soil2data: Concept for a mobile field laboratory for nutrient analysis

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Abstract. Error! Bookmark not defined. *Knowledge of the small-scale nutrient status of arable land is an important basis for optimizing fertilizer use in crop production. A mobile field laboratory opens up the possibility of carrying out soil sampling and nutrient analysis directly on the field. In addition to the benefits of fast data availability and the avoidance of soil material transport to the laboratory, it provides a future foundation for advanced application options, e.g. a high sampling density, sampling of small sub-fields or dynamic adaptation of the sampling line during field sampling. An innovative key component is the NUTRI-STAT ISFET sensor module. It measures values for the ions "NO_3^-", "$H_2PO_4^-$" and "K^+" as well as the pH. The ISFET sensor module was specially developed for soil nutrient analysis. The phosphorus measurement was further developed for the project "soil2data". First results from the ISFET sensor module show a measurement signal settling time of significantly less than 100 seconds and a further consistent stable measurement signal. The measurement signal dynamics of approx. 58 mV per factor 10 of concentration change is given for the measured variables pH and K^+. For the measured quantities of NO_3^- and $H_2PO_4^-$, the measurement signal dynamics are lower.*

Keywords. *concept mobile field laboratory, field-lab, ISFET-sensor module, soil sampling, soil nutrients analysis, lab on a chip, soil2data*

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Introduction

The aim of needs-based and sustainable fertilizing is to adjust the amount of fertilizer to the nutrient demand of the crop taking into account the current soil nutrient levels and, for logical reasons, the soil texture. In particular, the current soil nutrient levels must be known before the application of fertilizer.

It can generally be said that:

- the level of fertilizing/ nutrient rate depends on the current yield - ideally - on a sub-field basis

- very low soil nutrient content usually results in yield reductions,

- very high soil nutrient content presents the danger of an unproductive runoff or leaching of nutrients.

Sustainable fertilizing is designed to achieve the optimum economic yield while minimizing negative environmental impacts. It should be noted, that increased fertilizer input leads to nutrient discharge into groundwater and surface water and thus to negative environmental consequences. Furthermore, unproductive nutrient discharge reduces the economic success of crop production.

Arable land should generally not be considered a homogeneous unit. There are geogenic or pedogenic differences (e.g. soil texture, soil type) (Hinck 2009) and the yield varies across the field (e.g. Hinck and Kielhorn 2011). In general, a yield change can be registered when, for example, there is change in soil texture or soil type within the area. Thus, a field is to be divided into sub-fields according to defined criteria. For successful, site-specific crop production, detailed information on a small-scale, like yield, nutrient status and/or soil texture are of fundamental importance. Among other things, the current soil nutrient status has an important influence on the yield (Wagner and Marz 2017, Zhang et al. 2011, Cissé 2007). In the case of site-specific fertilizing, the fertilizer inputs are adjusted to the site-specific yield and corrected according to the current soil nutrient status of that specific sub-field (e.g. Buresh and Witt 2007). Soil nutrient status may be subject to significant variations within the area due to differences in nutrient removal by plants and soil texture (Hinck et al. 2013). For an economical and ecologically sustainable crop production, knowledge of the small-scale distribution of soil nutrients is an important information (e.g. Wagner and Marz 2017, Hinck and Kielhorn 2011).

If the fertilizer inputs during fertilizing are adjusted taking into account the current soil nutrient status and the yield level on a sub-field basis, the risk of “over-fertilizing” - excessive fertilizer application - or too little fertilizer - and thus the risk of reduced yields – can be avoided. Thus, the goal of optimizing fertilizer use and improving fertilizer efficiency can be achieved.

Several working groups are working on the implementation of an on-the-go nutrient analysis for field application. An automatic on-the-go Nitrate Measuring System (SNMS) has been developed and deployed at the Nova Scotia Agricultural College. During the sampling process, soil samples are taken from the topsoil and the nitrate content (NO_3^-) is analyzed by means of an ion-selective electrode. (Sibley et al. 2010, Sibley 2008)

Another on-the-go measurement system for the pH of the upper layer of topsoil has also been developed at the Australian Center for Precision Agriculture (ACPA) at the University of Sydney in collaboration with the Swedish Institute of Agricultural and Environmental Engineering (JTI) in Uppsala and it has been field tested for practicality. A soil sample is collected from the upper layer of topsoil during the sampling trip and prepared for the measurement. The pH is measured with an ISFET pH electrode. (Rossel et al. 2005, Viscarra Rossel et al. 2004)

