Chapter 2.3

Precision Farming – Adaptation of Land Use Management to Small Scale Heterogeneity

U. Schmidhalter, F.-X. Maidl, H. Heuwinkel, M. Demmel,
H. Auernhammer, P. Noack and M. Rothmund

2.3.1 Basics and objective

Site-specific farming can contribute in many ways to long-term sustainability of agriculture production, confirming the intuitive idea that precision agriculture should reduce environmental loadings by applying inputs such as fertilisers only where they are needed, when they are needed (Bongiovanni and Lowenberg-Deboer, 2004), and in site-specific amounts. Site-specific crop management aims at optimising agriculture production by managing both the crop and the soil with an eye towards the different conditions found in each field.

Site-specific management requires detailed information about the heterogeneity of fields to adapt soil cultivation, seeding, fertilising, and fungicide and herbicide application to the locally varying conditions. Previously

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existing soil and plant information seldom matches the requirements either with respect to the intensity of the required information or with respect to the quality of the derived maps to delineate management units. Conventional methods are too costly and time-consuming. Preferably fast, non-contacting and non-destructive methods should be available to obtain the required information. Management recommendations corresponding to within-field site-specific characteristics are rarely available (Robert, 2001). Implementing the knowledge gained in sound management practices is clearly lagging. In this respect some differences between the two land-use systems studied by the FAM project (integrated farming and organic farming) have to be emphasised: Organic farming generally lacks the potential for a short-term on-the-go reaction especially with respect to fertiliser application. Further on, in organic farming, nitrogen, the key nutrient for agricultural production, will mainly enter crop rotation via the symbiotic legume-rhizobium N_2 fixation, i.e. a biological process that already strongly interacts with site-specific conditions as well as organic manure, that delivers plant-available N also strongly in accordance with site-specific conditions.

The spatial and temporal variability of soil water and nitrogen supply capabilities, as well as the spatial and temporal changes in plant nitrogen uptake on the field and farm levels, require different (fertiliser) management strategies to obtain economically and ecologically reasonable yields. This report focuses on recent developments to characterise the spatial and temporal variability of soil water, soil nitrogen, plant nitrogen uptake, biomass development, and yield more efficiently, with the aim to optimise inputs relative to the site-specific yield potential. In the integrated farm, site-specific crop management approaches have been designed and tested to optimise agricultural production, while for the organic farm appropriate management options are still investigated.

2.3.2 Development of methods to characterise spatial variability of soils, crops, and yield

Soils and crops are not uniform but vary according to the spatial location. To get information on their spatial variability and their local distribution, soil, crop, and yield parameters have to be measured on as many locations in the field as possible. These locations have to be defined by position information.

To get such geo-referenced information all over the field, traditional sampling strategies would require a large amount of time and labour in the field as well as in the lab. Therefore, the development and availability of continuously and on-the-go measurement systems and accurate and reliable positioning systems as well as electronic communication systems are prerequisites to detect small-scale heterogeneity.

Technical development – Prerequisites for precision farming

Developments of electronic devices and information technique in all industrial and private sectors made these technologies also available for agriculture. Some applications could be integrated in the FAM project and other related projects of the Technical University of Munich with little modifications, e.g. receiver for the global satellite navigation systems. Others needed and some still need a lot of effort for development and evaluation such as sensor systems for soil and crop parameters.

Geo-referencing and communication

Although radio navigation systems are available since World War II, reliable, affordable, and easy-to-operate position detection and navigation render possible not until global satellite navigation systems were operable.

With the increasing number of sensor and actuator systems, the electronic communication on agricultural machines became very important (Auernhammer, 1997). Although starting with point-to-point connections, the need for bus system-based communication system increased with the complexity of the systems. Therefore, development and standardisation of an agricultural bus system started very early and reached the level of International Standardisation Organisation ISO (Ehrl, 2005).

Positioning systems for agricultural use. At the end of the 80s different positioning systems have been evaluated for the use in agriculture, especially with yield sensor systems and for tractor guidance. Most of them were based on the radio navigation principle with either active or passive beacons (Searcy et al., 1989). The accuracy was sufficient for the investigated applications, but the necessary ground-based infrastructure made a widespread use in agriculture impossible.

