Analyse-to-go on the field: prototypes4soil2data[1]

Stefan Hinck[1*], Andreas Möller[2], Matthias Terhaag[3], Thomas Meyer[3], Daniel Mentrup[4], Hendrik Kerssen[4], Elena Najdenko[5], Frank Lorenz[5], Tino Mosler[6], Heinrich Tesch[6], Walter Peters[7], Walter Nietfeld[8], Vadim Riedel[1], Arno Ruckelshausen[1]

[1] University of Applied Sciences Osnabrueck, Postfach 1940, 49009 Osnabrueck, Germany
[2] ADVES GmbH & Co. KG, Eschstr. 23, 49424 Goldenstedt-Lutten, Germany
[3] ANEDO GmbH, Huelsmeyerstr. 35, 49406 Barnstorf - Eydelstedt, Germany
[4] iotec GmbH, Albert-Einstein-Str. 1, 49076 Osnabrueck, Germany
[5] LUFA Nord-West, Jaegerstr. 23-27, 26121 Oldenburg, Germany
[6] MMM tech support GmbH & Co. KG, Weigandufer 18, 12059 Berlin, Germany
[7] Bodenprobetechnik Peters GmbH, Bahnhofstr. 36, 49635 Badbergen, Germany
[8] Bodenprobetechnik Nietfeld GmbH, Nietfeldsweg 25, 49635 Badbergen, Germany
* Corresponding author. E-Mail: s.hinck@hs-osnabrueck.de

Abstract

Knowledge of the small-scale nutrient status of a field is an important basis for decision-making when it comes to optimising the fertiliser use in crop production. Currently, the traditional method involves soil sampling in the field and soil sample analysis in the laboratory as two separate working processes.

The previous research project "soil2data" developed a mobile field laboratory for different carrier vehicles. In the follow-up project "prototypes4soil2data", the results of soil2data are further developed. A mixed soil sample is collected during the drive on the field. The soil sample is then wet-chemically prepared and analysed. The overall soil sampling and analysis process is divided into the following process steps: soil sampling planning, soil sampling, soil preparation, soil analysis and data management. The process steps are modified for the mobile field laboratory and the process steps run in parallel. The new soil extraction method is based on official German methods (VDLUFA) to ensure the interoperability of the analysis results with the VDLUFA fertiliser recommendations. An innovative key component is the NUTRISTAT analysis module (lab-on-chip with ISFET measurement technology). It can measure pH, the nutrients NO_3^-, $H_2PO_4^-$, K^+ and the electrical conductivity. In addition to the advantages of rapid data availability and no need to transport soil material to the laboratory, it provides a future basis for new application,

[1] This publication was presented at the 22nd World Congress of Soil Science in Glasgow, Scotland, on 4th August 2022 as a presentation entitled "Analysis-to-go on the field: prototypes4soil2data".

e.g. verification of current results in the field during soil sampling with existing results or dynamic adjustment of soil sampling during work in the field.

Keywords: mobile field laboratory, ISFET measurement technology, soil sampling, soil nutrients analysis, lab on a chip, soil2data, digital farming

1 Introduction

For optimized and effective fertiliser management, e.g. in the precision farming management system, information on the – site-specific – soil nutrient status is an important calculation parameter, in addition to other decision variables, such as the site-specific yield potential or the soil texture (LWK 2022, Hinck et al. 2013). Optimization potential on a subfield basis is given under both ecological and economic framework conditions (e.g. Struijs et al. 2011, Hinck and Kielhorn 2011) since variability in nutrient supply within a cropland is common and often underestimated (Zimmer et al. 2014). The investigation of sub-fields or even their further subdivision according to nutrient status into smallest fields with a size of about ¼ to ½ ha (Domsch and Schirrmann, 2009) offers considerable potential for resource savings through differentiated sub-field fertilisation (Lorenz & Münchhoff, 2015).

Targeted soil sampling - especially in the Precision Farming management system on a subfield basis - and a further use of the analysis results, e.g. for multi-year assessment purposes, is recommended. Ideally, soil sampling should be planned. For example, in the case of large agricultural fields, it is advisable to divide the land into sub-fields (or management zones) according to defined criteria. Sampling documentation allows a service provider to document its work in the field to the client. Furthermore, a geo-referenced documentation of the sampling locations (of the soil samples) allows a spatially reproducible repetition of a future sampling. Various methods are described in the literature for delineating sub-fields (or also called management zones) within an area. Some examples of a procedure for a sub-fields delineation are given below. Hinck et al. (2014) use data fusion of measured values of soil geoelectric conductivity (EC values) and soil texture from soil maps (soil assessment) to produce small-scale field soil maps with sub-fields. Hornung et al. (2006) use yield data and soil colour to delineate sub-fields. Anderson-Cook et al. (2002) use data fusion of perennial yield data and soil EC values.

