Sensing Principles for Site-specific Data Acquisition

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Abstract
Since precision farming utilises higher spatial resolution than traditional farming, extensive soil and plant data have to be managed. Therefore, fast measuring techniques are looked for, which provide information on the state of soil and plants. Knowledge on heterogeneity of the fields is essential for precision farming. The heterogeneity can be derived from aerial image evaluation as well as by direct methods like harvest monitoring or different kinds of measurements of biomass distribution. Whereas fast and low cost mapping of soil texture is not solved, there are known principles for fast determination of humus, soil nitrogen, soil density and soil moisture. Advantages and shortages are being discussed. Spectral sensing and spectral imaging of crop in the visible and infrared range show the ability for fast crop surveying. Although intensive research has been performed, and imaging seems to have the best potential for weed recognition, the automatic weed determination in crops is an open question till today.

Key words : Measuring methods, precision farming, heterogeneity, soil nitrogen, soil moisture, soil density, chlorophyll, weed recognition

1 Introduction

Traditional cropping has regarded the field as the smallest unit of management. Tillage, sowing, fertiliser and pesticide applications are uniform. Only one data set, describing the homogeneous properties of the field, is necessary. Site-specific cropping aims at optimising economic returns and environment friendly farming by taking into consideration the actual stage of the soil in relation to the local need of the specific crop. Therefore, precision agriculture matches resource availability to crop capability. Knowledge on soil spatial variability is essential in this case. Information on the state of the soil and plants may be get as on-the-go monitoring of variable quantities in line with immediate responds of the machine system. The other possibility is the separation in time of sensing and control action. This is possible for quantities, which will not change essentially meanwhile or where the change can be calculated accurately. This type of temporally separate control in agriculture requires positioning and field mapping. Sensors are needed in each case, since all actions must be based on necessary information. An overview on some sensing principles for site-specific data acquisition is given in Table 1.

The number of data sets increases in precision farming in dependence with the spatial resolution. The smaller the sites, which are treated uniformly within the field, the more data sets must be supplied. Low-cost and fast measuring procedures are the basis for precision agriculture. If the degree of heterogeneity of the fields is low, the number of the required data will reduce, or the field can be treated uniformly. Therefore, the knowledge of heterogeneity is essential for the decision, to use GPS and more precise techniques.

Yield mapping, evaluation of aerial images or soil mapping give information on the variability of the field. For the determination of local variations in soil properties, the force during tillage or acting on a horizontally moved penetrometer may be used. Usually the soil structure is anisotropic with different semivariance (or auto-correlation) lengths. Site-controlled tillage
depth may improve local fertility or save energy due to reduction of tillage depth. The more important field for economic returns in site-specific cropping is the application of chemicals (fertiliser, plant protection). Principles for sensing nutrients and plants will be discussed more deeply in the following.

<table>
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<tr>
<th>Parameter</th>
<th>Measuring period</th>
<th>Traditional method</th>
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<th>Principle for non contact sensing</th>
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<tr>
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<td>soil analysis</td>
<td>open</td>
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<td>soil moisture</td>
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<td>nitrogen content</td>
<td>several times per year</td>
<td>N_min determination of soil solution</td>
<td>colour measurements with reactants, ion-sensitive electrodes, chemosensors</td>
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<tr>
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<td>every 5 (3 ... 8) years</td>
<td>soil and plant analysis; pH-meter</td>
<td>open</td>
<td>open</td>
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<td>carbon content</td>
<td>every 5 (3 ... 8) years</td>
<td>oxidation with CO2-analysis</td>
<td>(C13-NMR - as a method for scientific studies)</td>
<td>colour analysis, VIS- and IR-remission</td>
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<td>plant growing, biomass development</td>
<td>at cultivation</td>
<td>inspection and classification</td>
<td>conductivity (top plant to soil), force measurement by moved bending of plants</td>
<td>height of plants and plant density by moving light barriers or ultra sonic measurements, radiometric methods, machine vision, spectral aerial imaging</td>
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<td>before treatment</td>
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<td>(H1-, P31- and C13-NMR - as a method for scientific studies)</td>
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<td>spectral aerial imaging, plant recognition by imaging, classification by conditions (time of cultivation, position in field, etc.)</td>
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<tr>
<td>yield</td>
<td>harvest</td>
<td>gravimetric mass determination using volume, momentum, radiometric methods...</td>
<td>yield classification by spectral aerial imaging</td>
<td></td>
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</table>