With the development and operability of the Global Positions System – Navigation System by Time and Range (GPS-NAVSTAR) of the USA and the Global Navigation Satellite System (GLONASS) of Russia – satellite positioning and navigation systems covering the whole world without any individual user-owned infrastructure became available not only for military use but also for civil use.

Both systems work on the same principles (Figure 1).

The system is based on three segments. The space segment consists of more than 24 satellites on six orbital planes at an altitude of 20 183 km. These satellites are continuously sending messages that identify the satellite vehicle (sv). It provides the positioning, timing and ranging data, satellite status, and orbit parameters to the user. The master control station, monitor, and uploading stations (control segment) control the space segment. The user segment consists of all equipment that receives and tracks the satellite signals. Time synchronisation with the satellite clocks enables the GPS receivers to calculate the distances between satellite and

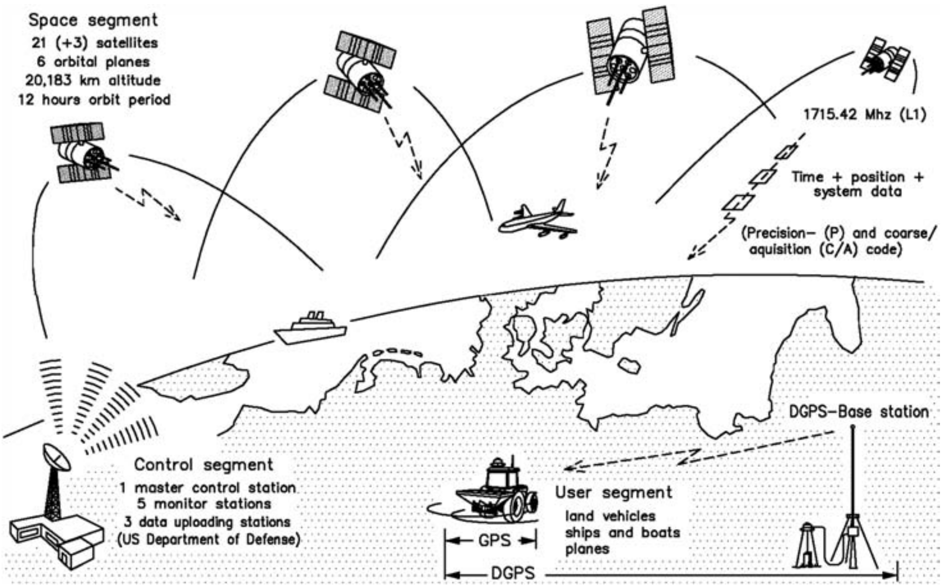

Figure 1 Principle of the global satellite navigation systems GPS NAVSTAR. AQ14

receiver by run-time measurement. Based on these 'pseudo ranges' to more than three (or more than two for two-dimensional) satellites and the information on the positions of the satellites, the receiver can calculate the position of the receiver antenna. The GPS NAVSTAR provides accuracies of absolute position detection within ±10–15 m.

For higher accuracy a differential global positioning system is needed. DGPS additionally uses a base station (or a network of base stations) that calculates the errors of the run-time and pseudo-range measurement by comparing the calculated position with the real position of the antenna. With this correction information, normally transferred via radio link, the positioning accuracy of the mobile receivers can be reduced to ± 2–5 cm depending on the used DGPS principle (see the section 'Accuracy of GPS and DGPS').

Accuracy of GPS and DGPS

Beginning with the first application of GPS in agriculture in 1990 (Auernhammer et al., 1991), the first integration in local yield detection systems on combine harvesters in 1991 (Auernhammer et al., 1993), the availability of pseudo range correction DGPS in 1992 (Auernhammer et al., 1994), the declaration of full operational capability (FOC) on 17th June 1995 and the switching off of selective availability (SA) for civil users on 2nd May 2000, a lot of investigations have been made to define the accuracy of GPS and DGPS for different applications and configurations.

On one hand, technical developments and system developments increased the accuracy of GPS and DGPS equipment continuously. On the other hand, investigations of the positioning accuracy became more and more difficult with increasing system accuracies, especially in dynamic applications like on agricultural vehicles and machines (Steinmayr et al., 2000; Stempfhuber, 2001; Ehrl et al., 2003).