For the same purpose, the analysis or data fusion of satellite imagery (NDVI) and yield data is used by Toscano et al. (2019). A summary literature review on sub-field delineation is provided by Nawar et al. (2017).

For a representative and spatially reproducible soil sampling within the (sub-)field, it is recommended to define a sampling line (Gourley & Weaver, 2019, Carter & Gregorich, 2007). Likewise, by defining a sampling line or sampling locations, small-scale areas with special features can be excluded from sampling, e.g. headlands, knolls, hollows or field storage areas of manure, lime, etc. (Gourley & Weaver, 2019). The specification of sampling lines helps the driver to find his way around the field.

Furthermore, a representative soil sample means that it is a mixed sample. A mixed sample is made up of 15 to 25 individual soil cores - at a defined and consistent sampling depth - for a defined (sub-)field (VDLUFA, 2012). Spatial reproducibility of sampling is realized by defining georeferenced sampling lines or sampling locations (Gourley & Weaver, 2019).

Several papers and research projects have demonstrated the feasibility of field analysis of pH (Kweon et al. 2012, Rossel et al. 2005) and/or nutrients (Sibley et al. 2010, Sethuramasamyraja et al. 2008) and have developed mobile field laboratories (see Table 2, Section 3.7).

Kweon et al. (2012) and Rossel et al. (2005) show good to very good correlations between pH field results and laboratory results. However, attention must be paid to the soil sampling depth. Kweon et al. (2012) sample in the upper topsoil (sampling depth to 10 cm) and Rossel et al. 2005 report a sampling depth of 10 cm to 20 cm.

Sibley et al. (2010) analysed nitrate content (NO_3^-) in the upper topsoil (sampling depth of 0 cm - 15 cm) in the field and show very good correlations with laboratory results.

Sethuramasamyraja et al. (2008) and Adamchuck et al. (2005) worked on a mobile device for soil analysis in the field. Soil samples were collected from the upper topsoil (sampling depth up to 10 cm) (Adamchuck et al., 2005). Sethuramasamyraja et al. (2008) analysed soil material under laboratory conditions. The analytical results for pH, potassium, and nitrate showed satisfactory to good correlations between mobile analysis results and laboratory results.

Kim et al. (2013) investigated soil preparation methods for use in a mobile field laboratory; this basic research was conducted in the laboratory.

A mobile field laboratory provides real-time analytical results in the field. However, it is important that the relevant applicable results obtained have a high correlation with the national standards. If this is the case, the analysis results can be used to make fertiliser recommendations. The use of a mobile field laboratory should therefore be considered in a holistic approach, from soil sampling planning to fertiliser recommendation. The soil2data mobile field laboratory is presented below. In the associated soil2data concept, this principle - from soil sampling planning to fertiliser recommendation - has been consistently implemented.

2 Material and Method

2.1 Traditional procedure: Soil sampling and analysis in the laboratory

To determine soil nutrient status on agricultural land, two main work processes are required:

1. Soil sampling on the field and
2. Nutrient analysis in the laboratory. (see fig. 1)

The first main process "soil sampling in the field" can be divided into the following sub-process steps:

- Soil sampling planning
- Soil sampling and
- Transport of sample material to the laboratory.

The second main process "Nutrient analysis in the laboratory" can be divided into the following sub-process steps:

- Soil preparation,
- Analysis,
- Disposal of the soil material and
- Documentation and delivery of the results.

