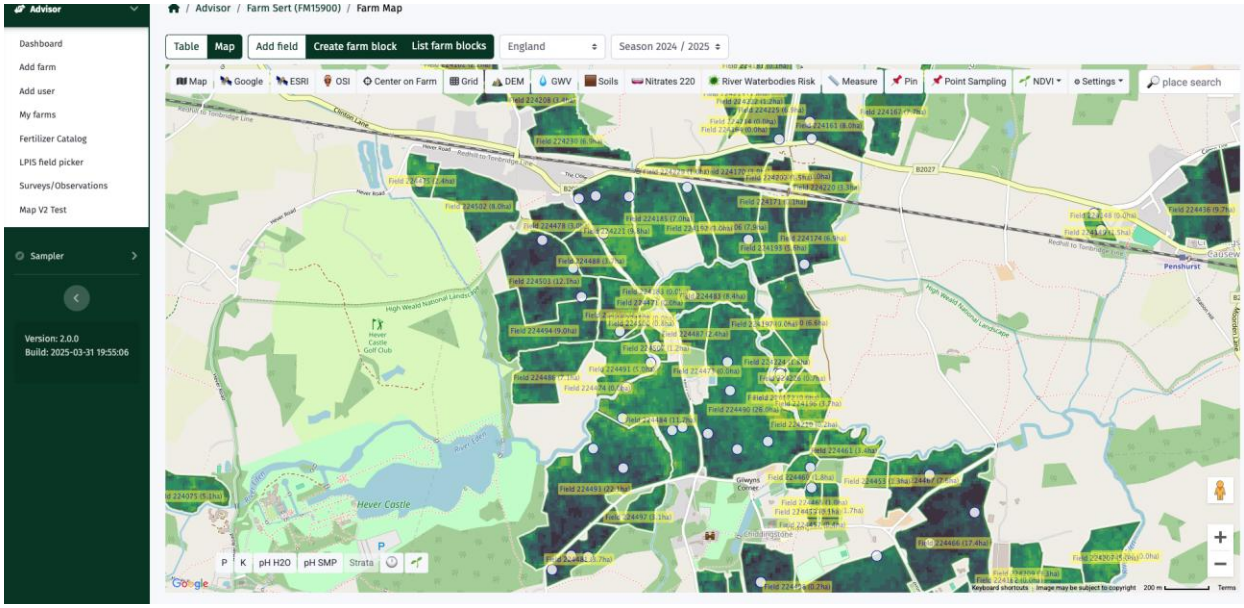


Figure 3 Example of stratification layers on the Senus platform. Points indicate sampling locations

4.6.2 Challenges encountered and how they were addressed

No challenges in the current reporting period

4.7 Key Performance Indicators (KPIs)

4.7.1 Status of defined KPIs

At this stage, there are no specific Key Performance Indicators (KPIs) to report for this period. While progress has been made in various aspects of the project, measurable benchmarks or quantifiable outcomes for this use case have not yet been formally recorded within this reporting cycle.

As the project advances and more concrete results become available, a structured framework for tracking KPIs will be established to ensure measurable impact assessment.

Future reports will aim to incorporate detailed performance indicators, providing insights into progress, efficiency, and overall effectiveness in achieving project objectives.

4.7.2 Assessment of progress toward meeting the KPIs

This use case is currently in the conceptual phase, with foundational elements being defined to establish a structured approach for soil organic carbon (SOC) measurement and verification. Thus far, significant progress has been made in identifying key stakeholders, outlining Measurement, Reporting, and

Verification (MRV) methodologies, and determining the standards and protocols that the use case must adhere to in order to ensure scientific rigor and credibility. These efforts lay the groundwork for the next phase of development.

As the project progresses, the next reporting period will focus on defining and refining the Key Performance Indicators (KPIs) that will guide the evaluation of the use case. These KPIs will serve as benchmarks for assessing the effectiveness, efficiency, and scalability of the proposed methodologies. Some of the anticipated KPIs include:

1. Stratification Layers – Each test site will be stratified using the methodology outlined in earlier phases. Stratification is a critical factor in ensuring that SOC estimations are representative of the landscape's variability in soil type, topography, and land management practices. A key KPI will be the number of strata per farm, which will help assess the resolution and precision of the applied stratification techniques when integrating with SOC measurement technologies.

2. Soil Sampling Points – One of the most important considerations for SOC assessment is the optimal number and distribution of soil sampling points per farm. Advanced modelling techniques will be used to estimate the most effective sampling locations, balancing scientific accuracy with cost-efficiency. The feasibility of minimising sample density while maintaining data reliability will be a crucial KPI, as it will directly impact the financial viability of large-scale SOC measurement efforts.

3. Carbon Stock Quantification (Tonnes per Hectare) – A core objective of the use case is to determine the quantity of SOC stocks present in the soil at different sites. This KPI will provide a baseline for understanding carbon storage levels and serve as a reference for future comparisons to assess sequestration trends over time. Accurate quantification of carbon stocks is essential for verifying the climate benefits of SOC sequestration projects and for ensuring compliance with carbon market requirements.

4. Sequestration Potential – By leveraging predictive models and baseline SOC measurements, the use case aims to estimate the sequestration potential of different land management practices. This KPI will help quantify how much additional carbon can be stored in the soil over time, offering valuable insights into the long-term climate mitigation potential of improved agricultural practices.
5. Financial Viability of the SOC Quantification and Assessment Tool (SQAT) – A critical aspect of the use case is evaluating whether the proposed SQAT system is cost-effective and scalable. The financial viability KPI will assess the affordability of measurement and verification methodologies, ensuring that the approach can be adopted at scale without placing an undue financial burden on farmers, agribusinesses, or policymakers.

By defining and tracking these KPIs, the use case will establish a robust framework for evaluating SOC estimation methods, ensuring their practicality for real-world implementation. This process will also help refine methodologies, improve decision-making for SOC programs, and align with global carbon crediting standards to facilitate participation in voluntary carbon markets.

4.8 Results and impact

4.8.1 Key results obtained

No results to date

4.8.2 Contribution to the overall SQAT project goals

Not applicable

4.9 Lessons learned and recommendations

Most of the lessons learned so far in soil organic carbon (SOC) initiatives in Ireland centre around stakeholder engagement and the assessment of the broader macro-environment in which SOC programs operate. As Ireland continues to explore the role of SOC sequestration in climate action and sustainable agriculture, several key insights have emerged:

- SOC sequestration is essential for the Irish grassland ecosystem – Given that Ireland's landscapes are dominated by highly productive grasslands, maintaining and enhancing SOC stocks is critical for soil health, biodiversity, and long-term agricultural sustainability. The potential for SOC sequestration in these systems is seen as a valuable tool in mitigating climate change and improving resilience against extreme weather conditions.

- Robust methodologies are required to ensure accuracy – Various measurement techniques exist, but some may overestimate SOC stocks if not carefully applied. For instance, errors in bulk density calculations have been shown to significantly affect estimates. Therefore, standardised and validated methodologies must be used to provide reliable and consistent SOC assessments.

- Strict adherence to MRV (Measurement, Reporting, and Verification) methods – A high level of rigor in SOC estimation is essential to build credibility and ensure that sequestration claims can be accurately validated. MRV protocols help provide transparency and consistency, making SOC projects more suitable for integration into carbon markets and regulatory frameworks.

- A hybrid approach combining sampling and modeling is likely optimal – While direct soil sampling provides accurate, localized SOC data, modeling techniques (such as RothC or DayCent) allow for broader spatial and temporal estimations. A combined approach leverages the strengths of both, balancing precision with scalability in SOC projects.

- Adherence to established carbon standards such as Verra VM0042 – To ensure environmental integrity and market recognition, SOC initiatives should align with internationally recognized carbon crediting methodologies, such as Verra's VM0042 Methodology for Improved Agricultural Land Management (IALM). Compliance with such frameworks ensures that SOC sequestration efforts can be effectively monitored, reported, and potentially monetized through voluntary carbon markets.

These lessons reinforce the need for a structured, science-based approach to SOC sequestration, ensuring that Ireland's initiatives are both environmentally effective and economically viable.

4.10 Next steps and action plan

To ensure the successful execution of the project and to refine our methodology, we will undertake the following key steps:

1. Estimating Strata on a Sample of Farms. As part of our methodological approach, we will conduct an in-depth analysis of farm stratification by selecting a representative sample of typical Irish farms. This will allow us to assess the impact of stratification on the overall study and refine our classification framework accordingly. By identifying distinct farm strata, we aim to enhance the accuracy and applicability of our research findings across varying agricultural landscapes.
2. Estimating Sampling Points In alignment with established scientific methodologies, we will determine the optimal system for selecting sampling points. This process will involve assessing different sampling techniques to ensure efficiency, reliability, and statistical robustness. By considering factors such as geographic diversity, soil variability, and farm typology, we will develop a sampling framework that minimizes bias and maximizes data representativeness.
3. Identifying Suitable Locations for Field Trials To facilitate the practical implementation of our research, we will conduct a thorough evaluation of potential field trial sites. This process will involve consulting with relevant stakeholders, analysing environmental conditions, and ensuring compliance with project objectives. Selecting appropriate locations will be critical for generating meaningful insights and validating our methodological approach.
4. Developing a Comprehensive Field Trial Plan In collaboration with our project partners, we will design a structured field trial plan that aligns with the overall research goals. This plan will outline key experimental parameters, logistical considerations, data collection protocols, and risk mitigation strategies. Coordination with stakeholders will be essential to ensure seamless execution and alignment with broader project milestones.

By implementing these steps in a structured and systematic manner, we aim to enhance the quality, reliability, and impact of our research outcomes.

5 Use case 4 in the Netherlands: Improved soil management and profitability for intensive potato farming in the Netherlands

5.1 Brief context

The sandy soils around Reusel are characterised by high variability in SOM. Also, parcels are often bordered by forest or lines of trees, creating shadows and competition for nutrients and water. Creating soil properties maps helps farmers in their cultivation management.

The use case involves potato farmers (including vdBorne with 500 ha), contractors (including those linked to vdBorne), De Dommel water board, and a potato processor. The result will be to improve crop density tuned to relevant soil conditions, and hence use less seeding material, but with better yield, for an economically more viable operation.

The use case has been starting up last year. Several meetings have taken place.

5.2 Overall objective and specific aims updates

The overall objective is to test and demonstrate the SQAT system for generating high-resolution prescription maps for planting potatoes, based on nutrient carrying capacity.

To deliver this objective, the specific aims are:

5. *To develop an autonomous platform in tandem with satellite imaging for mapping of soil properties in a high spatial resolution. To be used as an input for VRA of seed potatoes;*
6. *To analyse currently used sensors as a viable method of determining appropriate VRA of seed potatoes;*
7. *To validate remote sensing based maps with existing datasets from other sources;*
8. *To optimize sampling locations for increased capacity;*
9. *To test the SQAT system in the field;*
10. *To conduct demonstrations and field days for transferring results to farmers, service providers and agri-consultants.*

5.3 Partners involved

The partners involved are:

- AeroVision
- Vdborne

5.4 Description of key stakeholders' involvement and feedback

In this period the stakeholders were not yet involved.

5.5 Test locations

5.5.1 Justification for any changes or additions to test sites

No changes.

5.5.2 Test location description

Table 9 Test location Netherlands

Location name	VDBORNE Campus, Reusel
Sampling area size (ha)	We are now working with 3 fields, (approx. 20 ha) but the plan is to expand.
Number of composite samples	None taken yet.
Number of individual samples combined for composite sample	None taken yet.
Sampling depth	0-30 cm is the standard.
How sampling location was determined	Sampling based on zoning by satellite data.

5.6 Activities and Implementation Steps

5.6.1 Detailed description of activities carried out

The team has been working on zoning. Three parcels have been selected to start the activity. These three parcels have also been scanned by the EM38 scanner operated by SoilMasters BV. The first exercise is to find out how zoning based on satellite data compares to the in-situ scanner-based zoning.