Summarising the published investigations of different GPS and DGPS configurations following positioning accuracy can be determined (Table 1).

From Table 1 it can be concluded that at present GPS and DGPS technology offers all ranges of accuracies to fulfil the requirement of most agricultural applications. The investment for the systems increases with increasing accuracy.

Communication systems for agricultural equipment

Sophisticated farming, especially precision farming, integrates a variety of computerised equipment and tools. Until now most of these mechatronic systems are based on specific controllers with integrated man–machine interfaces and point-to-point connections to the actuators on the machines. These circumstances often result in tractor cabins filled with a high number of controllers for different machines, which lead to a confusion of the tractor driver, increase the operating errors, and decrease the acceptance of electronic control systems (Ehrl et al., 2003).

To overcome these problems, compatible electronic communication systems are needed like in other fields of application (e.g. industry automation). For that purpose BUS Systems for mobile applications have been developed and first introduced to automotive applications. But also for agricultural electronics two communication standards have been developed, both using controller area network (CAN) (Auernhammer, 2002).

– German ‘Landwirtschaftliches BUS-System’ (LBS), codified as DIN 9684/2–5, is based on the 11-bit identifier of CAN V2.0A. It connects a maximum of 16 controllers, including the terminal; data transfer

Table 1 General positioning accuracy of different GPS and DGPS configurations.

GPS or DGPS configuration	Absolute positioning error range (m)	Pass-to-pass error range[a] (m)
Standard GPS, single frequency	$<\pm 10$	$<\pm 5$
DGPS, pseudo range correction	$<\pm 3$	$<\pm 1$
DGPS, 2-frequency, code smoothing	$<\pm 0.5$	$<\pm 0.1$
RTK DGPS, real-time kinematik	$<\pm 0.05$	$<\pm 0.02$

[a] Pass-to-pass error = error between two points within a short time (<15 min).

speed is 125 kB s^{-1}. It was only used by a small number of German agricultural equipment manufacturers and is not further supported.

- ISO 11783 standard works with the extended identifier of CAN V2.0B, 256 kb s^{-1} data transfer speed, and is able to connect a maximum of 32 controllers. Its detailed structure using the ISO/OSI layer model and 13 parts of special definitions tries to cover all requests of agricultural tractor–implement combinations. Most agricultural equipment manufacturers support the standard and integrate it in their electronic development (Figure 2).

Machine guidance

A fast-spreading application of precision farming technologies to optimise the production process are navigation systems based on the satellite navigation system GPS NAVSTAR. A wide range of configurations from guidance up to automatic steering are available. The basic principles of the different systems are identical. With the satellite positioning system, the positions of a first trace in the field are stored and parallel tracks in a distance defined by the machine user are calculated.

Using guidance systems a display shows the driver the new/next reference track or the deviation from the new/next reference track and the driver tries to follow with his vehicle (tractor, combine, sprayer) as exactly as possible along this virtual line.

Automatic steering systems on agricultural machines use an additional solenoid steering valve or a small electric servo drive at the steering wheel to navigate the vehicle along the reference line.

The accuracy of the satellite-based guidance and steering systems depends on the used GPS systems and DGPS correction principles and services. The accuracy of guidance systems is also influenced by the skill of the driver to steer the vehicle along the displayed track.

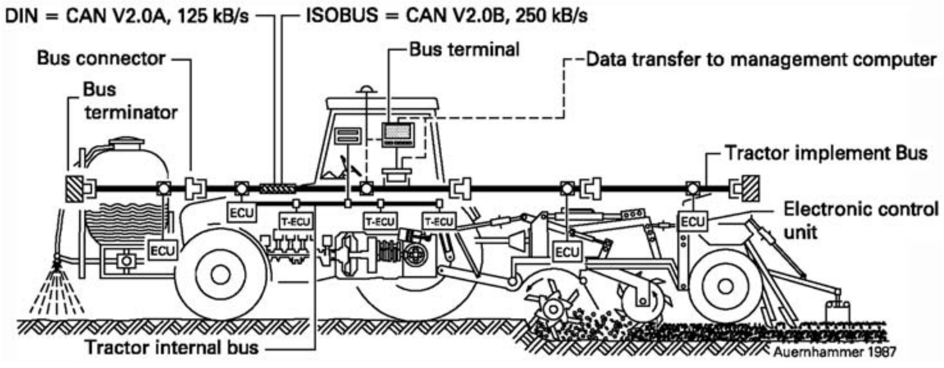

Figure 2 Communication between tractor and implement using ISO 11783 (Auernhammer, 1997).