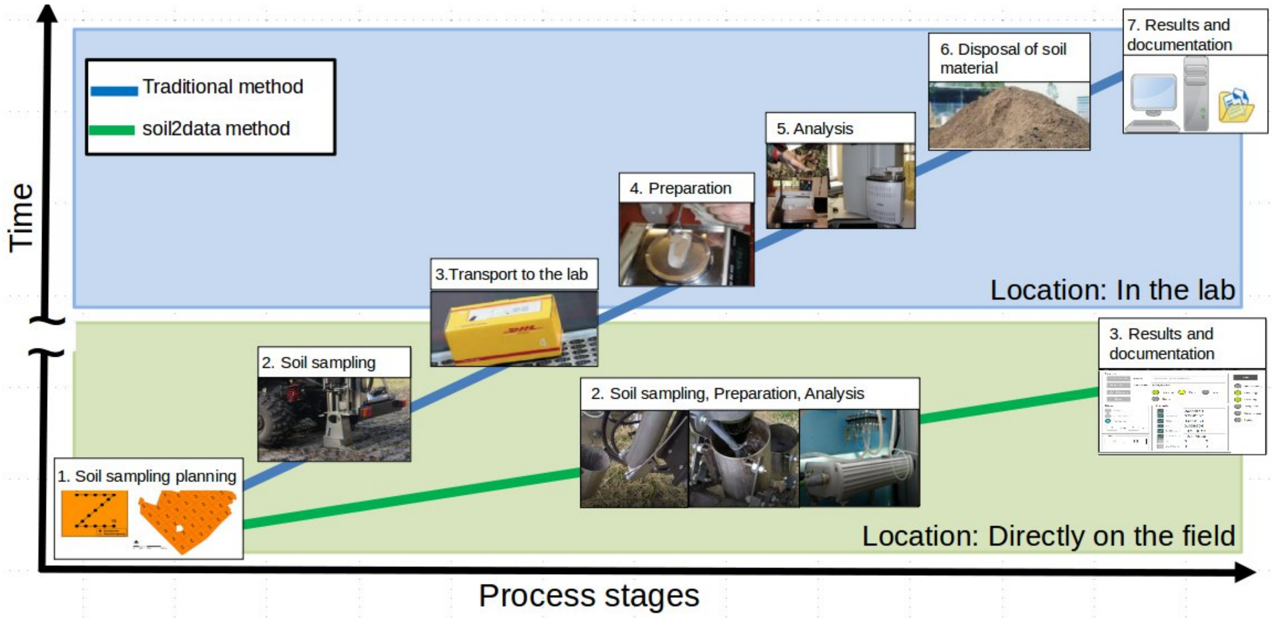

Fig. 1: Process flow of traditional soil sampling in the field and analysis of soil samples in the laboratory (upper blue line) and soil2data method with a combined process flow of soil sampling and analysis in the field (lower green line)

2.2 Main process "soil sampling in the field"

Planning soil sampling in the field is recommended for traditional soil sampling. By providing digital and geo-referenced sampling plans for sampling, the operator can be guided as to which fields or sub-fields to sample. By defining a sampling line with individual sampling points where necessary, the areas to be sampled in the field can be delineated. This makes it easier for the driver to know where to take soil samples within the area. Orientation within the area is provided by using a GNSS system and a mobile device to visualise one's own position on maps.

Soil sampling in the topsoil to a depth of up to 30 cm is often carried out using a drilling system. Drilling systems have the advantage that they are very fast, quiet and reliable (Peters, 2022). Reliable means that the selected sampling depth is reached exactly, a representative amount of soil is taken from all areas over the entire depth and the drill is emptied completely. In Germany, a mixed soil sample with 15 to 25 individual cores is taken as a representative soil sample for basic nutrient analysis.

2.3 Main process "Nutrient analysis in the laboratory"

In the laboratory, the soil sample is prepared, extracted and analysed according to defined procedures. The analysis results are sent to the farmer on paper with a fertiliser recommendation. Finally, the soil sample material is disposed of at the laboratory site.

In Germany, the testing methods for soils are based on the VDLUFA standard work "Handbuch der Landwirtschaftlichen Versuchs- und Untersuchungsmethodik; Die Untersuchung von Böden" (Handbook of Agricultural Experimentation and Investigation Methodology; The Analysis of Soils [VDLUFA, 2016]). Nutrients and pH are analysed according to the methods listed in Table 1.

The preparation and extraction methods are country-specific and vary as do the fertiliser recommendations; see for example Jordan-Meille (2012) on phosphorus analysis and fertilisation recommendations in Europe.

Tab. 1: Analysis method, extraction agent, ratio soil:extraction agent and preparation time for selected nutrients and pH value

Nutrient	Analysis method	Extraction agent	Ratio soil:extraction agent	Processing time
Nitrate nitrogen	VDLUFA / A 6.1.1	$CaCl_2$, c = 0,0125 mol/l	1:10	60 min
Phosphorus (plant available)	VDLUFA / A 6.2.1.1	Calcium acetate lactate (CAL)	1:20	90 min
Potassium (plant available)	VDLUFA / A 6.2.1.1	Calcium acetate lactate (CAL)	1:20	90 min
pH value	VDLUFA / A 5.1.1	$CaCl_2$, c = 0,01 mol/l	1:2,5	60 min

The analysis result is sent to the farmer with a fertiliser recommendation. It should be moted that each fertiliser recommendation is based on a specific analysis method. Such a specific fertilising recommendation cannot be applied 1:1 to another preparation or analysis method. In such a case, it is necessary to check whether there is a good correlation between the analysis results of two different analysis methods and whether there are any deviations between the absolute values. If necessary, a factor can be used to correct the analysis result so that the fertilisation recommendation of another analysis method can be applied.

In general, it takes up to several weeks from the time the soil is sampled until the analysis results are available to the farmer. It is therefore not possible to repeat the soil nutrient analysis immediately if there are questions or uncertainties about the test results.