A sensor platform for soil nutrient analysis is being developed at McGill University (Montreal / Canada) in cooperation with Veris Technologies (Salina / USA) and the University of Nebraska

(Lincoln / USA). A soil sample is taken from the upper layer of topsoil during the sampling trip and processed. pH, nitrate and plant-available potassium are measured with ion selective electrodes. (Sethuramasamyraja et al. 2008; Adamchuk et al. 2005)

A method development for soil preparation for mobile field laboratories has been presented by Kim et al. (2007 and 2013). Various analytical methods were used and the results compared. The measurement of nitrate, plant-available phosphorus and potassium is carried out with ion-selective electrodes.

Concept mobile field laboratory "soil2data"

The aim of the interdisciplinary research project "soil2data" is a method development for the preparation of soil and the technical development of a mobile field laboratory (field-lab) for nutrient measurement on the field. A mixed soil sample will be collected during the sampling trip on the field. The soil sample is processed and analyzed. The soil material remains on the field and the analysis results are sent to an external data platform (cloud) and stored (see Fig. 1). The farmer has access to the results of the analysis via the Cloud.

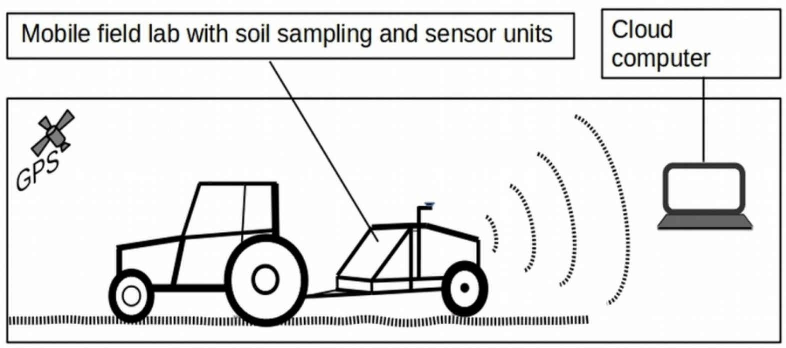

Figure 1: Sketched illustration of the mobile field-lab

The overall concept with the various technical process levels is shown in Figure 2. The main components are:

- the carrier vehicle

- the mechatronics module with sampler and soil preparation, as well as

- the sensor unit with the ISFET sensor module.

The 3 major components make up the overall system platform. Other components are:

- human-machine interface

- local data management and

- external data platform.

The human-machine interface enables the operation of the system. With the help of local data management, various information and data sets, e.g. sampling plan and navigation, are linked together. The analysis results are recorded and stored with a GPS position. If several different sensor systems are installed on the carrier vehicle, these are likewise processed with the aid of local data management, linked with a GPS stamp and stored. After completion of the measurement, the measurement results are sent to an external data platform and stored there.

The mobile field laboratory can be implemented on various carrier vehicles. A distinction can be made between manually controlled (e.g. N2012 or Speedprobe) and autonomous (e.g. the BoniRob research platform) carrier vehicles. Soil sampling may be done in stop-and-go (e.g. N2012) or on-the-go sampling (e.g. Speedprobe).