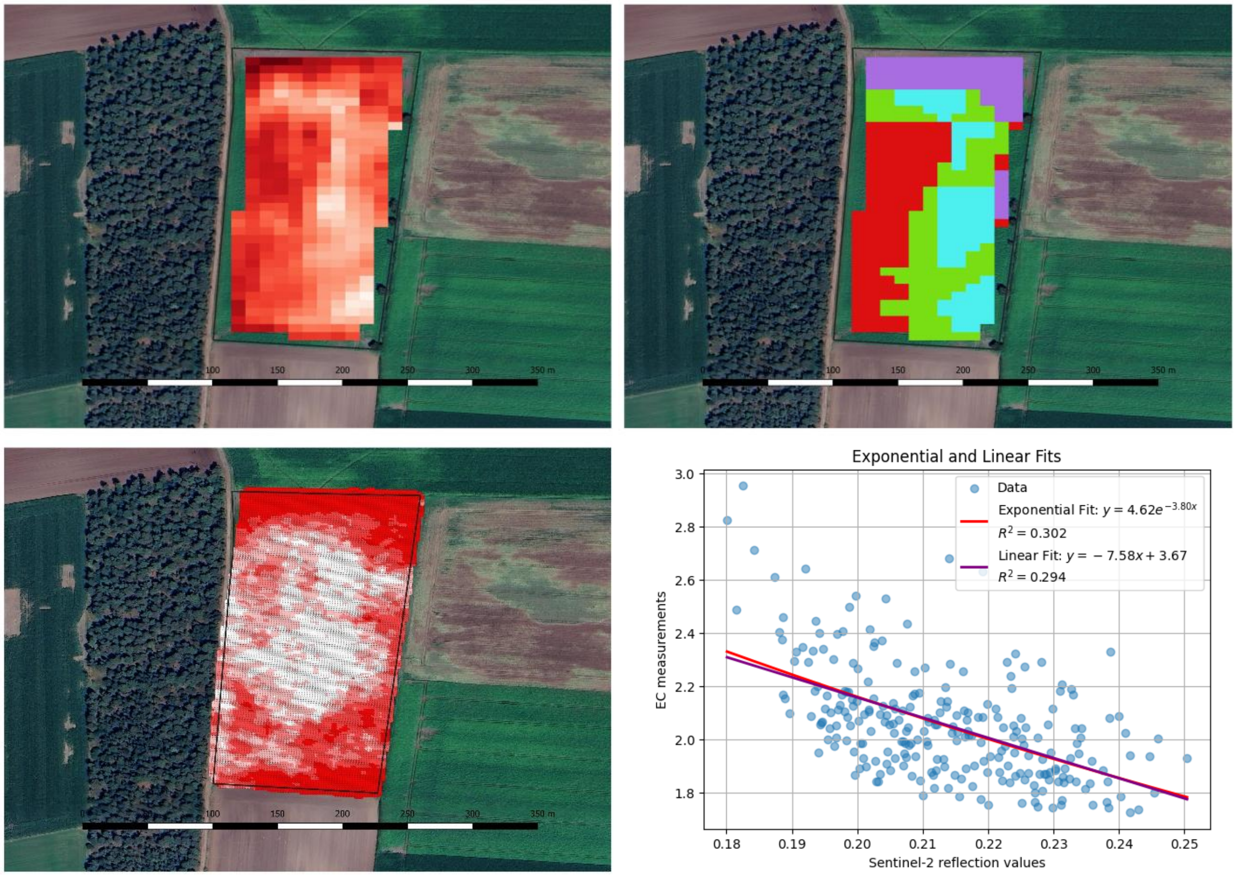


Figure 4: Images for parcel "Jacob KCm cirkelf". From top left to bottom: Sentinel-2 bare-soil image from 30-05-2023 (more red means lower reflectance values). Soil stratification partially based on that same image. Proximal sensing EC taken on 24-03-2020 (more red means higher electronic conductivity). Scatter plot with mean EC over Sentinel-2 pixels.

For the satellite-based zoning, two methods were applied. The first method is the so-called 'bare soil' method as developed by AeroVision in the past years. This method uses bare-soil images from satellite archives to identify homogeneous zones. The 'bare soil' method has been validated already in different fields and situations and has proven to be a stable and reliable way to determine soil zones within a parcel. Although there is no pre-defined objective to quantify the soil properties of each zone from satellite imagery, the method reveals zones in order (low-high) of dominant soil properties, mostly clay and organic matter. See figures 1 till 3 for examples of the vdBorne fields together with proximal sensing EC (electronic conductivity) measurements.

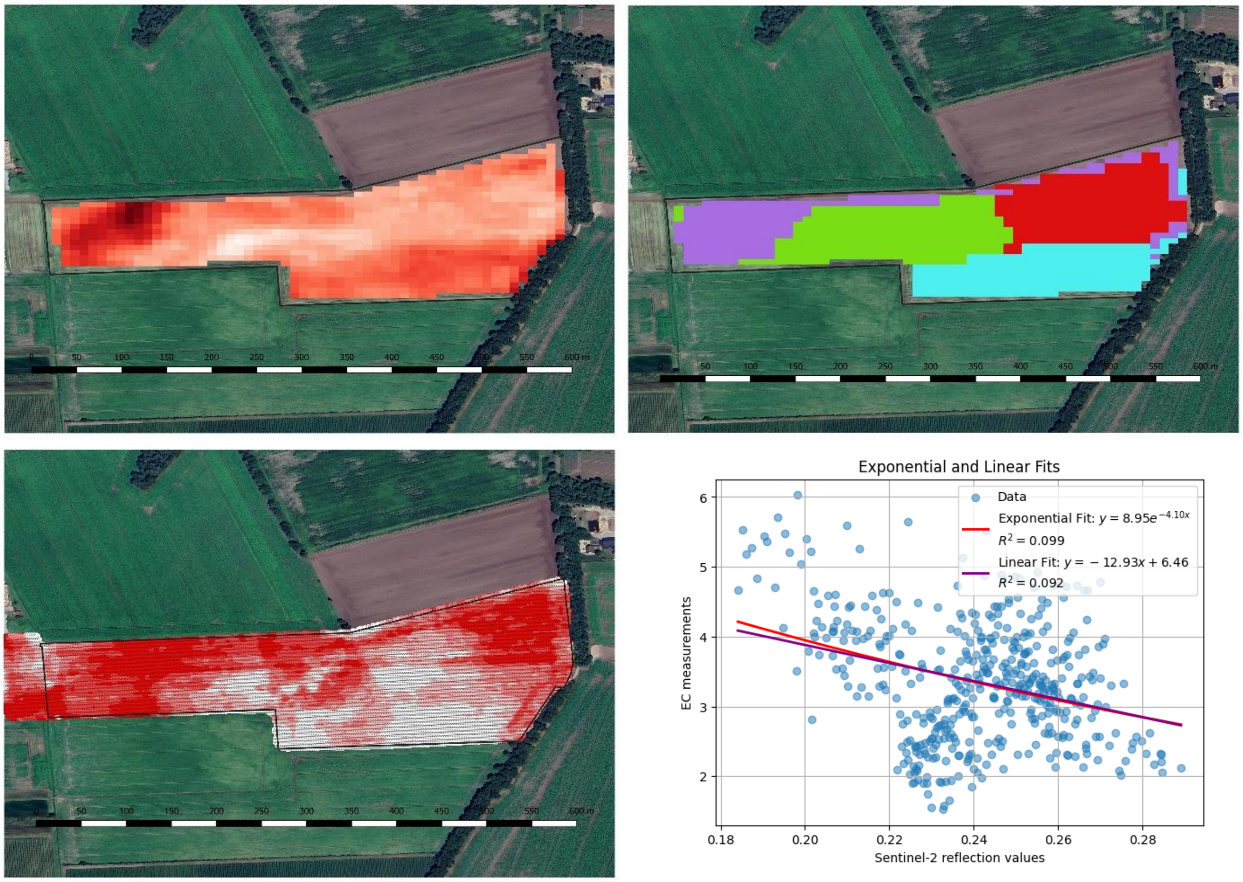


Figure 5: Images for parcel "Peter van gompel KCs herdersdreef". From top left to bottom: Sentinel-2 band of a bare-soil image from 30-05-2023 (more red means lower reflectance values). Soil stratification partially based on that same image. Proximal sensing EC taken on 27-03-2017 (more red means higher electronic conductivity). Scatter plot with mean EC over Sentinel-2 pixels.

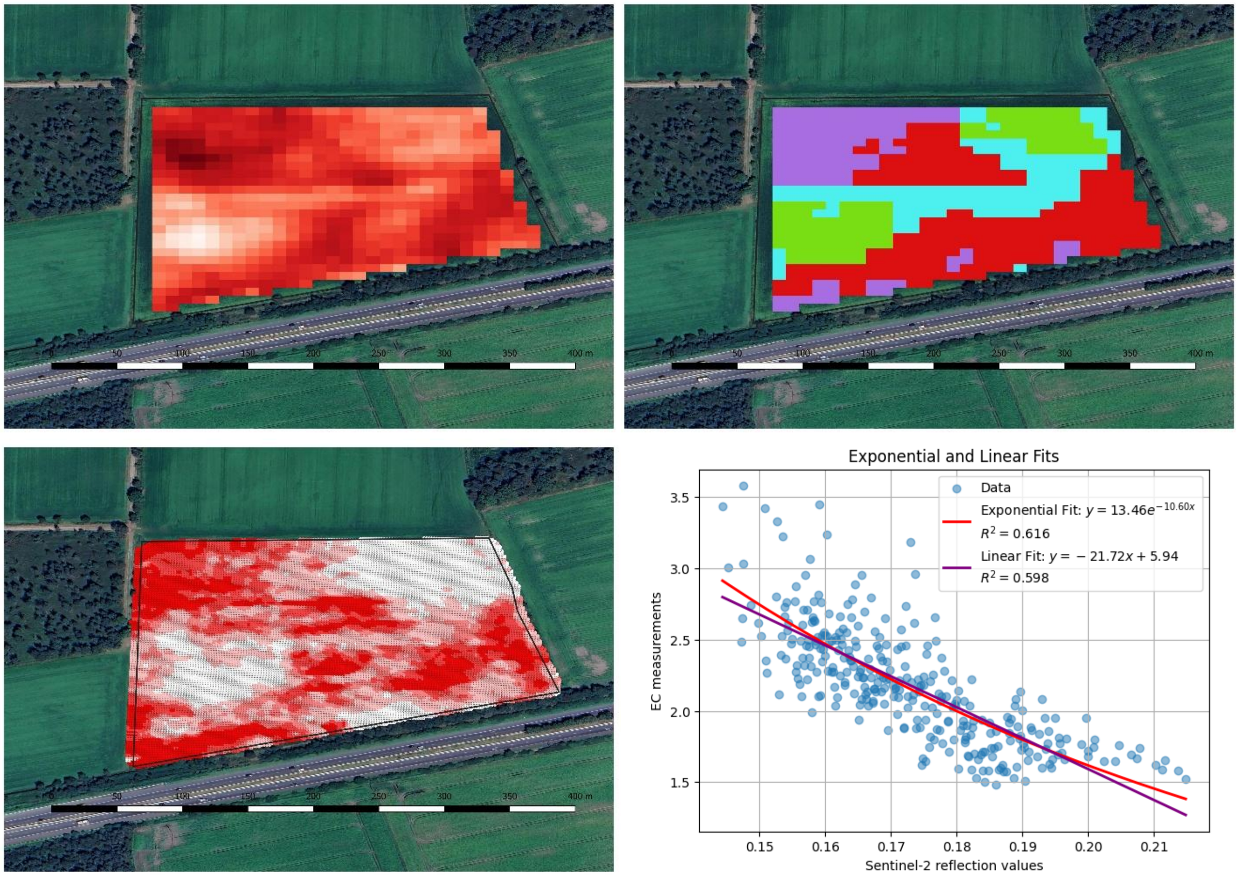


Figure 6: Images for parcel "Jan Wolfsven achter koraan". From top left to bottom: Sentinel-2 bare-soil image from 30-05-2023 (more red means lower reflectance values). Soil stratification partially based on that same image. Proximal sensing EC taken on 03-03-2021 (more red means higher electronic conductivity). Scatter plot with mean EC over Sentinel-2 pixels.

The second method is the so-called 'vegetation proxy' method. This has been developed in the past year to accommodate grassland parcels and fields in regenerative agriculture practices that strive for maximum vegetation covered soils. Because of these practices, these fields have no bare soil image in the archives, hence the need for an alternative method. It is logical that vegetation growth responds to soil properties, so that differences in biomass accumulation within the same field *can* indicate differences in soil properties. But other factors can influence the vegetation too, like biotic and abiotic stress, sowing errors or fertilisation and irrigation. Therefore, vegetation-based soil zoning needs to be carefully approached.

In the 'vegetation proxy' method we take satellite imagery of at least 5 years of the field and after quality checks of the imagery these images are integrated into a zoning algorithm.

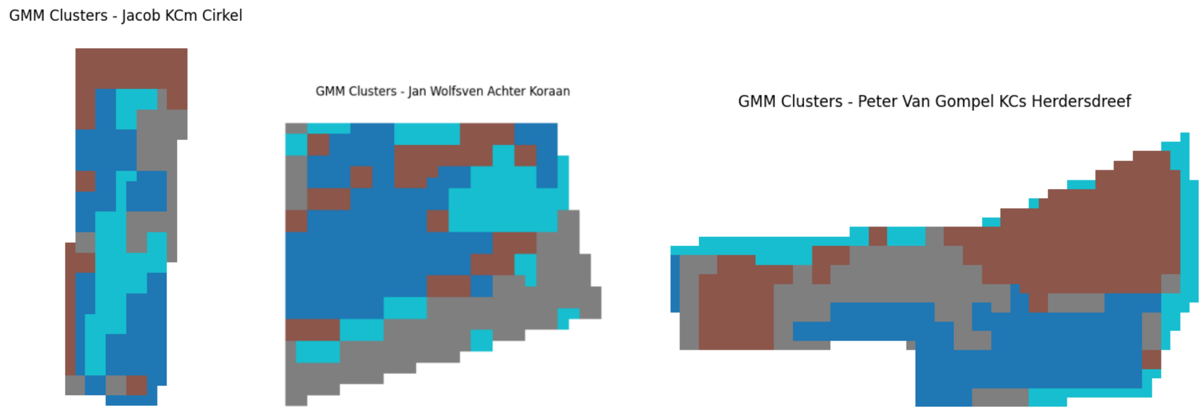


Figure 7: Vegetation zoning for parcels Jan Wolfsven achter koraan, Jacob KCm cirkelf and Peter van gompel KCs herdersdreef. Soil stratification based on vegetation indices NDVI, WDVI and SAVI derived from satellite images of 5 years (2020 – 2024).