3 Results and Discussion

3.1 Design of the mobile field laboratory "soil2data"

A mobile field laboratory has been developed for soil sampling and soil nutrient analysis directly in the field (Hinck et al., 2018). The two main work processes "1. soil sampling on the field" and "2. nutrient analysis in the laboratory" were analysed and broken down into individual sub-processes (see Fig. 1). The two previously independent and spatially separated processes of "soil sampling" and "soil analysis" are combined into one process in the mobile field laboratory "soil2data". This has several advantages. On the one hand, it eliminates the need to transport soil sample material from the field to the laboratory and its "disposal" at the laboratory site. On the other hand, the analysis results are available immediately after completion. The rapid availability of data provides the basis for future new applications, such as the verification of current analysis results with available results from previous soil sampling or the repetition or dynamic adjustment of soil sampling during fieldwork in the case of unclear or unexpectedly deviating analysis results. The digitally available analysis result can also be connected to a cloud and used immediately for further applications. In this way, a fertiliser recommendation can be generated automatically. This fertilisation recommendation and the analysis results are immediately available to the user and can also be integrated into subsequent work processes. This shows the advantage and benefit of a mobile field laboratory with data connection.

In the previous research project "soil2data", the corresponding concept for a mobile application in the field was designed and built in the form of the mobile field laboratory "soil2data" (see Fig. 2).

Fig. 2: Mobile field laboratory "soil2data" implemented in a trailer

The previously separate work processes "soil sampling in the field" and "nutrient analysis in the laboratory" were carried out as a parallel and combined process in the field (see Fig. 1).

In the current project "prototypes4soil2data", the mobile field laboratory "soil2data" has been further developed into a modular structure. The data management has been extensively extended so that a fertiliser recommendation can be generated automatically (Riedel et al., 2022). A trailer was chosen as the carrier platform, as this constellation offers the greatest operational flexibility for a practical application.

The two work processes "soil sampling in the field" and "nutrient analysis in the laboratory" are carried out by 5 application modules – so called apps – with specified tasks:

- app2field,
- field2soil,
- soil2liquid,
- liquid2data and
- data2app. (see Fig. 3)

The 5 individual modules together form the mobile field laboratory "soil2data". Each module can also be used as a stand-alone application.

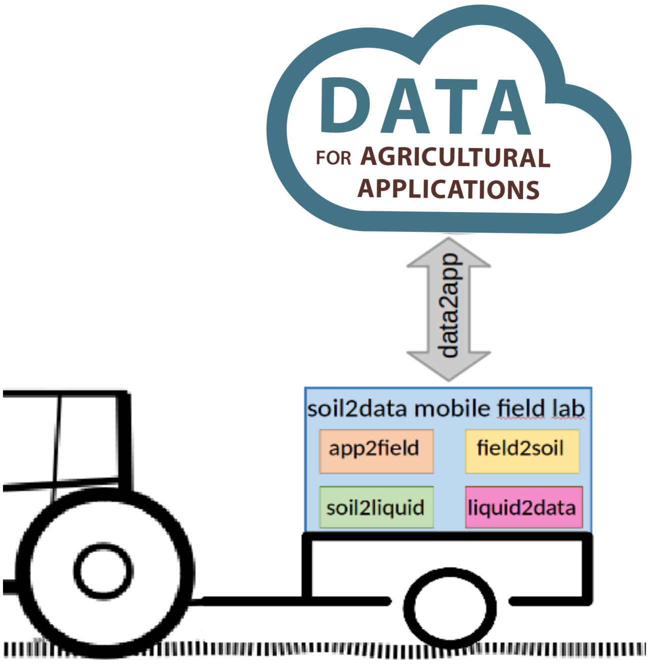

Fig. 3: soil2data app concept: The mobile field laboratory "soil2data" includes 5 combined modules

3.2 Module "app2field"

The planning of soil sampling is very important for the use of the mobile field laboratory and has been implemented with the module "app2field". The following information can be used and stored: field name, field boundaries, field name, sub-field boundaries, sampling lines and/or sampling locations, and address information. Additional maps, such as OpenStreet Map, Google Map or Bing aerial images can be loaded online or the OpenStreet Map dataset can be loaded as an offset map. This information helps the driver to orientate spatially and is a visual navigation aid to the field to be sampled. It provides the driver also with orientation within the fields and identifies the sampling area based on the sampling lines and, if applicable, sampling locations. During sampling, the soil sampling locations are saved geo-referenced and used for later documentation. In addition, the saved sampling locations and the travelled sampling line can be used for future sampling.