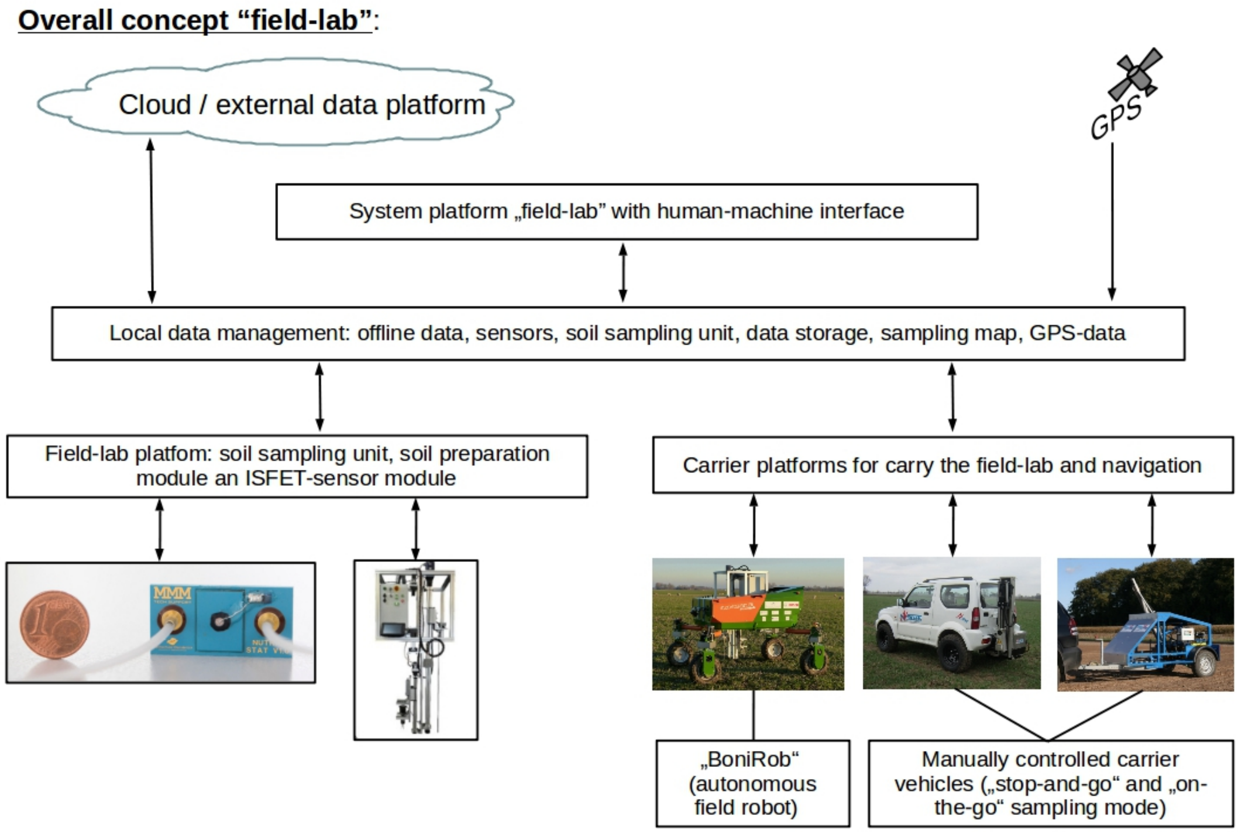

Figure 2: Overall concept for a mobile field laboratory

The design of a procedureal process for "soil sampling and analysis" for a mobile field laboratory is based on the conventional procedure. This process can be simplified into the following sub-process steps:

1. Planning: design of soil sampling route

2. Soil sampling: collection of a mixed soil sample on the field and transportation of the soil sample to the laboratory,

3. &. 4. Physical and chemical soil preparation,

5. Analysis,

6. Results and documentation,

7. Sending the results to the farmer.

(see Fig. 3)