After performing these zoning actions, the EM38 sensor readings were also mapped and run through a zoning algorithm. The correspondence between zones from satellite and sensor is enormous. This will be further analysed and quantified in the following period.

5.6.2 Challenges encountered and how they were addressed

There were no major challenges.

5.7 Key Performance Indicators (KPIs)

5.7.1 Status of defined KPIs

The defined KPIs refer to later stages in the project.

5.7.2 Assessment of progress toward meeting the KPIs

It is now too early for the defined KPIs to work on. However, some starting actions have taken place and the team is well aware of the requirement to meet these KPIs.

A Field event is planned for August 2025.

5.8 Results and impact

5.8.1 Key results obtained

The actions so far have been focussed on the validation of the satellite based zoning methods. With satellite imagery we mean to deliver prior-knowledge providing insights in the heterogeneity and variety in soil properties. As this is a more cost-effective method then field visits with sensors, it can help farmers and advisors in how and where to deploy their sensors. In this project we also want to investigate if we can base a solid advice on these satellite imagery on in-situ measurement characteristics, such as measurement density or preferred directions.

5.8.2 Contribution to the overall SQAT project goals

The results contribute explicitly to specific objective 1, and to lesser extend to the other specific objectives.

5.9 Lessons learned and recommendations

It is too early in the process to come with lessons.

5.10 Next steps and action plan

For the coming period the following activities are planned:

- For the three fields, the imagery and sensor maps are transferred into quantitative soil property maps that are of relevance to the farmer. Hereto, soil samples will be taken on the locations set out by the satellite-imagery based mapping;
- The soil property maps are verified by the farmer – on the usability and actionability. In particular the farmer will be asked if and how these maps can be the source for variable rate application maps;
- All other fields of the farmer are also run through the zoning algorithm;
- In August a demonstration is planned. This will be prepared also with the nearby partners.

6 Use case 5 in Serbia: Improving soil management to reverse negative long-term trends in soil organic matter

6.1 Brief context

- The Serbian use case within the SQAT project aims at addressing the critical issue of declining soil organic matter (SOM) due to intensive agricultural practices prevalent across Serbia, especially in the Vojvodina region. With over 3.25 million hectares of arable land, the primary crops cultivated include corn, wheat, soybeans, sunflower, and rapeseed. Due to the intensive use of mineral fertilizers(especially with high nitrogen fertilizer – e.g. Urea..), insufficient organic fertilization, and extreme weather conditions, Serbian soils have experienced a significant reduction in organic matter. Currently, only about 1% of Serbian soils have more than 5% humus content, highlighting the urgent need for intervention. This issue directly aligns with the SQAT project's overarching objective to enhance agricultural productivity and sustainability by developing smart soil property mapping solutions. The Serbian use case uses advanced satellite imagery analysis, precise soil sampling techniques, and based on that create data to generate actionable insights for farmers, aiming to optimize fertilization and seeding practices.
- Recognizing these challenges, Terra Controlling TMD has actively engaged in educating farmers about proper soil sampling and has implemented advanced soil sampling practices, leveraging historical satellite images to create detailed sampling zones based on Vegetation Indices (VI) and Bare Soil Indices (BSI).
- During the reporting period, significant progress was achieved, including the establishment of partnerships with local stakeholders such as farmer organizations. Sampling is conducted using automated probes mounted on vehicles. Analyses are performed in accredited laboratories following national standards. For this use case, several representative fields have been selected and committed in the first year, covering:
    - PG Tišma Milan (33.951 ha) wheat crop 24
    - Vasić Agrar(17.574 ha); Wheat crop 24
    - PG Petar Matijević (24.657 ha); corn crop 24
    - PG Frug (5 ha); Vineyard
    - PG Nemanja Jovičić (3 ha) walnut orchard
- In 2024, the broader implementation context of the Serbian use case was significantly influenced by extreme climatic events. Serbia experienced unprecedented weather conditions, characterized by record-high temperatures and severe drought, with annual average temperatures exceeding the 1991–2020 mean by 2.3°C. Particularly challenging were the four severe heatwaves during summer, culminating in a maximum recorded temperature of 40.6°C in Sombor on August 14th. These harsh weather conditions substantially reduced soil moisture levels, emphasizing the critical importance of enhanced soil management practices.
- These climate-driven challenges directly reinforced the relevance and urgency of precise soil property mapping and sustainable agricultural solutions—core objectives of the SQAT project. Consequently, the Serbian use case provided essential tools and adaptive strategies, enabling farmers to respond effectively to climate variability, optimize resource use, and improve the resilience of agricultural production in the face of future climate uncertainties.

6.2 Overall objective and specific aims updates

- The overall objective of the Serbian use case remains to collect comprehensive information on soil health parameters to support the development, ongoing maintenance, and further enhancement of the SQAT platform. Additionally, the objective includes developing tailored services that specifically address the needs and conditions of Serbian agriculture, promoting sustainable soil health management across multiple crop types.
- The specific aims designed to deliver on this objective include:
  - Mapping selected agricultural fields using Vegetation Indices (VI) or Bare Soil Indices (BSI) based on historical satellite imagery.
  - Creating detailed soil sampling zones through the processing and analysis of satellite imagery and associated indices.
  - Conducting precise soil sampling, taking approximately minimum 15 subsamples per defined sampling zone.
  - Performing laboratory analysis of soil samples in accredited laboratories according to national standards.
  - Integrating and interpolating laboratory results with remote sensing mapping outputs to create actionable insights and services aligned with SQAT project needs.
- During the reporting period, the selection of test plots was refined based on practical considerations and emerging agricultural trends. Specifically, the original plan to sample larger orchard areas was adjusted, and a strategic decision was made to add walnut orchards (PG Nemanja Jovičić, 3 ha), acknowledging the rapid expansion and growing economic importance of walnut cultivation in Serbia. This adjustment enables better alignment with current agricultural priorities and maximizes the relevance and applicability of the collected data.

6.3 Partners involved

- The following partners are involved in the Serbian use case, each contributing distinct roles and responsibilities:
  - TerraTMD. Main contact: Dušan Jovanović (dusan.jovanovic@terracontrolling.rs). Role: Use Case Lead. Specific responsibilities: Overall management of the use case, identification and selection of appropriate test fields, conducting precise soil sampling using automated probes, overseeing laboratory testing procedures, integrating and analyzing collected data. Additionally contact: Miodrag Miodragović (miodrag.miodragovic@terracontrolling.rs).
  - ABE (Association for Balkan Eco-Innovations). Main contact: Srđan Pavlović (srdjan@balkanecoinnovations.org). Role: Support partner. Specific responsibilities: Coordination and communication support, facilitating stakeholder engagement, assistance in identification and selection of test fields, and promoting the adoption and dissemination of project results within the local ecosystem.
- During the reporting period, no changes occurred in the partnership structure or distribution of responsibilities. All partners maintained their initially planned roles, ensuring smooth collaboration and continuity of planned activities.

6.4 Description of key stakeholders' involvement and feedback

During the reporting period, key stakeholders were actively engaged through direct collaboration, field visits, and ongoing consultations. Their involvement was instrumental in ensuring the practical applicability and relevance of the Serbian use case.

- **Farmers (Vasić Agrar, PG Milan Tišma, PG Petar Matijević):** Farmers provided access to their fields for soil sampling and mapping, shared historical data, and actively participated in discussions about soil management practices. Their feedback highlighted the importance of precise data for optimizing fertilizer use, emphasizing cost savings, and environmental sustainability. Farmers particularly appreciated the detailed mapping approach, recognizing the potential for significant productivity gains.
- **University of Novi Sad, Faculty of Agriculture (Laboratory for testing soil, fertilizer, and plant material - Department of Agrochemistry):** The Faculty provided crucial support through expert consultations, laboratory testing of soil samples, and validation of analytical methods. Their feedback contributed significantly to methodological refinements, ensuring the accuracy and reliability of results.
- **Vineyards (PG Frug):** The vineyard stakeholder engaged actively in sampling activities and provided valuable feedback on the relevance of precise soil mapping to vineyard management practices. Their feedback highlighted the value of targeted interventions to improve soil health and grape quality.

Overall, stakeholders positively assessed their involvement, expressing high satisfaction with the practical applicability of the SQAT approach and actively recommending ongoing collaboration.

6.5 Test locations

6.5.1 Justification for any changes or additions to test sites

All initially selected agricultural test sites remained unchanged and were conducted as originally planned, ensuring consistency and continuity of the study. However, minor adjustments were made regarding vineyard and orchard test sites:

- Vineyard: The originally planned vineyard area of 10 hectares was reduced to 5 hectares. This adjustment was necessary due to practical limitations related to the availability of sufficiently large continuous vineyard plots in the Srem region. The smaller area still provided adequate data for the purposes of the use case while maintaining representativeness and relevance.
- Orchard: A 3-hectare walnut orchard was added as a test site in the Šumadija region. This inclusion was strategically decided upon due to the rapid expansion and increasing economic importance of walnut cultivation in Serbia.
- Additionally, the originally planned 12-hectare orchard of "Oblačinska višnja" (cherry) is scheduled to be included for sampling during the upcoming year. This site experienced a deliberate pause in sampling due to previous soil analyses performed shortly before the start of

the SQAT project. Consequently, to ensure validity and optimal comparability of soil sampling results, a sufficient interval was established between sampling rounds.

6.5.2 Test location description

Table 10 Test location Serbia

Location name	Frug Sremski Karlovci
Sampling area size (ha)	5 ha
Number of composite samples	12
Number of individual samples combined for composite sample	15-25
Sampling depth	0-30
How sampling location was determined	Based on variety/type of vines

Location name	PG Nemanja Jovičić,- Šumadija
Sampling area size (ha)	3 ha
Number of composite samples	1
Number of individual samples combined for composite sample	15-25
Sampling depth	0-30
How sampling location was determined	W method

Location name	Vasić Agrar - Ašanja
Sampling area size (ha)	17.573 ha
Number of composite samples	4
Number of individual samples combined for composite sample	15-25
Sampling depth	0-30
How sampling location was determined	Zoning based on VI and BSI 2020-2024

Location name	PG Milan Tišma - Zmajevo
Sampling area size (ha)	33.951 ha
Number of composite samples	7
Number of individual samples combined for composite sample	15-25
Sampling depth	0-30
How sampling location was determined	Zoning based on VI and BSI 2023

Location name	PG Petar Matijević - Hetin
Sampling area size (ha)	24.657 ha
Number of composite samples	5
Number of individual samples combined for composite sample	15-25
Sampling depth	0 - 30
How sampling location was determined	Zoning based on VI and BSI 2020-2024

6.6 Activities and Implementation Steps

6.6.1 Detailed description of activities carried out

During the reporting period, the following main activities were systematically carried out:

- Establishing Field Boundaries (March-April 2024):
    - Precise field boundaries for all selected agricultural plots were identified and validated, ensuring accurate geospatial data.
- Satellite Imagery Acquisition and Processing (April-June 2024):
    - Sentinel-2 satellite images were downloaded and processed for each field for selected years.
    - Four Vegetation Indices (VI) were computed for each year and used to perform zoning annually and cumulatively.
    - Specific dates representing bare soil conditions were selected each year, and Bare Soil Indices (BSI) zoning was performed.

- Integrated Zoning and Sampling Locations Definition (June-July 2024):
    - Final sampling zones were created by combining VI and BSI data.
    - Sampling patterns and exact locations were established, with tailored approaches for vineyards and orchards due to practical constraints.
- Soil Sampling Execution:
    - PG Nemanja Jovičić Walnut Orchard (3 ha): April 4, 2024
    - PG Frug Vineyard (5 ha): May 29, 2024, and November 1, 2024
    - PG Milan Tišma (33.951 ha): August 5, 2024
    - Vasić Agrar (17.574 ha): September 6, 2024
    - PG Petar Matijević (24.657 ha): September 20, 2024

Sampling was guided by GNSS navigation to ensure precise locations.

- Laboratory Analysis and Mapping (August-November 2024):
    - Collected soil samples were analysed in accredited laboratories.
    - High-resolution soil property maps were generated based on the laboratory results.
- Recommendation Generation and Stakeholder Engagement (2024):
    - Data-driven recommendations for fertilization and seeding were developed.
    - Results and recommendations were reviewed and discussed with experts from the Faculty of Agriculture laboratory and end-user farmers to ensure applicability and effectiveness.