When the "app2field" application is used as a stand-alone module on a conventional soil sampling unit, a label printer can be added to the module. This allows the field name, subplot name, sample number and address information to be printed on a label. This label can be attached to the sample material container during traditional soil sampling.

3.3 Module „field2soil“

The "field2soil" module consists of a commercial soil sampling device modified for the mobile field laboratory "soil2data" and an additional mechanism for transferring the collected soil sample material to the soil preparation unit of the mobile field laboratory. The soil sampling device is a drilling system with an all-electric drive. The sampling depth can be set to up to 30 cm depth.

3.4 Module „soil2liquid“

Within the module "soil2liquid", the collected soil sample material is mechanically and chemically processed. For the mechanical and chemical preparation, the soil material is mixed with extraction agent and mechanically crushed and homogenized. For the mobile application, the individual steps of the soil preparation sub-process have been modified and adapted to the conditions of the mobile field laboratory. Two extraction stages with different extraction agents are available (see fig. 4). Thus, the soil preparation is very flexible in the application to make changes in the sub-process flow or in the choice of extraction agents if necessary (Tsukor et al. 2019, 2018). After preparation, filtering is performed and the filtered suspension is made available for analysis.

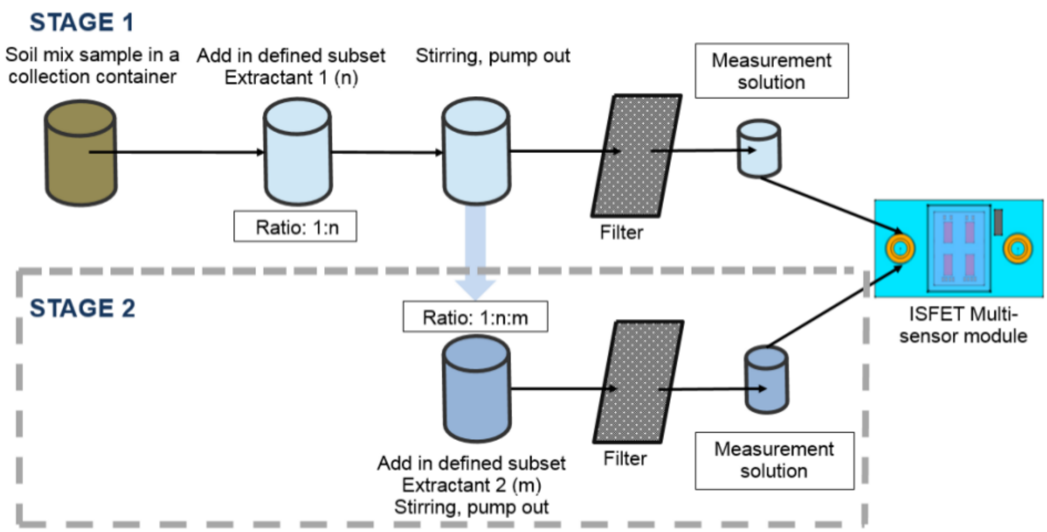

Fig. 4: "soil2data" 2 stages soil nutrient extraction procedure (Source: Tsukor et al. 2018)

The newly developed soil sample preparation method has been specifically adapted to the needs of the mobile field laboratory and is based on the current VDLUFA standard method (Najdenko et al., 2023; 2022). In particular, the preparation times have been shortened and the extraction agents modified for the soil2data preparation method. Comparative laboratory tests have been carried out. A comparison of the analysis results using the soil2data preparation method and the results using the VDLUFA standard method (see Table 2) shows good to very good correlations (Najdenko et al., 2023; 2022).

3.5 Module „liquid2data“

The nutrient analysis is performed in the "liquid2data" module. The key component of this application is the Nutristat analysis module (see fig. 4), the mobile nutrient analysis laboratory on a chip (lap-on-chip). This lab-on-chip (ISFET measurement technology) is used to analyse the nutrients nitrate (NO_3^-), potassium (K^+) and dihydrogen phosphate ($H_2PO_4^-$) as well as pH and electrical conductivity of the soil suspension. As part of the project, specified control and readout electronics has been developed for the Nutristat analysis module. The control and readout electronics are optimized for practical online operation and are an important prerequisite for the operation of the ISFET measurement technology in the mobile field laboratory.

Fig. 4: Nutristat analysis module (lab-on-chip) with ISFET measurement technology to measure NO_3^-, K^+ and $H_2PO_4^-$ as well as pH and electrical conductivity of the soil suspension

3.6 Module „data2app“

The data connection and data flow between external data from the farmer, the service provider, the mobile field laboratory "soil2data" during work in the field and the cloud is established by the module "data2app" (Riedel et al. 2023). Among other things, the soil sampling planning data are made available and transmitted for the "app2field" module.