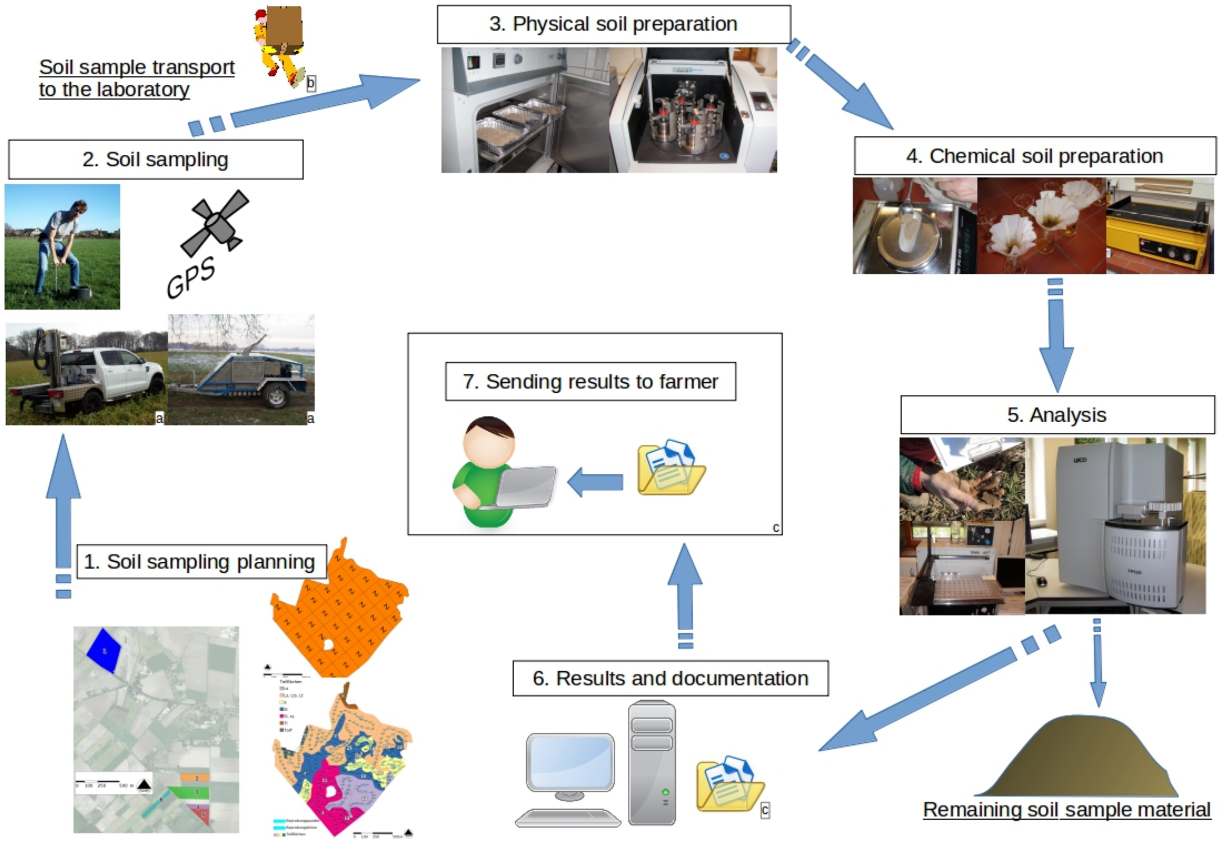

Figure 3: Simplified process of conventional soil sampling and analysis as a conceptual basis for a mobile field laboratory (Image sources: a) Bodenprobetechnik Nietfeld GmbH (http://www.bodenprobetechnik.de); b) francesco_rollandin (openclipart.org); c) Clipart OpenOffice and own images)

These process steps are to be adapted and modified according to the technical conditions of the mobile field laboratory. Preparatory process steps are necessary, in particular the planning of soil sampling and the creation of sampling lines. The actual soil sampling can be combined with the soil preparation and analysis process steps. This process takes place entirely on the field. Finally, the analysis results are transmitted to an external data platform, are made available to the farmer and can be used for further analysis. (see Fig. 4)

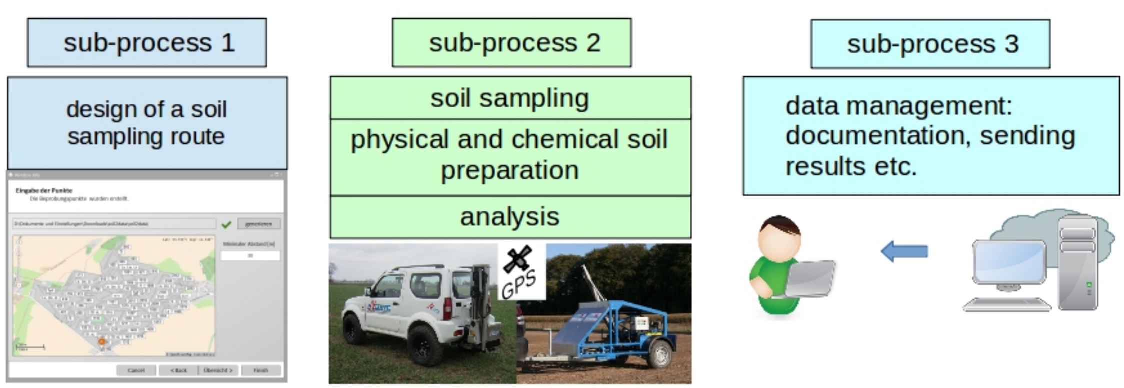

Figure 4: Simplified process of the mobile field-lab

Benefits of a mobile field laboratory

An advantage of the mobile field laboratory is that the soil analysis is done directly on the field. This does not require transport of soil material to the laboratory. There is no "disposal requirement" for the soil material at the laboratory. The analysis results are available quickly. This opens up the possibility of updating the current nutrient status for subsequent planned fertilizing measures, e.g. to be considered in the spring.