6.6.2 Challenges encountered and how they were addressed

- Extreme Climatic Conditions:
    - Serbia experienced severe drought and extreme temperatures in 2024, complicating soil sampling procedures and potentially affecting sample quality.
    - Strategy: Sampling schedules were adjusted to mitigate the effects of drought conditions. Additional consultations with drought management and soil moisture experts were conducted to ensure the accuracy and representativeness of samples collected under these challenging conditions.
- Size and Accessibility of Test Fields:
    - The originally planned vineyard area of 10 hectares was reduced to 5 hectares due to the unavailability of sufficiently large continuous plots within the targeted region (Srem).
    - Strategy: Methodologies were adapted to accommodate smaller vineyard sizes while ensuring representative and high-quality data.
- Specific Sampling Requirements in Orchards and Vineyards:
    - The restricted accessibility of vehicles in orchards and vineyards posed challenges for the standard sampling approach.
    - Strategy: Alternative sampling locations and approaches were identified, and GNSS-based navigation was employed to accurately guide sampling teams to these specifically determined locations, ensuring precise and effective sampling despite access limitations.

6.7 Key Performance Indicators (KPIs)

6.7.1 Status of defined KPIs

So far we can only refer to KPI with title "Leverage on field demonstration events to engage customers"

- ○ We organized a practical session with final-year students from the Faculty of Agriculture, demonstrating proper soil sampling techniques. Students were educated on the importance of accurate soil sampling, best practices in the field, and introduced to the objectives and activities of the SQAT project. Further details are available via the following link: Facebook Reel - Soil Sampling Demonstration.
- Additionally, we actively promoted the SQAT project at the Horizons of Innovation - EU Research Collaboration Forum in Croatia!

6.7.2 Assessment of progress toward meeting the KPIs

The majority of KPIs have demonstrated steady progress toward their intended targets, with particular success observed in KPIs related to stakeholder engagement, data acquisition, and the utilization of remote sensing techniques

6.8 Results and impact

6.8.1 Key results obtained

- Although only one year has passed since the implementation of the use case, several encouraging results have already emerged:
  - Enhanced field-level nutrient management:
    - Soil sampling and analysis have enabled the identification of spatial variability in NPK levels within fields.
    - This has laid the foundation for site-specific fertilization planning, tailored to actual crop needs.
- Positive user feedback and increased awareness among farmers regarding:
  - The benefits of variable-rate fertilization (VRA)

6.8.2 Contribution to the overall SQAT project goals

- The results of this use case directly contribute to the overall SQAT project objectives in several key ways:
  - It promotes the use of smart technologies in agriculture, supporting SQAT's aim to modernize and digitalize soil monitoring and nutrient management practices.
  - It encourages farmers to transition from uniform to variable-rate input application, in line with SQAT's goals of precision, efficiency, and environmental responsibility.

6.9 Lessons learned and recommendations

- Two key insights were gained throughout the implementation of the use case, which can help improve future activities:

- Need for flexibility in planning: Certain phases required adjustments to the original plan to better reflect on-the-ground realities and user needs.
- Importance of early and continuous user engagement: Regular communication with end users enabled the early detection of issues and improved alignment with user expectations.

6.10 Next steps and action plan

- Based on practise from the previous phase, a minor adjustment in the data processing methodology is planned to improve the accuracy and speed of analysis. This change aims to better address the specific needs of end users.

7 Use case 6 in Switzerland: Automatic soil sample collection and field analysis

7.1 Brief context

ISF has secured the commitment of Swiss Future Farm, the Swiss advisory public-private equity, and will engage government/private agri-advisor. The quadrupedal robot is deployed in several farmer fields with high-value crops and high intra-field heterogeneity: apple orchards and berry fields (strawberries, raspberries). The experiment will test and compare a novel lightweight drilling and soil-sample compartmentalisation (spring, mid-summer and autumn with high density of samples, 2 per 5m2) to state-of-the-art soil-sampling manual soil sampling tools. Farmers will provide input on fertilisation procedures and participate in the experiment design process.

7.2 Overall objective and specific aims updates

The primary objective of this use case is to advance soil sampling techniques in agricultural fields by implementing control software for a state-of-the-art quadrupedal robot featuring a groundbreaking drilling device. The project will involve designing and constructing a robotic system capable of independently traversing diverse agricultural terrains, identifying optimal sampling locations, and executing precise soil sample collection while minimising environmental disruption. Furthermore, the project will entail extensive research and development efforts to optimise the drilling device for various soil compositions and environmental conditions, including integrating advanced sensors for real-time data acquisition and analysis. The aim is to establish a highly dependable and efficient tool for conducting meticulous soil monitoring and analysis tailored to the specific requirements of agricultural settings.

The project's next phase will focus on developing a novel container for the soil samples. This container will securely store and preserve the collected soil samples, allowing easy retrieval and analysis. The goal is to create a container that can maintain the integrity of the soil samples during transportation and storage, ensuring that the data obtained from the samples remains accurate and reliable. Additionally, the container will be equipped with tracking and labelling capabilities to streamline the organisation and cataloguing of the samples, facilitating efficient data management and analysis in agricultural research and monitoring.

Furthermore, the robotic system will have an automatic delivery mechanism to transport the soil samples from the collection site to the field lab for analysis. This feature will enable seamless and timely transfer of the samples, reducing the risk of contamination or degradation and expediting the overall soil analysis process. The automatic delivery system will be designed to ensure the safe and efficient transportation of the soil samples, maintaining the integrity of the data throughout the entire sampling and analysis workflow. This integrated approach aims to revolutionise soil sampling practices in agricultural fields, offering a comprehensive solution for precision agriculture and environmental monitoring.

7.3 Partners involved

Table 11 All participating partners use case Switzerland

Use case role	Organisation	Main contact	Specific responsibilities
Use case lead	ISF-OST		Overall management and testing of the robotic solution on the
Soil sampling	ILVO	Axel Wilkens	Commercial, heavy-duty soil sampling
Homogeneity Map	Aerovision	Tamme van der Wal	Homogeneity map from satellite images

7.4 Description of key stakeholders' involvement and feedback

Table 12 Involved key Stakeholders use case Switzerland

	Farmers	Agrifood companies	Agri consultants	Soil mapping company	Other
Involved	✓	✗	✓	✗	✗
Name and description	Swiss Future Farm (SFF)		Swiss Future Farm (SFF)		
Hydraulic samples			ILVO		

7.5 Test locations

7.5.1 Justification for any changes or additions to test sites

7.5.2 Test location description

Table 13 Test location Switzerland

Location name	
Sampling area size (ha)	
Number of composite samples	
Number of individual samples combined for composite sample	
Sampling depth	
How sampling location was determined	

7.6 Activities and Implementation Steps

7.6.1 Detailed description of activities carried out

Main activities:

- Concepting and building a lightweight drill
- Sample delivery and carrier platform

7.6.1.1 Lightweight drill

Three student projects were done around an initial mock-up for the drill assembly. Each student was responsible for one function of the whole assembly. The initial design for the drill by the student could be used for drilling and Single Rod Soil Sample. The tilting mechanism should allow us to rotate the drill by 90°. The packaging unit would seal the soil sample in small plastic bags.

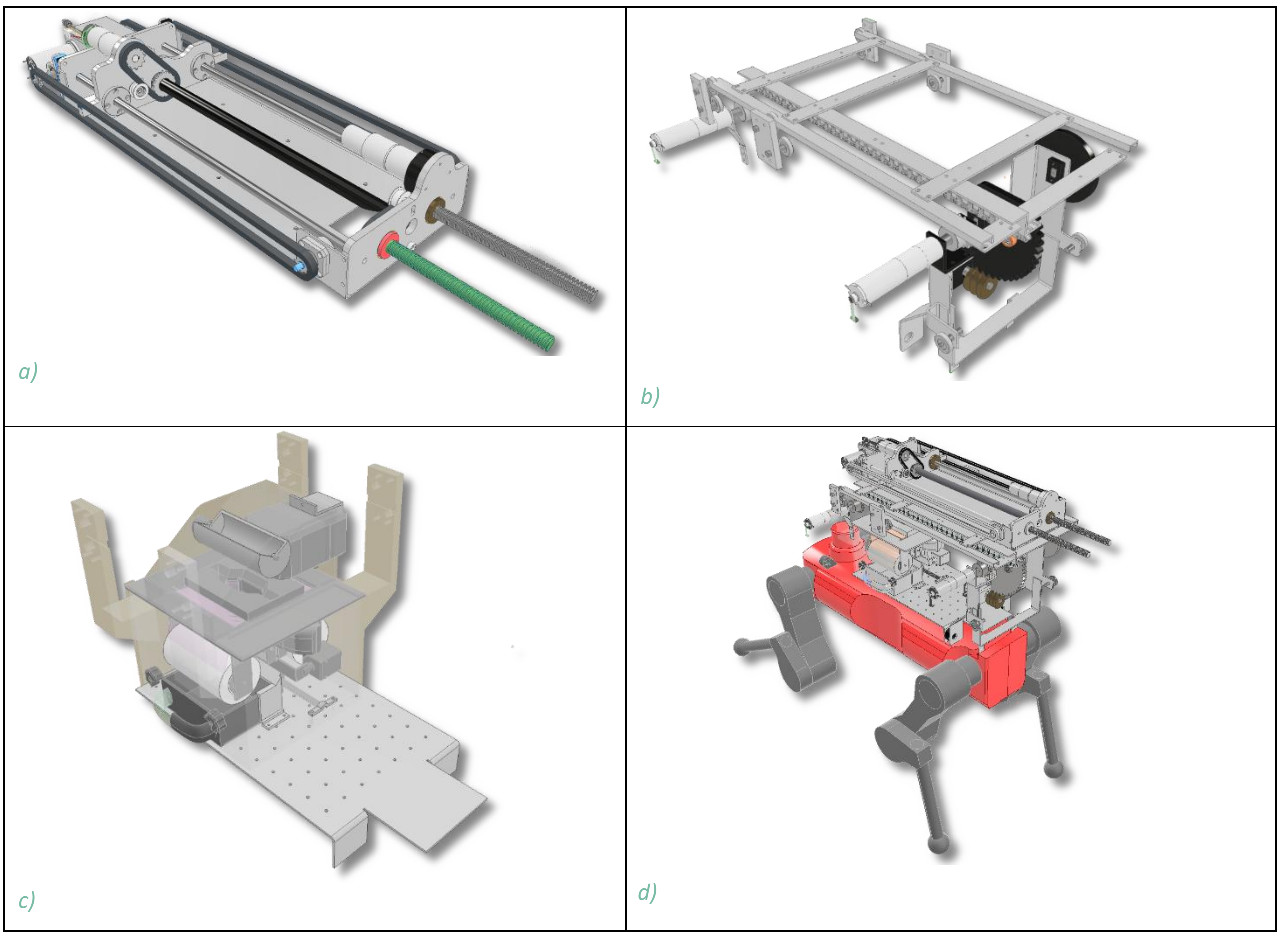
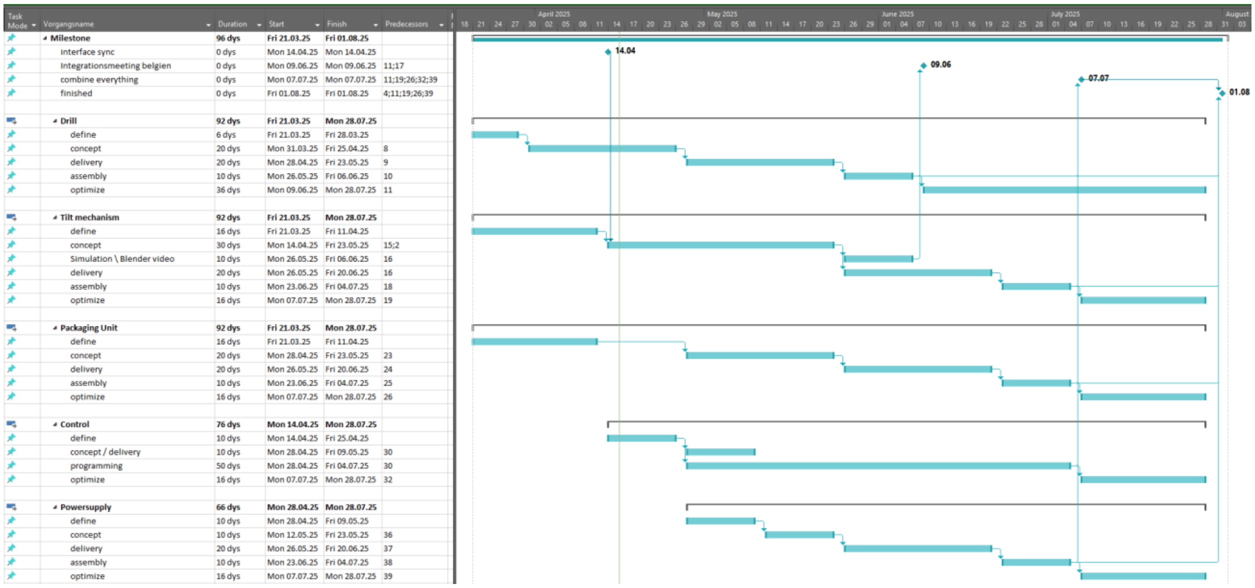


Figure 8 a) The first version of drilling device b) Tilt Mechanism c) Packaging unit d) full ANYmal payload

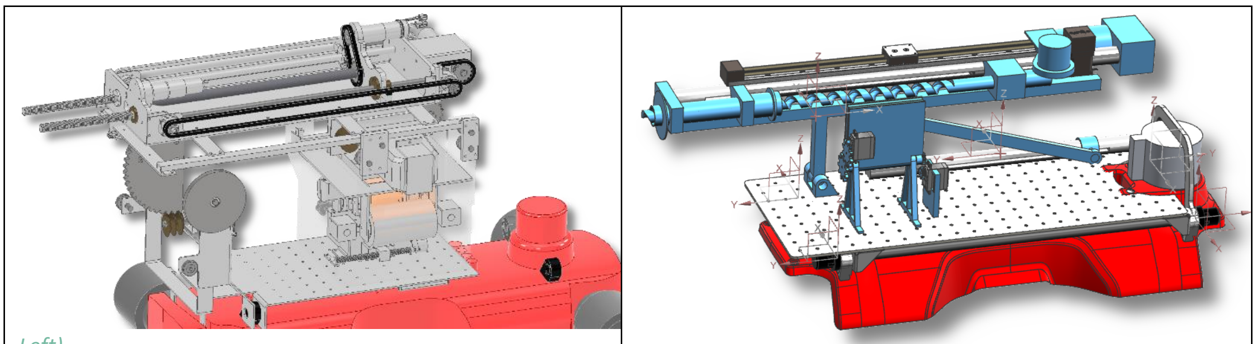
A refined mock-up has been developed to prove a functional concept. The ideas were then tested with 3D-printed parts in an accelerated iteration loop to determine each concept's go or no-go decision as quickly as possible.