After the analysis, the analysis data are sent to the cloud and stored. In addition, the calibration data of the Nutristat analysis module are also saved in the cloud. The measured values in volts are converted into a nutrient value in mg per 100 g of soil. The nutrient values can be assigned to the (sub-)fields.

Further external information is needed to make a fertiliser recommendation: cultivated crop, expected yield, soil texture and humus content are be used to make a fertiliser recommendation. This external data needs to be linked to the soil2data system. The external data and the collected soil nutrient results are sent to the LUFA Cloud. In the LUFA-Cloud, a fertiliser recommendation is generated and sent back to the farmer. The farmer also receives the results of the soil analysis and the documentation of the sampling. The soil nutrient values or fertiliser recommendation can be integrated into subsequent work processes and evaluations.

3.7 Mobile field laboratory „soil2data“

The new mobile field laboratory has several advantages over the mobile field laboratories known from the literature (see Tab. 2). The mobile field laboratory "soil2data" has a modular structure - the individual modules can also be used as stand-alone applications. The sampling depth is adjustable and can be down to 30 cm deep. The driver is supported during the sampling process by a visualisation of a soil sampling plan on a mobile terminal. The soil sampling locations and the travelled sampling route are stored, serve for documentation purposes and can be reused for future soil sampling. The soil preparation is a two-stage process based on the German standard for soil analysis. The ISFET measurement technology used in the Nutristat analysis module can measure pH, NO_3^-, $H_2PO_4^-$, K^+ and the electrical conductivity of the soil suspension. Data management allows external and internal information to be linked and a fertiliser recommendation to be generated automatically.

Tab. 2: Presentation and comparison of the specification of the mobile field laboratories mentioned in the literature and the mobile field laboratory "soil2data".

Reference	System platform available	NO_3^-	P	K	pH	Variable depth sampling (→ 30 cm)	Sampling planning with sub-fields and sampling lines/locations specifications	Sampling locations repeated sample-able	Data manage-ment	Automatic fertilisation recommen-dation
Sibley et al. 2010	X	X							X	
Kweon et al. 2012	X				X				X	
Rossel et al. 2005	X				X				X	
Sethuramasamyraja et al. 2008 and Adamchuck et al., 2005	X	X		X	X					
Kim et al., 2013		X	X	X						
Mobile fieldlab „soil2data“	X	X	X	X	X	X	X	X	X	X

4 Summary

The mobile field laboratory "soil2data" combines two main work processes: "Soil sampling in the field" and "Nutrient analysis in the laboratory". The process steps are carried out automatically. The individual process steps run in parallel.

Soil sampling planning is an important prerequisite for the digitisation of soil sampling, especially for the automatic allocation of results to the fields or sub-fields. The planning is done with the "app2field" application module. Soil sampling is carried out using the application module "field2soil". A modified commercial soil sampling device is used for this purpose. Soil preparation is done in the application module "soil2liquid", which has been adapted for the mobile field laboratory. Comparative results from the laboratory show a high to very high correlation between the standard laboratory method and the soil2data method. The measurement is performed in the "liquid2data" application module. The key component of the analysis is the Nutristat analysis module with ISFET measurement technology (lab-on-chip). The specified electronic control and read-out circuitry has been designed for reliable and practical use directly in the field.

Data management is done with the "data2app" application module. It allows external and internal data to be linked. The "data2app" application module is also used to record and link the measurement results and the required external data. The results are immediately available and a fertiliser recommendation can be automatically generated.

Furthermore, the data and information can be integrated into subsequent work processes and evaluations.

The rapid availability of data opens up additional new application possibilities in the field, such as checking current analysis results against available results from previous soil sampling or a dynamic adjustment of the soil sampling during the work in the field in case of unclear or unexpected test results. The mobile field laboratory "soil2data" enables the digitalisation of soil sampling in the field.

Acknowledgements

The project is supported by funds of the Federal Ministry of Food and Agriculture (BMEL) based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE) under the innovation support program.

With support from

Federal Ministry of Food and Agriculture

by decision of the German Bundestag

Federal Office for Agriculture and Food

ptble

Projektträger Bundesanstalt für Landwirtschaft und Ernährung

Note

This publication was presented as a presentation entitled "Analysis-to-go on the field: prototypes4soil2data" at the 22nd World Congress of Soil Science in Glasgow, Scotland, on 4 August 2002.

References

Adamchuk, V. I., Lund, E. D., Sethuramasamyraja, B., Morgan, M. T., Dobermann, A., & Marx, D. B. (2005): Direct measurement of soil chemical properties on-the-go using ion-selective electrodes. Computers and Electronics in Agriculture, 48(3), pp. 272-294.