On the other hand, the future potential of the mobile field laboratory is based on a very flexible measuring application. A mobile field laboratory offers the prospect of increasing the sampling density, either by decreasing sub-field size for mixed soil samples or by allowing for the extraction of every single soil sample. Transition areas between sub-fields or very small sub-fields can also be sampled at a small-scale, to describe boundaries between sub-fields relatively accurately. A repetition of the measurement in calendarial or seasonal intervales enables a representation of nutrient dynamics over time series.

Another innovative option is the dynamic adaptation of the sampling line during soil sampling if, the currently processed series of measurements on a sampling line show highly fluctuating measurement results. In the future, there is the prospect of subdividing this sampling line or re-sorting the individual results based on the GPS positions. However, this presupposes that every single soil sample can be analyzed. Likewise, there is the option of comparing current measurement results with existing measurement results in order to repeat the sampling in the event of severe deviations or to re-sample and reanalyze the area once again using a newly generated sampling line.

It is useful to use the mobile field laboratory in combination with an autonomous carrier vehicle in particular for a high sampling density, with short sampling time intervals or the dynamic adaptation of the soil sampling. In these deployment constellations, the economic viability of autonomous vehicles is higher in comparison to manually controlled/ driven vehicles (Scholz et al. 2016, Scholz 2015).

Main component "ISFET sensor module"

To analyze the extracted soil samples, a NUTRI-STAT ISFET sensor module (Lab on Chip) from Microsens is used (Lehmann and Grisel 2014). It has an extremely compact design (see Fig. 5). The ISFET sensor module was specially designed for soil nutrient analysis. The phosphorus measurement has been further developed for the soil2data project.

Figure 5: NUTRI-STAT ISFET sensor module; dimensions of the ISFET sensor module with plug-in socket (width, depth, height): 33 x 17 x 10 mm, (Image sources: University of Applied Scienes Osnabrueck)

This "Lab on Chip" (NUTRI-STAT ISFET sensor module) consists of 4 individual ISFET sensors (**I**on **S**elective **F**ield **E**ffect **T**ransistors) and additional components for measuring the nutrients nitrate (NO_3^-), potassium (K^+) and dihydrogen phosphate ($H_2PO_4^-$) as well as pH, temperature and electrical conductivity of the soil sample. The measureable value ranges (manufacturer specifications) are given in Table 1.

Tab. 1: Properties of the ISFET sensor module (manufacture's information)

Manufacturer	Microsens SA (Switzerland)
Measured variables and measuring range (indicated in brackets)	- pH value (1 - 12), - NO_3^- (0.5 - 100 mMol / l), - K^+ (0.5 - 100 mMol / l), - $H_2PO_4^-$ (1 - 100 mMol / l), - temperature and EC value
Membrane at the ISFET chip for NO_3^-, K^+ and $H_2PO_4^-$	- PVC polymer
Temperature range	- 0 – 45 °C

The basic function of the ISFET sensor module is illustrated by first measurement results. These functional test measurements were carried out with the help of calibration solutions. The calibration solutions for K^+, NO_3^- and $H_2PO_4^-$ were used at a concentration of 100 mMol/l, 10 mMol/l, 1 mMol/l, 0.1 mMol/l. For a calibration of the pH series, the pH values: 4.0, 5.1, 6.0, 6.9, 9.1 and 10.2 were used. Compared to the first measurements adjustments and optimizations made to the control electronics (not shown here) improved the measurements. Furthermore, a successful conditioning of the ISFET sensor modules had a significant influence on the measurement results. In particular, the measurement signal settling times and measurement signal stability were improved in this way. Measurement signal settling times of significantly less than 100 seconds are shown (see Fig. 6). The further measurement signal progression shows a stable progression after the first 100 seconds.