With the correction services exempt of charges like BEACON or WAAS/EGNOS, normally a pass-to-pass accuracy (within a time period of 15 min) between 10 and 50 cm can be reached. An accuracy between 5 and 10 cm can be reached using chargeable satellite-based correction services. To reach this accuracy, additional sensors to compensate rolling and tilting and their integration in the navigation controller are necessary.

The highest accuracy with errors between 1 and 5 cm can only be reached using real-time kinematik differential DGPS (RTK DGPS) with separate base stations within a distance <25 km and the integration of rolling, tilting, and jawing sensors. This level of accuracy is only used with automatic steering systems. The prices of the systems increase with their accuracy and with the level of automation (Demmel, 2002).

Manual operated guidance systems can be favourably used for the application of fertilisers and herbicides, especially if there are no tramlines available. Gaps and overlapping can be prevented. Especially in corn these systems avoid the counting of rows during turning at the headland. List prices (in 2006) vary between 2000 € and 6000 €.

Depending on the chosen (bought) accuracy, automatic steering systems are used for tillage, seedbed preparation, seeding, planting, and cultivation. Harvesting machines such as combine harvesters or self-propelled mowers can also be controlled. Overlapping, which occurs especially with large working width, can be minimised. Time for turning can be reduced driving every second pass first and filling the gaps later. Workload relieving and increase in performance of drivers especially at long-lasting workdays and under bad conditions (dust, fog, darkness) are enormous. Automatic steering systems cost between 10 000 € and 45 000 € and can create correction service fees up to 2000 € per year.

Soil Sensors

Site-specific management requires detailed information about the locally varying soil conditions. The lack of high spatial resolution topsoil data is a serious limitation to the establishment of site-specific soil and crop management. Simple methods to detect important soil properties would facilitate the development of optimised management strategies. In some countries, previously existing soil information from conventional soil coring may be available. However, such data seldom match the requirements either with respect to the intensity of the soil sampling or with respect to the quality of the derived maps to delineate management units. Additionally, conventional methods are too costly and time-consuming. Preferably fast, non-destructive and non-contacting methods should be available to obtain the required information.

Soil properties such as clay, organic matter, or plant-available water capacity are important factors of soil fertility. Classical methods to determine such parameters are lengthy, space consuming, and laborious. More rapid and inexpensive methods would be valuable in obtaining such information. With the recent advancement in non-destructive proximal or remote-sensing techniques, this goal of characterising field-site characteristics using high spatial resolution soil data seems to be within reach.

Non-destructive principles to sense soil properties – Mapping soils by apparent electrical conductivity measurements

Electromagnetic induction represents a fast non-contacting method to get information about field heterogeneity of soil texture and soil water content. Measurements of the apparent electrical conductivity represent the influence of several factors, including soil texture and organic matter content, soil salinity, soil water content, and soil bulk density. Whereas the influence of salinity plays normally a minor role under temperate conditions, information about clay content (de Jong et al., 1979) and water content (Kachanoski et al., 1988) can be derived. See also Sommer et al. (2007), this issue.

Determination of soil texture and soil carbon content by NIRS

Owing to the rapid progress in data processing during the last decade, the use of near-infrared reflectance spectroscopy in chemical, biological, and agricultural sciences has been enhanced. Near-infrared reflectance spectroscopy has already been demonstrated as an accurate method to obtain valuable information on soil texture and organic matter (Stenberg et al., 1995; Ben-Dor and Banin, 1995). Studies of soils encompassing very different origins and composition are rare and are addressed in this work.