Anderson-Cook, C. M., Alley, M. M., Roygard, J. K. F., Khosla, R., Noble, R. B., Doolittle, J. A. (2002): Differentiating soil types using electromagnetic conductivity and crop yield maps. Soil Science Society of America journal 2002, 66 (5), pp. 1562-1570.

Domsch, H. u. Schirrmann, M. (2009): Teilflächenspezifische Grunddüngung /Subfield-specific basic fertilisation). Bornimer Agrartechnische Berichte 72, pp. 1-131.

Gourley, C.J.P. und Weaver, D.M. (2019): A guide for fit for purpose soil sampling, Fertilizer Australia, Canberra, Australia. https://peel-harvey.org.au/wp-content/uploads/2020/03/Fertcare-Soil-Sampling-Guide.pdf

Hinck, S., Möller, A., Mentrup, D., Najdenko, E., Lorenz, F., Mosler, T., Tesch, H., Nietfeld, W., Scholz, C., Tsukor, V. & Ruckelshausen, A. (2018). soil2data: Concept for a mobile field laboratory for nutrient analysis. Proceedings of the 14th ICPA (unpaginated cd-rom). Montreal, Canada.

Hinck, S., Mueller, K., Emeis, N. (2014): Geoelectric measurements combined with traditional field mapping enable sample reduced site mapping. Vestnik Altaiskogo go-sudarstvennogo agrarnogo universiteta. Download: https://www.researchgate.net/publication/264329092_Geoelectric_Measurements_combined_with_traditional_Field_Mapping_enable_Sample_reduced_Site_Mapping

Hinck, S. Emeis, N. und Mueller, K. (2013): Part Field Management: Comparison of EC-value, soil texture, nutrient content and biomass in two selected fields. In Proceedings 3rd Global Workshop on Proximal Soil Sensing, Potsdam, p. 270. Download: https://www.researchgate.net/publication/260502756_Part_Field_Management_Comparison_of_EC-value_soil_texture_nutrient_content_and_biomass_in_two_selected_fields

Hinck, S. und Kielhorn, A. (2011): Entscheidungsunterstützung–können Daten und Informations-technik helfen? (Decision support–can help data and information technology?). Proceedings of LAND.TECHNIK für Profis, pp. 103-114.

Hornung, A., Khosla, R., Reich, R., Inman, D., Westfall, D. G. (2006): Comparison of site specific management zones: Soil color based and yield based. Agronomy Journal, 98(2), pp. 407-415.

Jiang, G., Grafton, M., Pearson, D., Bretherton, M., Holmes, A. (2019): Integration of precision farming data and spatial statistical modelling to interpret field-scale maize productivity. Agriculture, 9(11), pp. 237.

Jordan-Meille, L., Rubæk, G. H., Ehlert, P. A. I., Genot, V., Hofman, G., Goulding, K., Recknagel, J., Provolo, G., Barraclough, P. (2012): An overview of fertilizer-P recommendations in Europe: soil testing, calibration and fertilizer recommendations. Soil Use and Management, 28(4), pp. 419-435.

Kim, H. J., Sudduth, K. A., Hummel, J. W., & Drummond, S. T. (2013). Validation testing of a soil macronutrient sensingsystem. Transactions of the ASABE, 56(1), pp. 23-31.

Kweon, G., Lund, E., Maxton, C. (2012). The ultimate soil survey in one pass: soil texture, organic matter, pH, elevation, slope, and curvature. Proceedings of the 11th ICPA, pp. 1-13.

Lorenz, F. und Münchhoff, K. (2015): Teilflächen bewirtschaften – Schritt für Schritt. AgrarPraxis kompakt, DLG-Verlag, Frankfurt am Main.

LWK (2022): Düngeempfehlung Grundnährstoffe der Landwirtschaftskammer Niedersachsen (fertiliser Recommendation Basic Nutrients of the Niedersachsen Chamber of Agriculture), https://www.lwk-niedersachsen.de/services/download.cfm?file=22858, last request: 01.11.2022

Najdenko, E., Lorenz, F., Olfs, H.-W., Dittert, K. (2023). Development of an in-field express method for NO3-, H2PO4- and K+ wet-chemical extraction and pH value for the measurement with ISFET. Journal of Plant Nutrition and Soil Science, in print.

Najdenko, E., Lorenz, F., Neuhaus, C. (2022): Fitting laboratory methods to “on-the-go” soil analysis on the field. Presentation at the 22nd World Congress of Soil Science (WCSS 2022), Glasgow, Schottland.