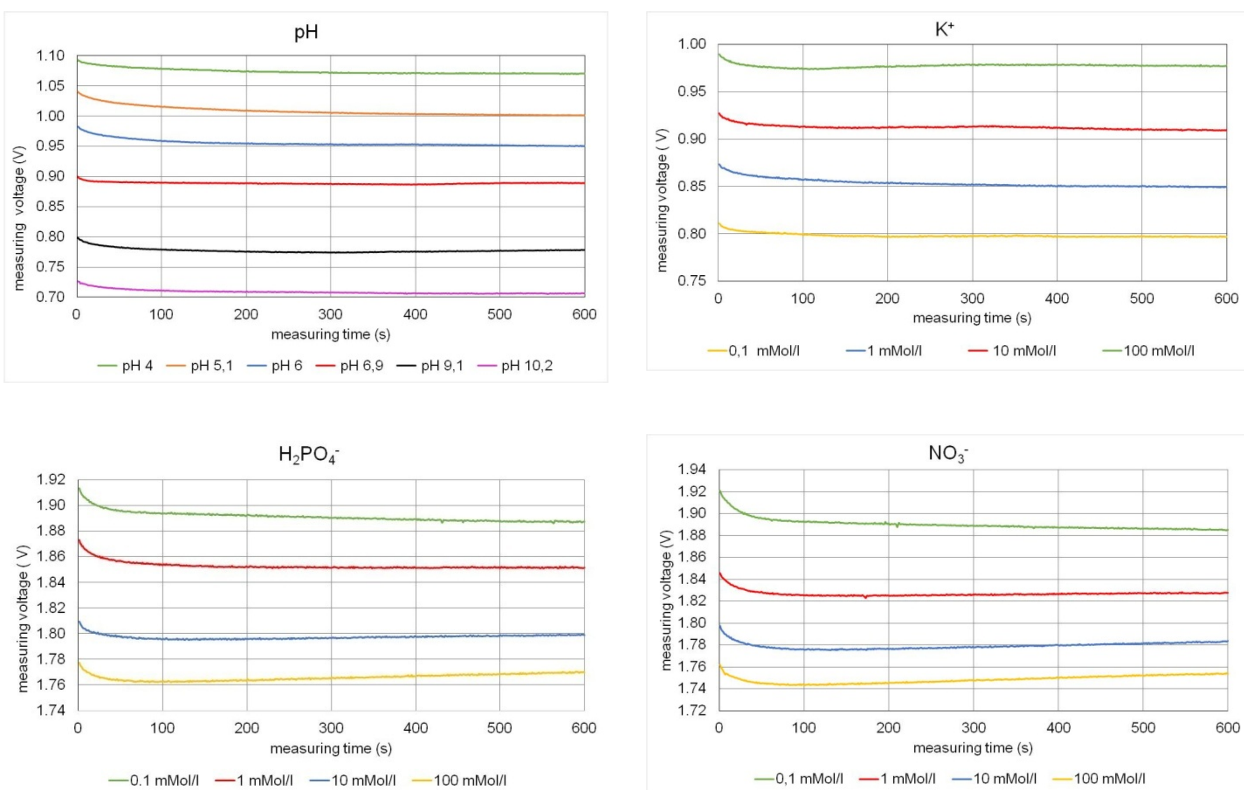

Figure 6: Measurement results using different solution concentrations over time for pH (top left), K^+ (top right), $H_2PO_4^-$ (bottom left) and NO_3^- (bottom right); measuring time: 600 s (10 minutes)

The expected measurement voltage change of about 58 mV per factor 10 of concentration according to the Nernst equation (Mikhelson, 2013) is achieved for the measured variables pH and K^+. For the two measured quantities NO_3^- and $H_2PO_4^-$ this value is lower. (see Fig. 7)