Table 1: Relevant parameters and principles for sensing in precision farming
2 Principles for the determination of heterogeneity

In soil we find spatial variations of texture and composition, which may change due to temperature, rain fall, biological and human activity, etc. Structural and compositional variability depend on the property considered. For the variation of nutrient levels in soil (content of nitrate-nitrogen, phosphorous and potassium) semivariance lengths in the range of 20 to 40 m have been observed [1]. Lengths between 10 m and more than 100 m have been reported in other studies [e.g. 2, 3]. The decision of the farmer to use the more costly machinery for precision farming will depend on the economic returns he will get. The profit may result from saving chemicals, seeds, energy or increased yield in comparison to traditional cultivation. The degree of heterogeneity is a decisive question in this connection.

There are different methods to determine the degree of heterogeneity. Combine harvesters with GPS yield mapping units are the simplest possibility to get the heterogeneity of a field. They are commercially available for cereal harvesters now, and needed in site-specific farming in any case. Forage harvesters with yield mapping will be commercial available soon, principles and prototypes were tested and published [e.g. 4, 5]. The biomass distribution at a field can be measured by simply mechanical equipment (pendulum or forced displacement) during regular drives (e.g. plant protection) at fields [6]. An additional and remote possibility to get first information on the heterogeneity of fields is the evaluation of aerial images. Image processing can be made on base of grey level (Fig.1), or more effective, aiming at biomass distribution by using vegetation index and multi-spectral images.

![Fig.1 Aerial grey level image of a heterogeneous field](image)

3. Principles of nutrient sensing technologies

There are several ways for nutrient sensing. The best possibility would be a complete concentration analysis of the plant available nutrient ions in the soil water. Since the ion concentration of the soil water is connected with soil structure and type of soil minerals, sensing of minerals could be a source for information on nutrient content. Unfortunately, the
most important nutrient nitrogen is supplied by deposition and soil organic sources only. The concentration of the other nutrients does not depend on the soil minerals directly, since several factors like pH or humic acids are involved. Only in case of potassium, gamma radiometry has been applied for remote sensing [8].

The chemical composition of plants is partially influenced by the nutrient content of the soil. Therefore, the analysis of plants might be used for getting of information on the nutrient content of the soil as well. Variations in the composition of plants indicate shortages in the availability of nutrients. In terms of quantity and cost, the important fertilisers in practice are nitrogen, potassium, and phosphorus. Magnesium and calcium (usually as lime) are widely applied too, because they are nutrients and support the soil fertility especially due to pH regulation. Nitrogen is not contained in minerals and its concentration in the soil depends on biological activity and on organic matter content. Therefore, the determination of organic matter content in the soil is a useful way in nutrient sensing.

Sensors for the measurement of ion concentration are commercially available already. Two principles are used, the diffusion controlled measurements (ion-selective electrodes and solid-state electrochemical sensors), and the chemical reaction controlled measurements (chemical reaction with colour evaluation or chemical surface reaction with change of measurable physical quantity like refraction index, charge at the gate of an FET, etc.). Usually, the measurement of ions is a time and money consuming process and requires contact sensing, a procedure difficult to realise in agricultural practice. But Adsett and Zoerb [9] have designed a prototype of a soil sampling and extracting equipment for automatic field monitoring of soil nitrate levels using a flow cell with a built in nitrate-selective electrode. Their results show that this technology gives acceptable accuracy, reproducibility and response times (in the order of few seconds). Difficulties occurred in the operation of the extraction unit and the calibration process. The durability of the mechanical unit for soil uptake is an open question too. Therefore, they recommend to use this type of equipment by specialised contractors only. On the other hand, one possible solution for on-the-go sensing of soil nutrients has been presented and could accelerate further research and development in this field.