Nawar, S., Corstanje, R., Halcro, G., Mulla, D., Mouazen, A. M. (2017): Delineation of soil management zones for variable-rate fertilization: A review. Advances in agronomy, 143, pp. 175-245. https://www.researchgate.net/profile/Said-Nawar/publication/316989177_Delineation_of_Soil_Management_Advances_in_Agronomy/data/591c1174aca272bf75c8d2b1/Delineation-of-Soil-Management-Advances-in-Agronomy.pdf

Rossel, V. R. A., Gilbertson, M., Thylen, L., Hansen, O., McVey, S., McBratney, A. B. (2005). Field measurements of soilpH and lime requirement using an on-the-go soil pH and lime requirement measurement system. In Proceedings of the 5th European Conference on Precision Agriculture, pp. 511-519. Wageningen, Wageningen AcademicPublishers.

Riedel, V., Möller, A., Terhaag, M., Meyer, T., Mentrup, D., Kerssen, H., Najdenko, E., Lorenz, F., Mosler, T., Tesch, H., Peters, W., Hinck, S., Ruckelshausen, A. (2023): Datenfluss bei der Applikation der Bodenbeprobung mit dem mobilen Feldlabor „soil2data“ (Data flow in the application of soil sampling with the mobile field laboratory "soil2data"). In Proceedings 43 Conference GIL, Osnabrueck, Germany, in print.

Riedel, V., Möller, A., Terhaag, M., Mentrup, D., Kerssen, H., Najdenko, E., Lorenz, F., Mosler, T., Tesch, H., Peters, W., Nietfeld, W., Hinck, S., Ruckelshausen, A. (2022): prototypes4soil2data: Modular designed mobile field laboratory for standardized soil nutrient analysis directly on the field. In Proceedings 20th International Commission of Agricultural and Biosystems Engineering (CIGR 2022), Kyoto, Japan, in print.

Sethuramasamyraja, B., Adamchuk, V. I., Dobermann, A., Marx, D. B., Jones, D. D., Meyer, G. E. (2008). Agitated soilmeasurement method for integrated on-the-go mapping of soil pH, potassium and nitrate contents. Computers andelectronics in agriculture, 60(2), pp. 212-225.

Struijs, J., Beusen, A., de Zwart, D., & Huijbregts, M. (2011): „Characterization factors for inland water eutrophication at the damage level in life cycle impact assessment“. The International Journal of Life Cycle Assessment, 16(1), pp. 59-64.

Thylén, L., Viscarra Rossel, R.A., Gilbertsson, M. & McBratney, A.B. (2004): Development of an on-the-go soil pH and lime requirement sensing system. Paper submitted to AgEng 2004, Engineering the Future, Leuven, Belgium.

Toscano, P., Castrignanò, A., Di Gennaro, S. F., Vonella, A. V., Ventrella, D., Matese, A. (2019): A precision agriculture approach for durum wheat yield assessment using remote sensing data and yield mapping. Agronomy, 9(8), pp. 437.

Tsukor, V., Hinck, S., Nietfeld, W., Lorenz, F., Najdenko, E., Möller, A., Mentrup, D., Mosler, T., Ruckelshausen, A (2019): Automated mobile field laboratory for on-the-go soil-nutrient analysis with the ISFET multi-sensor module. In Proceedings 77th International Conference on Agricultural Engineering (AgEng 2019), p. 377 - 382. VDI-Reports 2361, Düsseldorf, Germany.

Tsukor, V., Hinck, S., Nietfeld, W., Lorenz, F., Najdenko, E., Möller, A., Mentrup, D., Mosler, T., Ruckelshausen, A. (2018): Concept and first results of a field-robot-based on-the-go assessment of soil nutrients with ion-sensitive field effect transistors, 6th International Conference on Machine Control & Guidance, Proceedings, pp. 102-108, Berlin.

VDLUFA (2016): Handbuch der Landwirtschaftlichen Versuchs- und Untersuchungsmethodik (VDLUFA-Methodenbuch). Vol. I, Die Untersuchung von Böden, 4th edition. 7th part delivery. Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten. (Handbook of Agricultural Research- and Testing Methods, Vol. I, The Testing of Soils German Association of Agricultural Analysis and Research Institutes). VDLUFA-Publisher, Darmstadt

Zimmer, J., Ellmer, F., Kroschewski, B. (2014): Nährstoffversorgung Brandenburger Ackerböden (Nutrient supply of Brandenburg arable soils). In Bornimer Agrartechnische Berichte Heft 86, pp. 52 – 55. Hrsg.: Leibniz Institut für Agrartechnik Potsdam Bornim e.V. (ATB).

Web source

VDLUFA (2014): Hinweise zur Entnahme von Bodenproben auf Nährstoffe (Notes on the collection of soil samples for nutrient analysis). https://www.lufa-nord-west.de/index.cfm/action/downloadcenter?file=08E7CC

Peters (2022): http://www.bodenprobetechnik.de/index.php/en/n-2006-eng