Task Mode	Vorgangsname	Duration	Start	Finish	Predecessors
	Milestone	**96 dys**	**Fri 21.03.25**	**Fri 01.08.25**	
	interface sync	0 dys	Mon 14.04.25	Mon 14.04.25	
	Integrationsmeeting belgien	0 dys	Mon 09.06.25	Mon 09.06.25	11;17
	combine everything	0 dys	Mon 07.07.25	Mon 07.07.25	11;19;26;32;39
	finished	0 dys	Fri 01.08.25	Fri 01.08.25	4;11;19;26;39
	Drill	**92 dys**	**Fri 21.03.25**	**Mon 28.07.25**	
	define	6 dys	Fri 21.03.25	Fri 28.03.25	
	concept	20 dys	Mon 31.03.25	Fri 25.04.25	8
	delivery	20 dys	Mon 28.04.25	Fri 23.05.25	9
	assembly	10 dys	Mon 26.05.25	Fri 06.06.25	10
	optimize	36 dys	Mon 09.06.25	Mon 28.07.25	11
	Tilt mechanism	**92 dys**	**Fri 21.03.25**	**Mon 28.07.25**	
	define	16 dys	Fri 21.03.25	Fri 11.04.25	
	concept	30 dys	Mon 14.04.25	Fri 23.05.25	15;2
	Simulation \ Blender video	10 dys	Mon 26.05.25	Fri 06.06.25	16
	delivery	20 dys	Mon 26.05.25	Fri 20.06.25	16
	assembly	10 dys	Mon 23.06.25	Fri 04.07.25	18
	optimize	16 dys	Mon 07.07.25	Mon 28.07.25	19
	Packaging Unit	**92 dys**	**Fri 21.03.25**	**Mon 28.07.25**	
	define	16 dys	Fri 21.03.25	Fri 11.04.25	
	concept	20 dys	Mon 28.04.25	Fri 23.05.25	23
	delivery	20 dys	Mon 26.05.25	Fri 20.06.25	24
	assembly	10 dys	Mon 23.06.25	Fri 04.07.25	25
	optimize	16 dys	Mon 07.07.25	Mon 28.07.25	26
	Control	**76 dys**	**Mon 14.04.25**	**Mon 28.07.25**	
	define	10 dys	Mon 14.04.25	Fri 25.04.25	
	concept / delivery	10 dys	Mon 28.04.25	Fri 09.05.25	30
	programming	50 dys	Mon 28.04.25	Fri 04.07.25	30
	optimize	16 dys	Mon 07.07.25	Mon 28.07.25	32
	Powersupply	**66 dys**	**Mon 28.04.25**	**Mon 28.07.25**	
	define	10 dys	Mon 28.04.25	Fri 09.05.25	
	concept	10 dys	Mon 12.05.25	Fri 23.05.25	36
	delivery	20 dys	Mon 26.05.25	Fri 20.06.25	37
	assembly	10 dys	Mon 23.06.25	Fri 04.07.25	38
	optimize	16 dys	Mon 07.07.25	Mon 28.07.25	39

Figure 9 Time schedule of lightweight drill

The new design is lighter, more compact, and efficiently uses the build volume.



Left) *Right)*

Figure 10 left - first design; right - new design

7.6.2 Challenges encountered and how they were addressed

The centre of mass was very high in the first version of the drilling system, which could lead to unwanted behaviour from the robot, such as higher energy consumption and unsteady robot traversal. Those issues could be solved with the newer design.

7.7 Key Performance Indicators (KPIs)

7.7.1 Status of defined KPIs

7.7.2 Assessment of progress toward meeting the KPIs

7.8 Results and impact

7.8.1 Key results obtained

7.8.2 Contribution to the overall SQAT project goals

7.9 Lessons learned and recommendations

7.10 Next steps and action plan

1. To develop and test lightweight drilling devices for a range of soil types. The drilling and soil sample collection depth is 0.9 m... The drilling device and its components, particularly the mechanical structure, must be as lightweight as possible to maximise the entire system's efficiency. Thus, typical lightweight materials offering high stiffness (and strength) combined with low density will be used. One possible solution might be a pure composite or combining composites and aluminium/steel as a hybrid structure. To obtain an optimal stiffness/weight ratio, structural optimisation based on Finite Element Simulation (coupled with, e.g. genetic algorithms) will be used. The available construction space determines the envelope for this optimisation; thus, different geometries (e.g. tubes, framework, and beams) will be evaluated. Concerning composite and hybrid solutions, it is necessary to characterise all the materials (typically, no or only insufficient material data is available) and finished products (verification of simulation, failure analysis, fatigue life). A suitable manufacturing process must also be evaluated, as different methods (e.g. prepreg-autoclave, infusion, hybrid moulding) are feasible.
2. Implement software to control the quadrupedal robot and enable automatic and collaborative system behaviour during sampling.
    a. Robot executes preplanned routes for the individual sampling process
    b. The robot manages its energy levels and plans charging stops for autonomous operation.
    c. The robot reports system status and exceptions to the user via a predefined interface.

3. Path planning is performed on high resolution, and an actual map is created through a camera-equipped UAV.
4. Logging of sample acquisition location with 3 cm accuracy.
5. Simultaneously with the soil sampling, a UAV will collect high-resolution multispectral images of the field.
6. Collected samples are stored individually on the robot in containers without cross-contamination.
7. Specific containers will be delivered to the field lab.

8 Use case 7 in Ukraine: Higher efficiency for higher yields to safeguard food security

8.1 Brief context

Sown areas in spring 2023 will be reduced by ≥20%, resulting from direct damage of Russian aggression on agricultural resources and the linked economic effects (cost of production increased by 60%). To ensure Ukraine's food security and its role as a leading exporter for int'l agricultural markets, it is necessary to leverage appropriate agro-technological solutions to boost yields: maximising resource use and minimising risks. Agrilab will optimise use of inputs (20-50%) by providing farmers with: (i) soil analysis using the System, (ii) weather and climate alerts, (iii) determine effective productivity, (iv) develop task maps for variable fertiliser application, (v) develop task maps for variable sowing rates, (vi) digitalise field data in proprietary MyAgrilab software. Agrilab uses its own experimental fields those of select customers, working with agri-advisors, the All-Ukrainian Agrarian Council, and charitable recovery/ reconstruction funds. We include recently demined fields to demonstrate return to cultivation.

For 10 years of work on the territory of Ukraine, Agriab can offer the following competencies and apply them in the SQAT project.

1) Algorithm for calculating the average perennial potential yield of crops (the list of crops is limited)
2) Algorithm for calculating the crop nutrition system
3) Algorithm for calculating the need for amelioration measures for crops
4) Competences in the development of maps of the tasks of differentiated application of fertilizers, differentiated application of ameliorants, differentiated sowing of crops
5) Analytical database for more than 2,000,000 hectares of survey with geo-data of each selected soil sample, soil type, climatic data, crops in the field, etc.
6) Staff and competencies of specialists in the process of formation: soil selection routes, soil mixing and delivery methods, soil storage methods, soil preparation methods for analysis, evaluation of soil maps of fields, evaluation of agrochemical data, evaluation of technological features in the direction of crop nutrition
7) There is an own research base more ten hectares where tests of technologies, equipment, etc. can be carried out.
8) More than 600 agricultural companies. Among them are dozens of companies that can be participants for testing equipment, software and other products within the framework of the project.
9) Advertising activity about the project SQAT platform within the framework of demo fields that are held at the experimental fields of the head office (Kyiv, Boryspil) and of agricultural partners of Ukraine.
10) Advertising activity about the project SQAT platform within the framework of educational seminars held in the main office (Kyiv, Boryspil) and agricultural partners of Ukraine.

A reasonable and economically sound approach to the system of agriculture and crop cultivation, especially work with plant nutrients, allows you to reduce unproductive soil erosion, increase productivity and the economic results of farmers' activities.

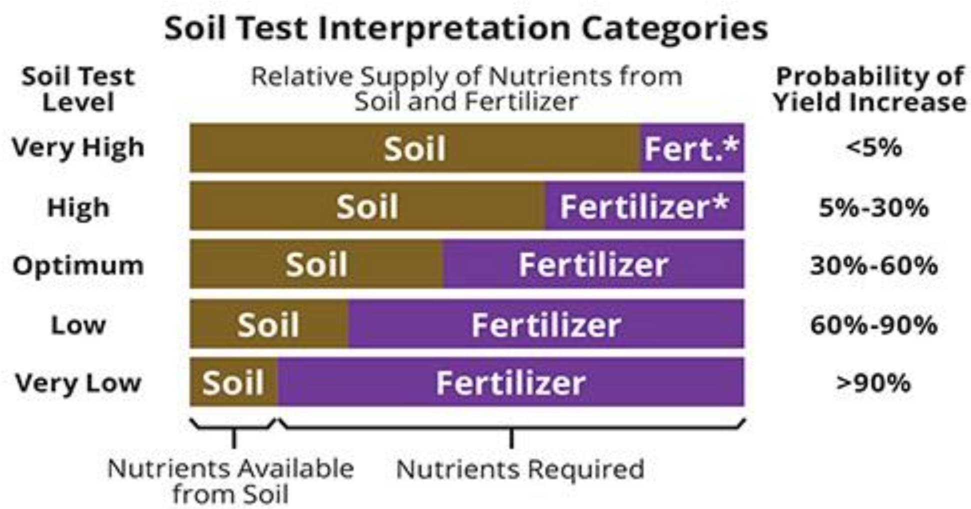
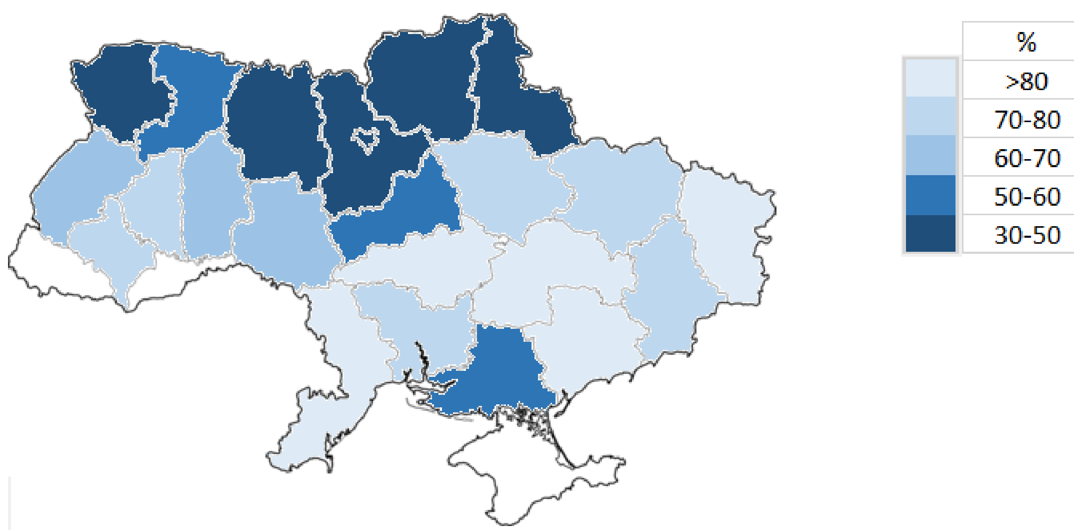
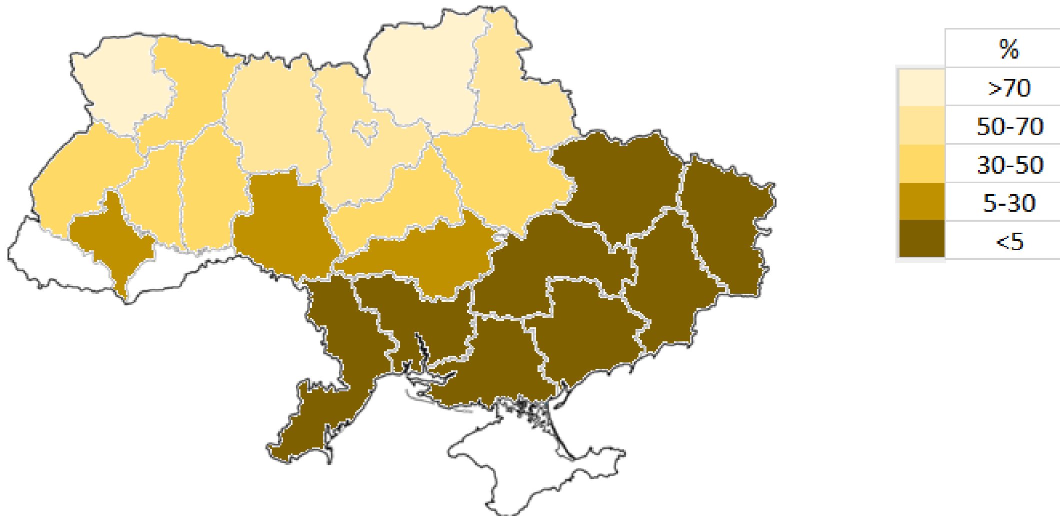


Figure 11 Probability of yield response to fertilizer depending on the level of soil nutrient supply (Adapted from Havlin et al., 1999.)