![Graph](https://example.com/graph.png)

**Fig. 2** Correlation between red edge inflection point and chlorophyll content of bean leaves (*Phaseolus vulgaris*) [after 12]
An indirect method for nitrogen sensing has been developed by Reusch and Heege [10, 11]. They used the idea that the colour of plants and the density of chlorophyll pigments depends on the nutrient availability in the soil. Since usually nitrogen is the limiting factor for the development of crops, the spectral evaluation of the plants on the field will respond to the nitrogen status of the soil. The chlorophyll density influence the inflection point in the red/infrared edge of the spectra of plants ([12, 13]; Fig. 2). Whereas the spectral remission of plants is difficult to measure (intensity and colour of illumination), the inflection point can be discriminated easier. The spectral signature of a plant results from the superposition of the absorption of different pigments within cells and absorption due to the surface of plants and corresponding cell structures. Therefore, there is no unique calibration curve for crops, but for each plant and stage of development calibration is necessary (Fig. 3).

![Graph showing red edge inflection point of rye plants in dependence on nitrogen fertilizing](image)

Fig. 3 Red edge inflection point of rye plants in dependence on nitrogen fertilizing [after 10]

True sensors for elementary analysis of plants and minerals are not known. Multi-elemental analysis methods are based upon spectral measurements of emission, absorption or fluorescence of excited atoms. The excitation may be produced by heating or by electromagnetic energy. Laboratory methods like Atomic Absorption Spectroscopy (AAS), Atomic Emission Spectroscopy (AES), or X-ray Fluorescence Analysis (XFS or AFS) are well known. The best potential for a sensor design has the old-fashioned spark spectrometry, which uses the characteristic spectral lines of atoms emitted from plasma discharge at atmospheric pressure. Higher accuracy and sensitivity are possible, when for the plasma generation a pulsed high power laser is used [14]. Since the laser applications are getting cheaper more and more, a sensor based on laser plasma emission or on laser plasma absorption may be the way for the on-the-go analysis of plants and soil in a more far future.

The organic matter content can be measured by thermal and chemical methods (combustion of dry soil and change in mass or CO₂-gravimetry). The best scientific method might be the C13-Magnetic Resonance, since one will get the concentrations of the components of the soil organic matter [15]. These methods are not suitable for sensor development. There are two other principles - CO₂-analysis and NIR-reflectometry. The CO₂-concentration of the soil air correlates with biological activity, which itself depends on organic matter too. Sensors would
be contact based, but the correlation between humus content and CO₂-concentration is limited due to several factors like soil texture, temperature, weather influence etc., which of course strongly limits the use of this type of sensors. The colour and NIR-absorptance (or reflectance) of the soil are influenced by the organic matter content. Therefore, optical methods have been used for the development of sensors for organic matter content determination [e.g. 16-20].

The difficulty in applying optical methods for soil sensing is caused by partial interrelation of soil properties influencing the reflectance like soil texture, surface roughness, composition of minerals, content of moisture or organic matter. To overcome this situation, the best way would be sensing of all properties by independent sensors. Additionally, reflection gives information about the reflecting surface with a depth of few microns only. Since the concentration profile of the organic matter content up to a depth of around 30 cm is of interest, the distribution function must be known or an equipment for three-dimensional on-the-go soil sample collecting must be used. The practical tests by the authors [16-20] have shown that a calibration according to the different type of soils to be controlled gives sufficient accuracy in soil sensing. Shonk et al [17] used a one-line sensor (LED at 660 nm) whereas Sudduth et al [18-20] found the best approximation by evaluation of 12 points (multi-spectral filter with a bandwidth of 55 nm) between 1700 and 2420 nm. In this spectral range we find excitation of electron and lattice vibrations leading to typical continuous solid state absorption. Groups of atoms like the radicals CH, NH, HO, or HS, which are components of organic matter, produce harmonic vibrations between 800 nm and 2500 nm, thus broad absorption bands of nearly all organic compounds are measurable in the NIR range.

4. Principles for plant evaluation and weed identification

The spectral analysis of the colour of plants has a tradition of more than five decades. Optical methods are the way for remote sensing of plants, since detailed information can be get from spectral and spatial intensity distribution. Therefore, spectral imaging is favoured in the research now. The additional advantage is that hard- and software solutions are commercial available and can easily be adapted to agricultural engineering research tasks. Since image evaluation is not a low-cost technology, simpler solutions are looked for simultaneously.