Mapping soil surface properties by aerial reflectance measurements

The spatial variability of topsoil texture and organic matter across fields can be studied using field spectroscopy and airborne hyper spectral imagery with the aim of improving soil-mapping procedures. Organic matter and clay content are correlated with spectral properties. Topsoil reflectance (330–2500 nm) can be measured in the field using airborne sensors such as the HyMap sensor for recording hyper spectral images (420–2480 nm, 128 channels) of bare soil fields. Using partial least square regression (PLSR) allows developing and calibrating models that establish a quantitative relationship between the spectra and soil parameters.

Mapping available soil water by aerial thermography or proximal reflectance measurements

Many applications in fields such as hydrology, meteorology, and agriculture require mapping of soil moisture, since the amount and status of water in soils impact crop growth. This requires reliable techniques to perform accurate soil water content measurements with minimal soil disturbance.

Crop growth depends on soil attributes. It should be feasible to use the crop stand condition as a bio-indicator of soil productivity. Biomass is one of the important parameters to differentiate crop stand conditions. For regions with negative water balance during the growing season, the site-specific availability of soil water is the main limiting soil resource. Biomass production and transpiration/evapotranspiration are related to each other linearly under water-deficit conditions (Schmidhalter and Oertli, 1991; Funk and Maidl, 1997). **AQ1** From this general relationship, it can be concluded that biomass production is related to the available soil water, particularly under water-deficit conditions (Selige and Schmidhalter, 2001; Brunner, 1998). Furthermore, because differences in evapotranspiration can be reflected by different canopy temperatures of crop stands, a feed-forward soil–crop response mechanism would allow the plant-available water capacity to be inferred from the surface temperature of sensitive crops such as winter wheat during specific, so-called 'bio-indicative', crop development stages. Thus, surface temperatures recorded by remotely sensed thermography could allow the pattern of plant-available water in fields to be detected (Selige and Schmidhalter, 2001).

Biomass sensors

Remote sensing has a great potential for characterising the effect of stresses on plants. Understanding the factors that influence the reflectance signal will greatly enhance the quality of the data and the potential for detecting stresses (Major et al., 2003).

Previous research has shown that spectral measurements can indirectly describe biomass, nitrogen concentration, and nitrogen uptake. In the past mostly hand-held spectrometers were used for this purpose. Reflectance measurements have been widely used in order to estimate the N status of plants. Leaf reflectance in the visible region is driven primarily by chlorophyll absorption, in the near-infrared region by leaf structure and in the short-wave infrared by water absorption. Primarily, leaf reflectance and absorption of light, the amount of leaves and the reflectance of the soil surface, or other background determine canopy reflectance.

Usually, biomass yield and nutrient status of canopies are assessed manually by cutting biomass, followed by laboratory analysis. Nevertheless, these methods are time-consuming, labour-intensive, costly, and of limited value for numerous examinations required within heterogeneous fields. Thus, different tools and sensors have been developed to replace manual biomass determination. These devices are used in direct contact with leaves or in the close-up range of plants and are applicable on agricultural fields.

The terms biomass yield and nutrient status of canopies are characterised by different parameters and need definition. A crop is composed of above-ground (leaves, blades, stems, ears, flowers, etc.) and sub-surface (roots, sprouts, etc.) material. The general aim of biomass sensors is the detection of above-ground biomass yield. In this context, fresh matter yield is defined as biomass per unit ground area, and is composed of dry matter yield and water content. Analogous, dry matter yield is defined as dry matter per unit ground area. Further parameters of a canopy with agronomic relevance are the concentration and content of photosynthetic active pigments (e.g. chlorophyll) or nutrients such as nitrogen. A concentration indicates the constituent per unit dry matter. In contrary, a content describes the constituent on an areal resolution (per unit soil or leaf area). When multiplying N concentration and dry matter yield, N uptake or N content is achieved, an areal parameter. Nevertheless, a comparable N uptake is achieved with different structured canopies: Either a high dry matter yield is in association with a low N concentration or a low dry matter yield is associated with a high N concentration. A further parameter of plant canopies is the leaf area index that indicates the leaf area per unit ground area.

Some sensors are only valuable in detecting specific parameters such as nutrient concentration (nitrate test; SPAD-Meter, Hydro-N-Tester), biomass yield (Pendulum-Meter), or leaf area index (LAI-2000 plant canopy analyzer). Other systems (reflectance sensors (YARA N-Sensor), laser sensors (MiniVeg N; Planto sensor)) generate measurement values that correlate to different parameters of plant growth.