The accumulated statistical data of the results of the analysis of Ukraine for the period 2015-2023 indicate a significant variability of indicators within Ukraine and the need for a comprehensive study and research of each region and farm individually. Significant attention should be paid to the issue of field variability and existing degradation associated with the characteristics of the terrain, parent breed, acidity, degradation associated with the irrational use of natural resources of the field without significant investments in the plant nutrition system.



Map of % of samples with a level of mobile phosphorus compounds from very low to medium by regions of Ukraine, except for Chernivtsi, Zakarpattia regions and the Autonomous Republic of Crimea (statistics of Agrilab LLC 2015-2023)



Map of % of samples with a level of supply of mobile potassium compounds from very low to medium by regions of Ukraine, except for Chernivtsi, Zakarpattia regions and the Autonomous Republic of Crimea (statistics of Agrilab LLC 2015-2023)

In Digital Field experiments in the Boryspil district of Kyiv region in 2020-2021, nitrogen fertilizers also contributed to an increase in corn yield. And if in the drier 2020, the application of 110 kg/ha of nitrogen (for an effective yield of 9 t/ha) allowed to obtain 1 t/ha more compared to a plot without fertilizers, then in the more favorable 2021 - by 2.5 t/ha. If we take into account the realities of the Ukrainian fertilizer and product market, nitrogen fertilizers should be applied, at least under wheat, corn, and rapeseed. But the norm should take into account the realistic possible crop yield, soil capabilities, and growing technology.

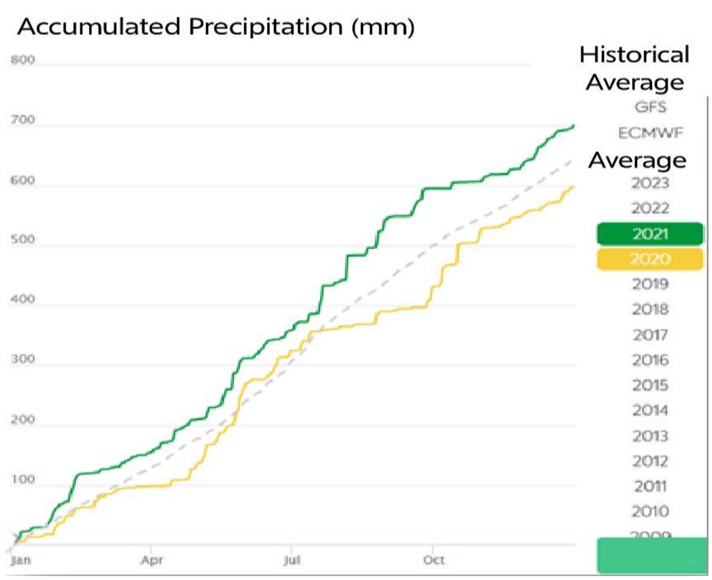


Figure 12 Precipitation accumulation graph (mm) in Boryspil district of Kyiv region: 2020 – orange line, 2021 – green, long-term average – gray

(data from the website https://earthdailyagro.com/)

What If you do not apply fertilizers for several years?

Again, let's turn to the studies of American colleagues who grew corn without applying phosphorus fertilizers in a long-term corn-soybean crop rotation. Between 1970 and 2002, corn yield decreased by an average of 1.08% per year, and the content of mobile phosphorus in the soil (Bray-1 P method) decreased by 1.09 mg/kg per year (Fig. 9). It would seem that nothing critical will happen in a few years! But are you sure that you have been working in the plus direction of the balance of nutrients in the soil until now? The data presented emphasize the importance of replenishing the removal of nutrients to maintain and optimize the agrochemical parameters of the soil. Otherwise, a decrease in crop yields is inevitable.

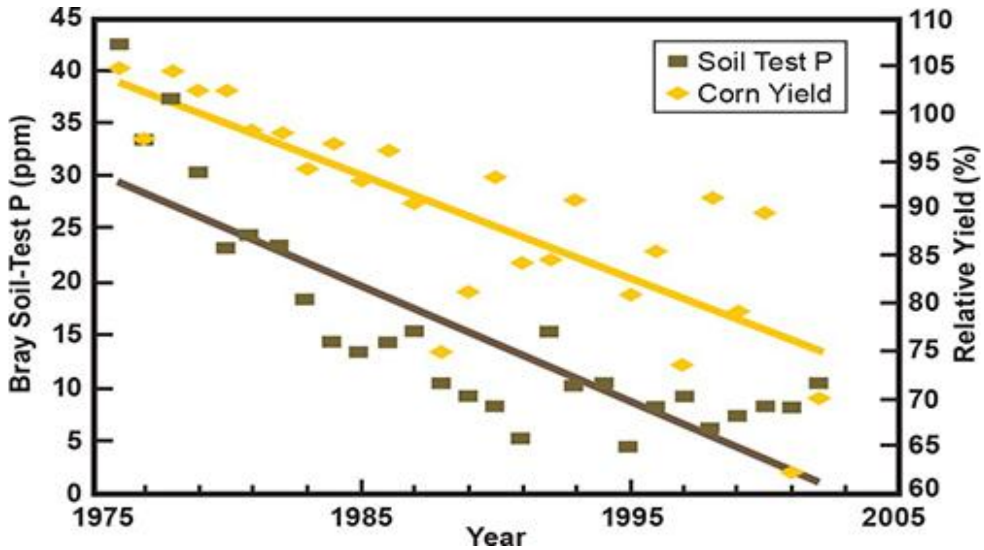


Figure 13 Reduction in corn yield and soil phosphorus content without phosphorus fertilizer application in corn-soybean crop rotation. Source: Nelson and Janke, 2007 (data from Dodd and Mallarino, 2005).

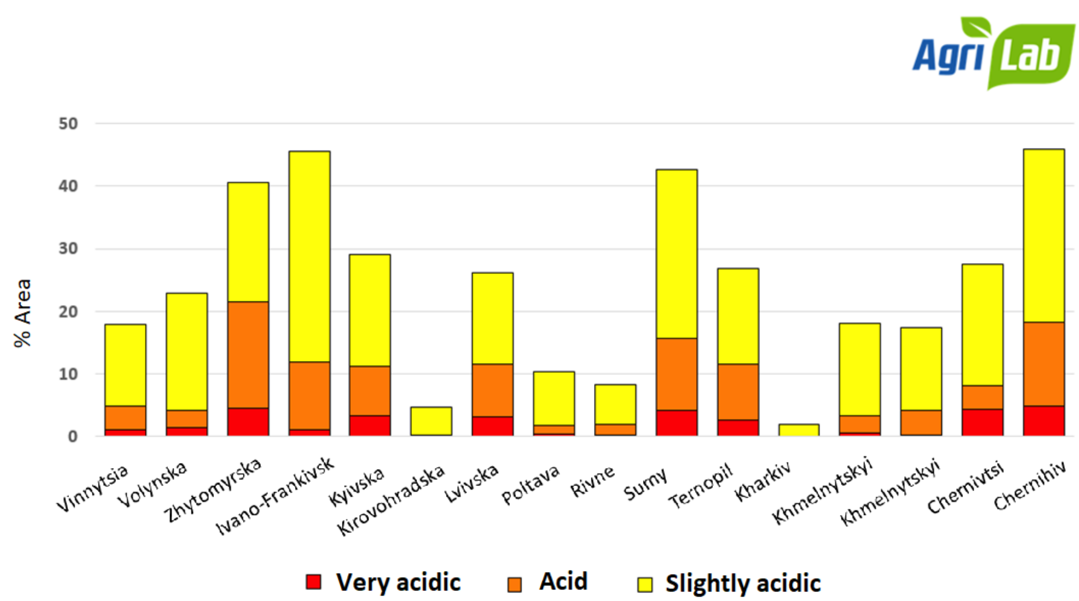


Figure 14 Statistics of surveyed areas in 2019-2023 by regions of the Polissya and Forest-Steppe zones by distribution of soil acidity

We present data from American scientists on the influence of soil pH on the availability of nutrients to plants. Thus, the optimal availability of most nutrients in neutral soils with a pH of 6.5 to 7.5. To a lesser extent than all others, the soil acidity index affects elements such as nitrogen, potassium and sulfur. Phosphorus is available in a limited pH range due to the formation of poorly soluble compounds: when phosphate ions interact in an alkaline soil environment with calcium and magnesium, and in an acidic one - with iron and aluminum. Microelements are available at lower pH values, with the exception of molybdenum.

The assimilation of nutrients from mineral fertilizers by plants also depends on the pH of the soil, which should be taken into account when applying them. Domestic research materials on the effectiveness of mineral fertilizers at different soil solution reactions indicate that only in the range of 6.5-7.0 the utilization rate of nitrogen, phosphorus and potassium is close to 100%. Even a slight change in pH in either direction by 0.5 units reduces this indicator by 25% for potassium and over 30% for phosphorus.

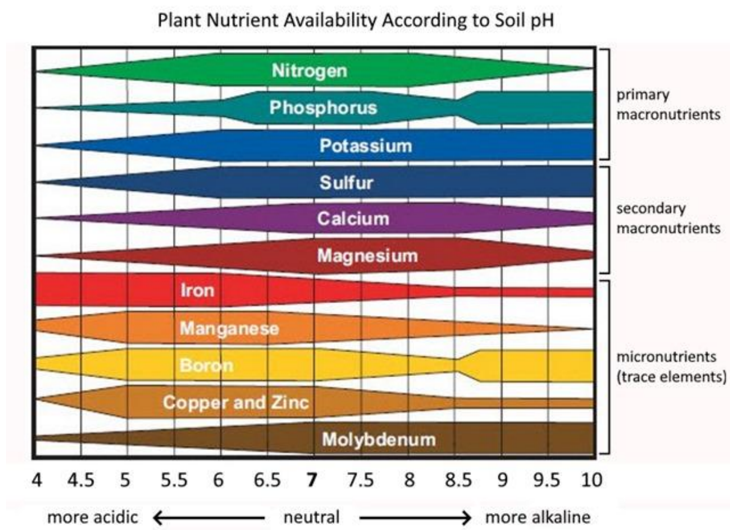


Figure 15 The effect of soil pH on the availability of nutrients to plants

pH	Nitrogen , %	Phosphorus, %	Potassium , %
4,5	30	23	33
5,0	43	34	52
5,5	77	48	63
6,0	89	52	77
6,5	100	95	100
7,0	100	100	100
7,5	100	70	75
8,0	100	30	45
8,5	78	20	30
9,0	50	5	10

Figure 16 Coefficients of use of nutrients from fertilizers depending on the degree of acidity

8.2 Overall objective and specific aims updates

The overall objective is to test the developed SQAT to create: -(program module) algorithm / logic for calculating the crop nutrition system depending on the indicators of soil analysis, climate, soil maps, predecessors, etc. -(program module) site specific management nutrients, taking into account the level of the crop yield and the possibilities of the field area -(program module) site specific management of amelioration -(program module) site specific management of seeding SQAT advertising and educational activities

To deliver this objective, the specific aims are:

1. Competences and analysis in the development of the above modules of the SQAT
2. Testing of modules in the demo-fields of the head office and partners / farmers
3. Analysis and adaptation of the algorithm and calculation modules based on the current Agrilab database of Ukraine
4. More than three own demo-fields for advertising and educational activities of the SQAT platform.