Weed identification can be based on time thresholds (“all green is weed before spring up“ or “all non-green is weed at time of blossoming“). Geometrical thresholds (outside of rows, plant density distribution] can be comparatively easy realised for on-the-go sensors [e.g. 21, 22] or used in grey-level imaging. There are reports on successful identification of weeds by means of spectral reflectance [e.g. 23-26] and evaluation of morphological properties [e.g. 27-29] under laboratory conditions, but it seems to be a long way to reach the power of humans eye and brain.

The state of plants may be sensed by spatially low resolved spectral measurements. As an example for the wide scope of this research the paper of Amon et al [30] may be quoted. They studied corn, barley, and wheat in the range 400-2000 nm with a receiver at 10 m above the plants and an evaluation site of about 6 m². A clear influence of the soil and plant management on the ratio of reflectance IR / VIS (800 nm / 670 nm) has been found.

High resolving techniques are necessary for plant recognition or plant identification. The digital image processing has a short history of around two decades. Meanwhile, hundreds of papers were published dealing with imaging in agriculture and life science. One way is the application of commercial video equipment with software for data reduction and evaluation.
The other way is the search for optimal wavelengths at first, to get maximum contrast for the special plant or effect looked for, then an adequate optical equipment for taking images must be chosen, and, finally the search for time- and cost-effective hard- and software follows. There are different principles and procedures in image processing. For weed identification textures analysis by two-dimensional FT-processing and fractal ratio analysis [29] seems to be promising. Broad and daily increasing experience is available now, but the present costs and the actual power of commercial image processing systems do not correspond to the real needs and practical conditions in plant protection so far.

5. Principles of soil moisture sensing

The field methods for fast soil moisture determination may be subdivided into contact and non-contact methods. There are many principles and studies concerning moisture determination. Reviews to this field have been given several times (e.g. 31-33). The measurement of conductivity, dielectricity, or heat conductivity is carried out by contact methods usually. The measurement of resistance or current (conductivity) gives principally incorrect results, since the concentration and mobility of ions and not the concentration of water molecules is measured. The change in capacitance is not determined by the moisture content alone but depends essentially on the density, anisotropy, and inhomogeneity of the dielectric. Thus, shape and structure of the specimen must be standardised. For on-the-go sensing, the measurement of the heat capacity or heat conductivity is less suitable because of long response times. The accuracy and reproducibility of other electromagnetic contact methods like time domain reflectometry (measurement of the wave velocity) or microwave moisture sensing (attenuation of electromagnetic energy at wave guides, strip lines, cables, etc.) is not satisfactory for field measurements (34, 35).

Out of the non-contact methods, the Proton-NMR has the best potential, because the concentration of water molecules is measured directly and sensing of water profiles up to a depth of about 15 cm is possible. Mass and costs prevent NMR to be a practicable sensor. The evaluation of the soil surface colour (VIS reflectance) and temperature (IR thermometry) gives insufficient results. The best way could soil radar of 3-10 cm wavelength in combination with an IR reflectance ratio meter for water absorption (Fig. 4; e.g. water bands at 1.9 µm or 1.4 µm in relation to regions with no absorption by water molecules), since IR gives information

Fig. 4 Infrared absorption of free movable water molecules
of surface moisture and with a top soil radar system a more detailed information on the distribution of the moisture in the top soil could be gained.

6. Conclusions

1. Sensors are needed in site-specific crop production for the control of those properties of soil and plants, which are spatially variable, essential for economy and environment, and which cannot be recognised by the farmer during field-work immediately.

2. The sensing of soil nutrient content by ion-selective electrodes has the advantage of direct concentration measurements, but is connected with the disadvantage of the more complicated and less reliable contact principle. By means of spectral reflectance analysis in the red and near infrared range the nitrogen status of plants and the organic matter content in soil may be estimated. Further practical experience must be collected to show the usefulness of these developments.

3. Sensors for plant recognition and plant evaluation are based upon spectral evaluation in the VIS and NIR range and image processing. Machine vision gives promising results, but is expensive and sensitive in field work still. Multi-spectral methods with low spatial resolution could be cost-effective alternatives in the development of sensors for the evaluation of crops.

4. Although there are many principles and methods for soil moisture determination, no solution has become the standard in on-line monitoring at field-work. The combination of microwave and infrared reflectance might have the best potential for remote soil moisture sensing.

7 References


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