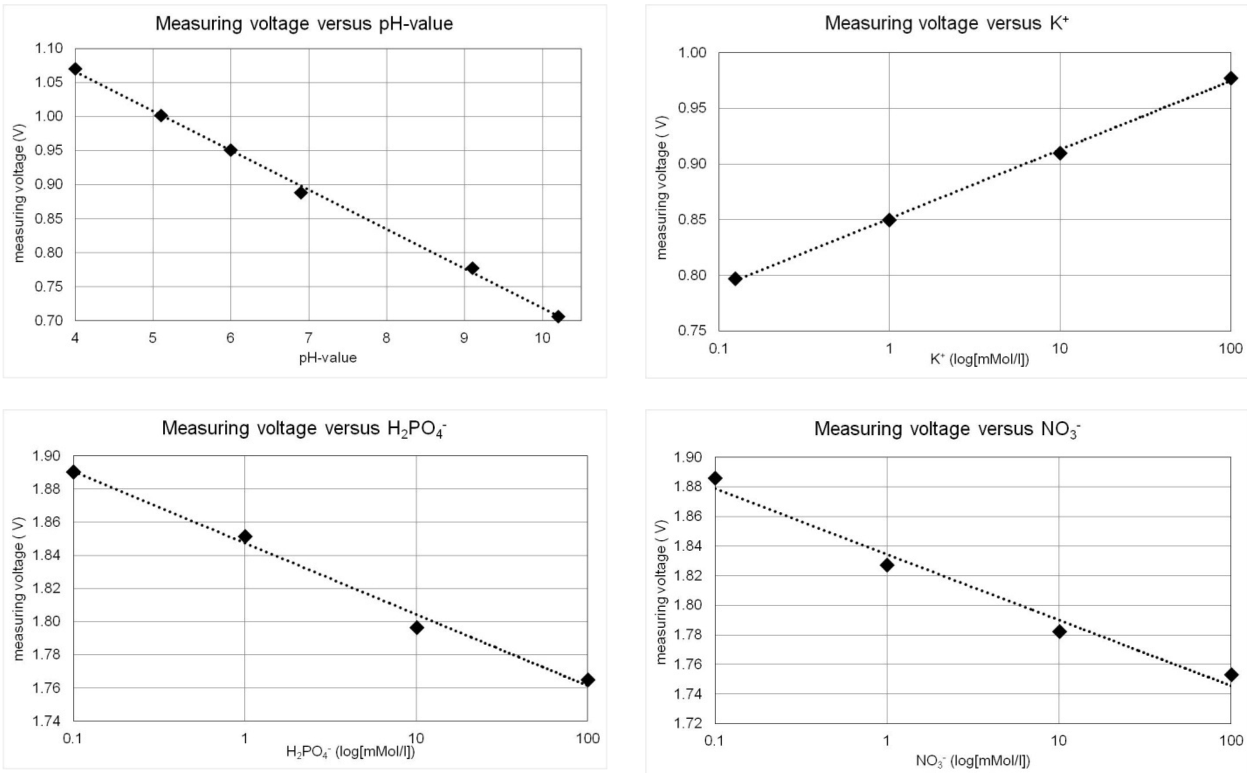

Figure 7: Measurement results using different solution concentrations and voltages for pH value (top left), K^+ (top right), $H_2PO_4^-$ (bottom left) and NO_3^- (bottom right)

Conclusion

The mobile field laboratory "soil2data" enables the nutrient analysis for pH, K^+, NO_3^- and $H_2PO_4^-$ to be carried out directly on the field. This not only eliminates the need to transport the soil samples to the laboratory, but makes the results available to the farmer within a very short time. Thus, it is possible to take into account the current soil nutrient status for planned fertilizer application, both for an entire field and on a sub-field basis. Further advantages of a mobile field laboratory are the extended application areas, e.g. the sampling of small sub-fields, the repetition of the measurement in relatively short periods of time (e.g. generating an annual, monthly or even daily series) or dynamic adaptation of the sampling line during soil sampling.

The mobile field laboratory may be operated on commercial support platforms (soil samplers) in stop-and-go operation (N2012) or in on-the-go operation (Speedprobe). Furthermore, the application can be based on autonomous field robotics (BoniRob).

The NUTRI-STAT ISFET sensor module is specially designed for soil nutrient analysis and is a key component of the field lab. For the project soil2data, the phosphorus measurement was further developed.

The listed first functional test measurements were carried out with the aid of calibration solutions. Measuring signal settling times of significantly less than 100 seconds and then stable measurement progressions are shown. For the measured quantities pH and K^+, the required measuring voltage change of approx. 58 mV per factor 10 concentration change is achieved. For the measured quantities NO_3^- and $H_2PO_4^-$ this value is lower. Further initial findings are that the measured and optimized control electronics of the ISFET sensor module and the procedure for successful conditioning of the ISFET sensors improve the measurement results.

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