An important and effective way to improve the effectiveness of field assessments and decisions to improve them is through the volume of statistical sampling and the frequency of tracking the reaction of soil minds to that Another factor comes up.

In 2024, follow-up was carried out on an area of over 200,000 hectares. For a number of strategic projects, methods have been developed and tested to determine soil performance and their effectiveness.

Below is an estimate of possible corn crop losses in one of the fields due to soil pH using data from American colleagues. Agrochemical survey of our client's lands from Zhytomyr region showed significant variability in soil pH distribution both between arrays, fields, and within fields. Probable corn crop losses within a field can reach 200 tons, even with very low grain prices this year, the cost of the unharvested crop can be 30 thousand US dollars.

pH	Crop losses t/ hectares	Area of the zone, hectares	Crop losses in the zone, tons	Cost of lost harvest, USD
6,6	-	35,50	-	-
6,0	0,36	28,04	10,2	1529
5,7	0,96	29,82	28,5	4268
4,9	3,99	40,53	161,6	24167
Total		**133,89**	**200,3**	**29964**

Figure 17 Possible losses of grain corn yield in areas with different soil pH

Culture	pH				
	4,7	5,0	5,7	6,8	7,5
	Relative average yield , %				
Corn	34	73	83	100	85
Wheat	68	78	89	100	99
Soy	65	79	80	100	93
Barley	0	23	80	95	100
Alfalfa	2	9	42	100	95
Oat	77	93	99	98	100
Timothy meadow	31	47	66	100	95

Figure 18 The effect of soil pH on crop yield as a percentage of potential yield

It is obvious in this example that applying a single rate of lime to the field will not fundamentally change the situation in areas with a strongly acidic pH, but will also lead to negative phenomena in neutral zones. Only redistribution of the amount of limestone materials within the field, i.e. its application using the variable rate technology, will allow for the effective implementation of this reclamation measure.

The approach of the Agrilab company to establishing the rate of limestone materials is based on calculating the need for CaCO3 to bring the pH to the optimal value of pH 6.5 p, taking into account the characteristics of the crops. The need is determined at each sampling point based on the results of the analysis of soil pH and buffer pH. To build a task for applying variable rates of limestone materials, the distribution of soil pH within the field is taken into account.

We share the results of our client's application of variable rates of limestone materials. Tasks with variable rates of limestone materials application developed by Agrilab were implemented for each field. Defecate was used as an ameliorant, the total cost of soil liming (with defecate delivery) over 5 years was at that time 1 USD/ha per year.

The NDVI image of sunflower in 2018 and in the first year after liming of corn in 2020 clearly identifies areas with low productivity, corresponding to zones with a strongly acidic soil reaction. The areas of low-productivity areas decrease in the next two years after soil reclamation.

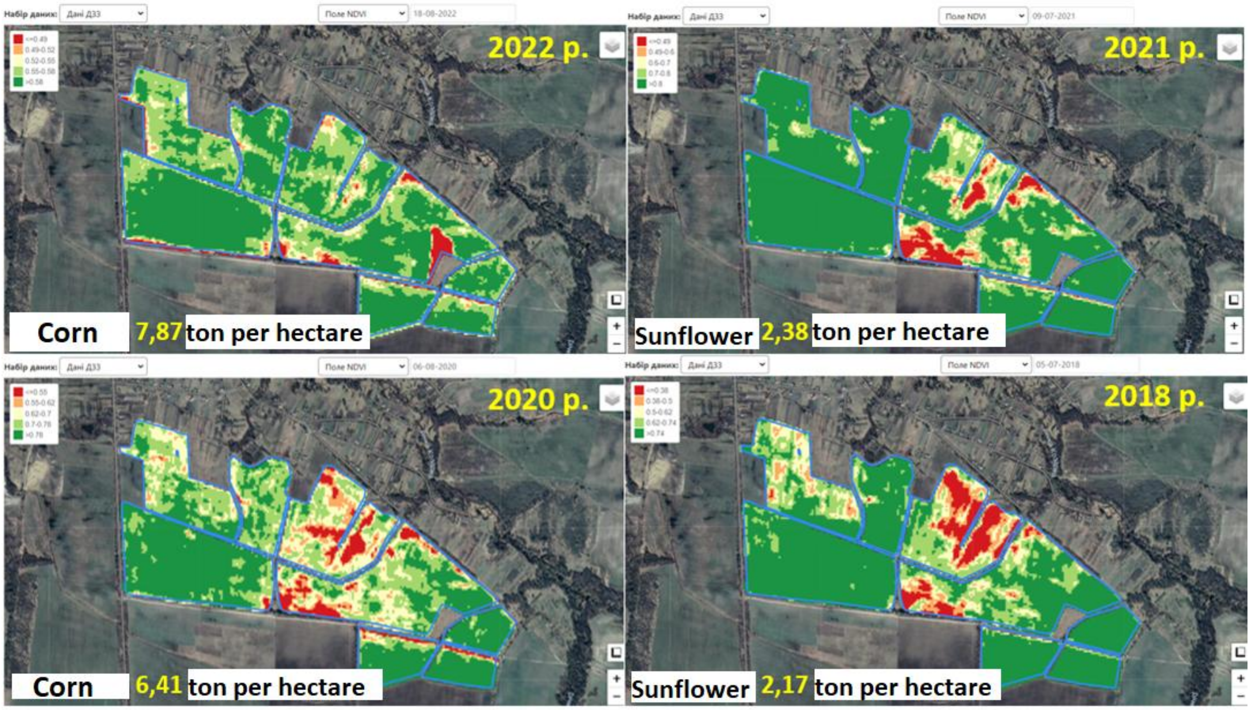


Figure 19 Distribution of NDVI index of crops e 2018-2022.

Weather conditions in the region for April-September 2018-2022
Sum of active temperatures and cumulative precipitation for the period April-September (2018-2022)

Year	Sum of active temperatures > 10°C	Precipitation amount, mm
2022	1245	297
2021	1230	397
2020	1388	327
2018	1536	323

The results of the liming are clearly demonstrated by the obtained yield data, satellite monitoring and UAV images, especially considering the weather conditions that have developed: more favorable for the crop in 2020 compared to 2022. Comparison of corn cultivation data in the 1st and 3rd year after liming.

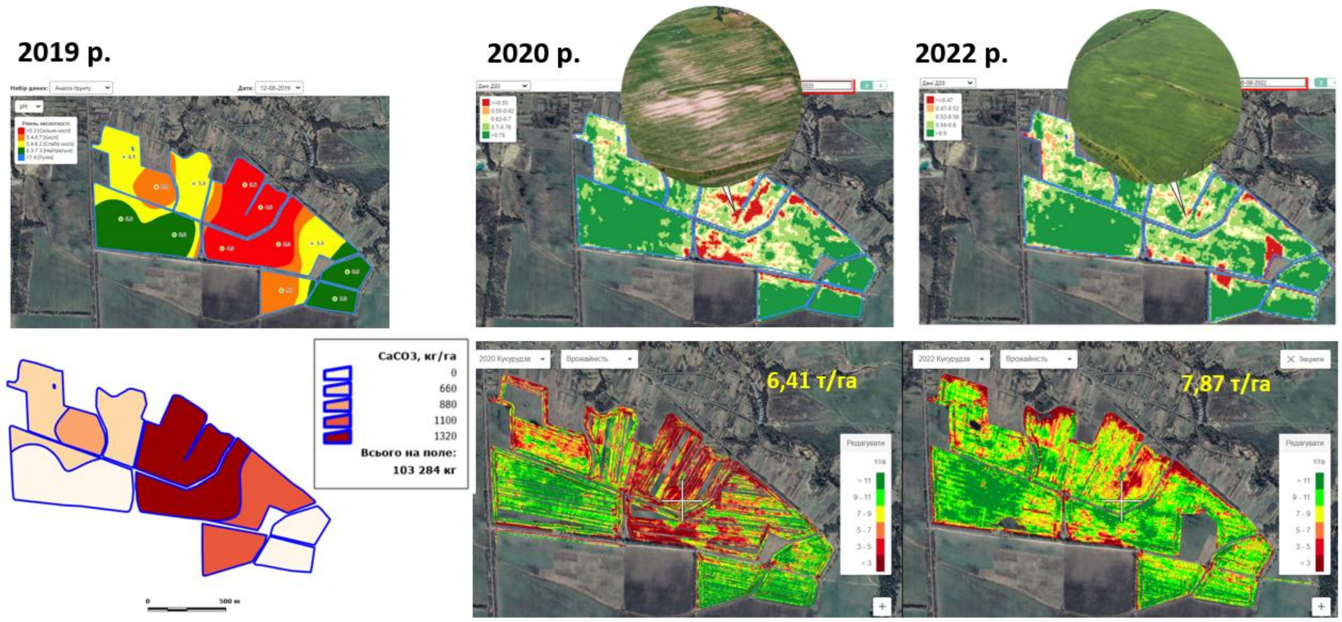


Figure 20 The result of the implementation of the task using the technology of variable rates of application of limestone materials

The above data and the statistical sample, which is systematically updated, clearly demonstrate the effectiveness of the use of technologies for the correct calculation of the introduction of plant nutrients, the effectiveness of field deoxidation measures.

The 2023-2024 experiment, statistical sampling, and research in 2025 will have a more fundamental analysis and assessment of the effectiveness of field acidity control measures with the aim of increasing its yield and economic efficiency.

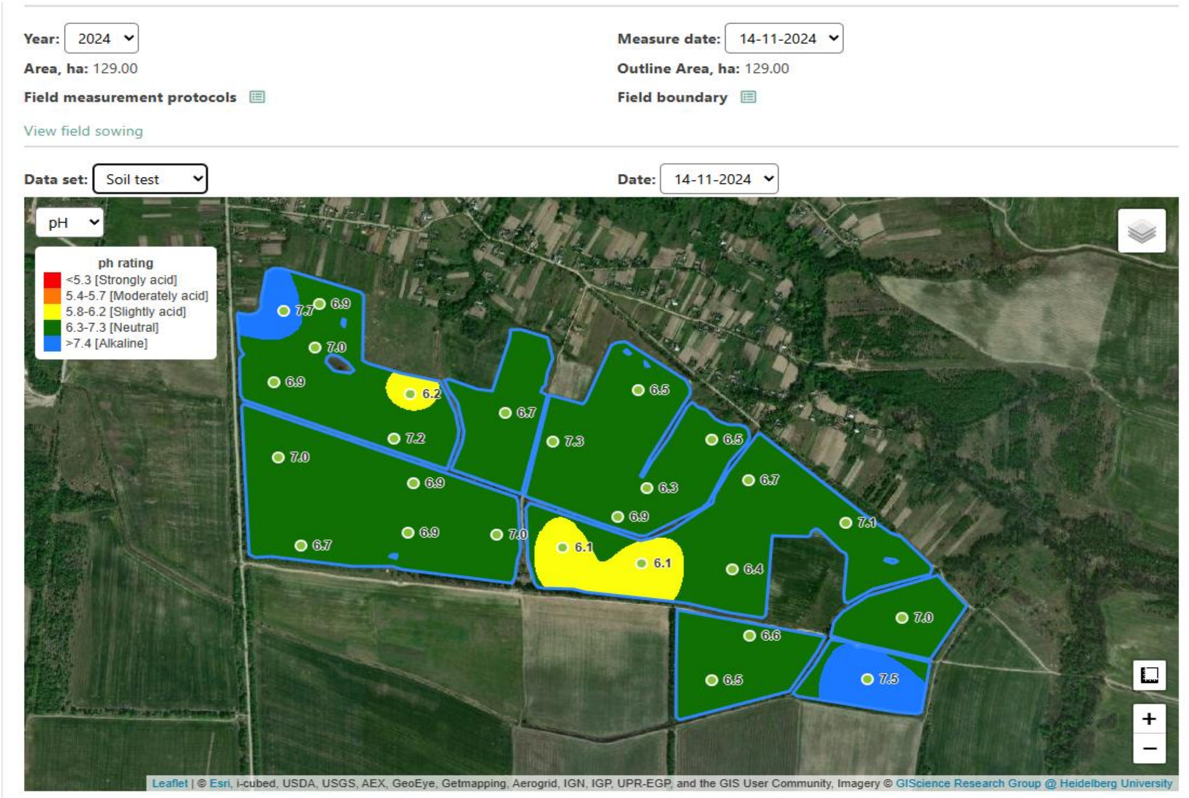


Figure 21 Dynamics of changes in indicators of soil acidity after the stagnation of melionarts 2019-2024 years.

8.3 Partners involved

- The following partners are involved in the Ukraine use case, each contributing distinct roles and responsibilities:
  - ABE (Association for Balkan Eco-Innovations). Main contact: Srđan Pavlović (srdjan@balkanecoinnovations.org). Role: Support partner. Specific responsibilities: Coordination and communication support, facilitating stakeholder engagement, assistance in identification and selection of test fields, and promoting the adoption and dissemination of project results within the local ecosystem.
  - During the reporting period, no changes occurred in the partnership structure or distribution of responsibilities. All partners maintained their initially planned roles, ensuring smooth collaboration and continuity of planned activities.
  - A proposal has been submitted to all project partners for consideration regarding the following issues for the 2025-2026 experiments:
    - The issue of choosing the method of soil sample selection and their detailing/density
    - Algorithm for determination and calculation model of plant nutrition system
    - Algorithm of calculation of plant nutrition system and needs
    - Effectiveness of the recommended calculation algorithm

8.4 Description of key stakeholders' involvement and feedback

The large agricultural producer Agroregion took an active part in the cooperation and studied the following issues:

- deacidification of fields with existing problems 2020-2025

- study of optimal norms of differentiated sowing of corn and sunflower 2022-2025

- study and improvement of the algorithm for calculating the plant nutrition system based on a statistical sample and survey 2024

The area of soil cultivation in the company reaches more than 40 000 hectares, of which over the past 5 years more than 80% have been studied by Agrilab LLC. The experimental fields have 3 or more soil surveys, with the aim of studying the variability and parameters of changes in soil indicators and their impact on yield indicators.

In 2025, a research project on more than 20 hectares of experimental fields near the Agrilab office - the village of Velyka Oleksandrivka, Boryspil district, Kyiv region.

Where research is conducted on different sowing rates, different fertilizer application rates, resource-saving soil cultivation technologies, and different methods of fertilizer application.

8.5 Test locations

8.5.1 Justification for any changes or additions to test sites

2 more locations for field surveys and studies were added to the project.

Poltava Sad - Poltava region, Poltava city, Komarova st., 7

Vegetable group, grain and oilseed crops, irrigation, seed crops. About 8 thousand hectares are cultivated.

Local feature of soils - powerful black soils with increased diversity of nutrients.

Top 20 world producers of coriander.

Agrobud - Vinnytsia region, Vinnytsia district, Oratov village, Lenina st., 2

Grain and oilseed crops, seed crops. About 7 thousand hectares are cultivated.

Heavy in terms of granulometric composition soils, with increased calcium indicators. Increased diversity of microelement indicators.

8.5.2 Test location description

Table 14 Test location Ukraine

Location name	AGRILAB - demofilds
Sampling area size (ha)	55 ha
Number of composite samples	42
Number of individual samples combined for composite sample	20
Sampling depth	0-30
How sampling location was determined	Zones of individual assessment

Figure 22 AGRILAB - demo fields

Location name	**Poltava Sad – demofilds**
Sampling area size (ha)	240 ha
Number of composite samples	33
Number of individual samples combined for composite sample	20
Sampling depth	0-30
How sampling location was determined	Zones of individual assessment

Figure 23 Poltava Sad – demo files

Location name	Agroregion
Sampling area size (ha)	130 ha
Number of composite samples	26
Number of individual samples combined for composite sample	20
Sampling depth	0-30
How sampling location was determined	Zones of individual assessment

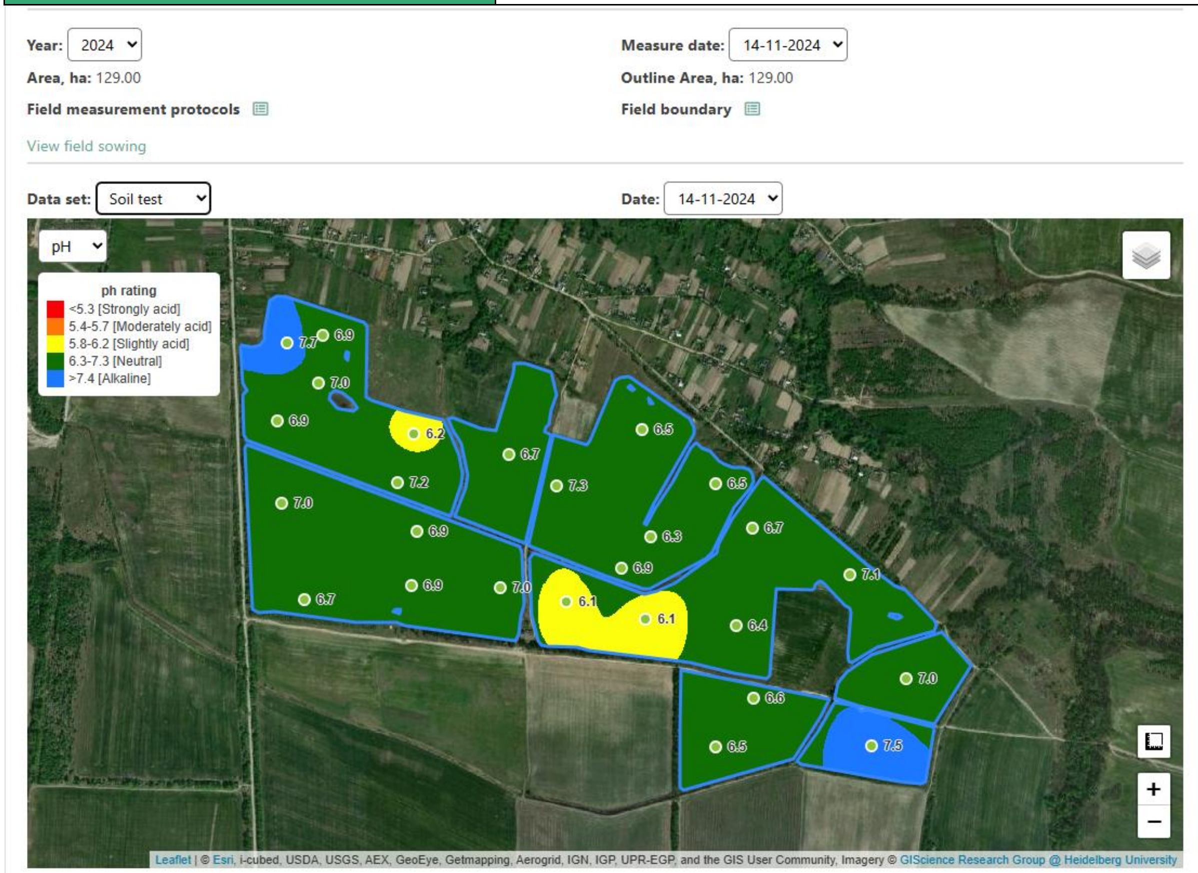


Figure 24 Agroregion - demo files

Location name	**Agrobud**
Sampling area size (ha)	195 ha
Number of composite samples	24
Number of individual samples combined for composite sample	20
Sampling depth	0-30
How sampling location was determined	Zones of individual assessment

Figure 25 Agrobud - demo fields

8.6 Activities and Implementation Steps

8.6.1 Detailed description of activities carried out

Based on the analytical sample and research of 2024, the algorithm for assessing fields and developing recommendations for the plant nutrition system and limiting factors of fields has been improved.

Within the framework of 4 locations, the following data package was accumulated and processed:

- Parcel boundary
- Satellite images
- VI and SI
- Zone based on VI and SI; soil types; relief; signs of the maternal breed
- Final zones
- Soil sampling points and trajectory
- Trajectory from the filed with heights
- Results from LAB
- Interpolated rasters from Lab results
- Maps

Experiments are still in the process of studying and accumulating data. The key task is to improve the algorithm for calculating plant nutrition system and risk factors and limitations for evaluating fields, local features, and methods for controlling field variability in order to increase yields and economic efficiency indicators.

Over 620 hectares of research demo fields, over 125 sample 2024-2025 years. Specialized 4 demo fields with targeted research.

Certain experiments have a duration of more than 3 years, the frequency of examinations is two or more times

8.6.2 Challenges encountered and how they were addressed

Military restrictions created by Russia's armed attack on Ukraine

Lack of highly qualified human resources

Issues of employee reservation and protection from mobilization

In general, in 2024-2025, serious work was carried out on the possibility of booking and protecting the majority of employees in order to be able to continue working on the project.

8.7 Key Performance Indicators (KPIs)

8.7.1 Status of defined KPIs

KPI title	Target	Means of verification	Status and stage of implementation
1. Test fields	3 or more locations for equipment testing and evaluation	Use case reporting	As of this reporting date, the process has been completed. Further experiments are ongoing - more details at the end of 2025
2. Model of evaluation of algorithms of variable application rates	Sensors tested on demo fields and the corresponding conclusion of the correlation of indicators	Use case reporting	Based on the 2024 surveys and the field researcher for the project, the calculation algorithm has been improved. Further studies are ongoing.
3. Algorithm for calculating variable application rates	The current algorithm is tested on demo fields and there is a comparison to the performance of wet chemistry	Use case reporting	Based on the 2024 surveys and the field researcher for the project, the calculation algorithm has been improved. Further studies are ongoing.
4. Leverage on field demonstration events to engage customers	3+ events with 60 stakeholders (farmers)	Use case reporting	The 2025 action plan is in the process of being approved. After meeting partners and exchanging marketing ideas, we are ready to start. Currently, there are 5 demo field locations available where implementation can be carried out
5. Judicious use of printed materials for promotion	Preparation and distribution of fact sheets to stakeholders	Use case reporting	After meeting partners and exchanging marketing ideas, we are ready to start 2025.
6. Advertising publications on Facebook, YouTube, and LinkedIn platforms	6+ publications devoted directly or indirectly to the platform and its activities	Use case reporting	After meeting partners and exchanging marketing ideas, we are ready to start 2025.

8.7.2 Assessment of progress toward meeting the KPIs

Most of the key performance indicators (KPIs) are confidently on track to be achieved. An important factor in the marketing component is access to the product with the aim of delivering the ultimate value to the end consumer.

8.8 Results and impact

8.8.1 Key results obtained

During the reporting period, the following main activities were systematically carried out:

1. Competencies and analysis in developing an algorithm for calculating the plant nutrition system
2. Testing of modules in the demo-fields of the head office and partners / farmers
3. Analysis and adaptation of the algorithm and calculation modules based on the current Agrilab database of Ukraine
4. Four demo-fields for advertising and educational activities of the SQAT platform.
5. Over 620 hectares of research demo fields, over 125 sample 2024-2025 year

8.8.2 Contribution to the overall SQAT project goals

Existing experience and analytical database can be the basis for creating a unique algorithm for calculating the plant nutrition system, elements of precision agriculture

The existing base of 5 locations throughout Ukraine can be a platform for attracting potential customers and interested farmers to test and use the project's achievements.

8.9 Lessons learned and recommendations

More interaction between partners is needed to better engage the participants' competencies in the interests of the project.

In order to conduct educational activities and advertise the project, it is necessary to create a clear vision of the system's functionality in order to attract the interest of the end user.

8.10 Next steps and action plan

Off-line Meeting 06.2025 of partners and discussion of marketing plan with the aim of educational activities at the locations of the demo fields in 2025.

Need and request for greater involvement in the experience and expertise of existing data partners, including Agrilab, with the aim of strengthening the project.

Agreeing on an individual action plan and requesting partners' needs regarding Agrilab's existing competencies and expertise

9 Conclusion

The use cases are making good progress in line with the use case plans (D2.1).

The implementation of the use case during the first year has yielded promising results, confirming the potential of integrated technological approaches for improving soil quality assessment and management. Key advancements include the successful validation of a novel mechanical resistance sensor, which demonstrated strong correlation with standard penetrometer measurements while offering increased repeatability and automation capabilities. This innovation lays the groundwork for efficient, data-driven soil compaction mapping—crucial for optimizing subsoiling practices and enhancing soil health.

Similarly, field trials have confirmed the value of site-specific liming based on high-resolution soil property data. The economic analysis highlighted the significant financial and agronomic benefits of precision lime application, revealing how conventional methods often lead to over-application and subsequent yield loss. These findings underscore the importance of accurate soil texture, pH, and SOM data for improving fertilization strategies and ultimately achieving more sustainable soil management practices.

Satellite-based zoning emerged as a cost-effective tool to support in-field decision-making, guiding the targeted deployment of in-situ sensors. The integration of satellite imagery with ground-based measurements is proving to be a scalable approach to characterize soil variability, especially when verified and co-developed with farmers.

The experience has also brought to light several lessons critical for the future development of the Soil Quality Analysis Tool (SQAT). Chief among them is the need for a flexible planning process and early, sustained engagement with end users. These elements have proven essential for aligning technical development with real-world needs. In terms of methodology, the value of combining vertical penetration data with other spatial layers—such as electrical conductivity, topography, and yield data—was reaffirmed as a path toward comprehensive soil assessments.

In the Irish context, the emphasis on robust, MRV-compliant soil organic carbon (SOC) methodologies has shown that environmental integrity and market credibility must go hand in hand. Hybrid methods that balance the accuracy of direct sampling with the scalability of modelling approaches are likely to be the most effective way forward, particularly when aligned with international standards like Verra's VM0042.

Looking ahead, the project will focus on developing and testing enhanced field tools, such as lightweight drilling devices and an automated penetrometer, while continuing to refine its methodologies through field trials, user feedback, and data-driven iteration. Demonstration events, extended zoning efforts, and targeted economic assessments will support the broader adoption of site-specific practices.

Overall, the use cases reinforce the viability and necessity of transitioning to precision agriculture techniques grounded in high-resolution data and stakeholder co-creation. These early findings validate the strategic direction of the SQAT development and offer a strong foundation for its next phase of implementation.

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