Tools used in the FAM research project and other important techniques for detecting canopies are shown in this chapter. The devices can be divided into three groups: chemical, mechanical, and optical devices. A chemical test is the nitrate-N test. The so-called pendulum-meter is a mechanical device. Owing to their measurement principle, the optical sensors can be further divided into passive (N-Sensor) and active sensors (SPAD-Meter, N-Tester, MiniVeg N, Planto N-Sensor, YARA N-Sensor *ALS*). Passive sensors rely on a minimal level and quality of irradiance, whereas active sensors use their own light source.

Nitrate test

The nitrate test determines the nitrate-N concentration in the sap of growing plants. This parameter is an indicator of N supply from soil. A specific gripper (Figure 3) is used for pressing out the sap at the stem basis of plants. Generally, 30 stems are needed to derive an adequate amount of sap (Baumgärtel, 2001). After contacting the sap with specific test strips, a colour reaction appears, which is dependent on the value of nitrate-N concentration. The comparison with a colour chart leads to the definition of N fertiliser demand. If the actual values of nitrate-N concentration in the plant sap are lower than those necessary to achieve maximal yield,

Figure 3 Nitrate-N-test: gripper and test strip (by courtesy of Sächsische Landesan-stalt für Landwirtschaft, Leipzig, Germany). (For colour information, please see the colour plate section.)

a nitrogen topdressing is necessary. The method only indicates the actual value of nitrate-N concentration, thus the measurements have to be repeated within 10–14 days to define the starting point of N deficiency, i.e. the timing of N topdressing. Nevertheless, the method is characterised by some disadvantages. The nitrate-N concentration in the sap of plants is strongly dependent on the water supply. So the derived values of nitrate-N test show a great variation, even in the course of a day (MacKerron et al., 1995). A further limitation is that the measurements are not applicable for site-specific N fertilisation within heterogeneous fields.

Pendulum-Meter (Crop-Meter)

The pendular sensor (Pendulum-Meter, Crop-Meter) is a physical pendular, attached in the front of a tractor (Figure 6). The mechanical device is a passive method for deriving information of the plant biomass status. With forward motion of the tractor, the pendular is guided through the canopy in a defined height and moves in accordance with the resistance of the plants. Nevertheless, a correction procedure is necessary for varying depth of lanes as well as for unforeseen tractor movements. Then, the degree of deflection of the pendular depends mainly on the mass of the plants. In this context, the angle of deflection proved to be highly correlated to the biomass yield of the canopy (Ehlert et al., 2004b).

Some limitations of the pendular sensor are evident. The application of the device is impractical for small plants such as during the period of tillering of cereals. Thus, Ehlert et al. (2004b) used the Crop-Meter starting from the third nitrogen dressing in winter wheat, at EC 37. As only plant mass leads to a deflection of the pendular, no information about the nutrient status of the canopy is available.

Nevertheless, the readings can be derived independent of external weather conditions. The detection of biomass yield enables the use of the

Crop-Meter for a site-specific application of fungicides and growth regulators (Dammer et al., 2001; Ehlert et al., 2004a), where reduced amounts in areas with low plant mass seems promising.

SPAD-Meter (or N-Tester)

The hand-held devices SPAD-Meter (Figure 4) and N-Tester (Co. YARA) are identical in their construction and measurement principle. Both optical tools are active sensors for detecting chlorophyll concentration of leaves. An internal radiation source emits light and the transmission through a leaf is measured in the red (650 nm) as well as near-infrared (920 nm) spectral regions. For the measurements, a single leaf is fixed in a defined position between two arms and the light source is activated with manual pressing. With the SPAD-Meter, every single measurement value is seen. The N-Tester depends on measurements of at least 30 leaves for deriving results.

As chlorophyll concentration of leaves varies within the horizontal profile of a canopy as well as within the horizontal and vertical areas of a leaf, the youngest and fully developed leaves have to be measured and the detection must be performed in the middle of the leaf. The derived measurement values display a relative information of the chlorophyll concentration of leaves. This parameter is closely correlated to the N concentration (Ercoli et al., 1993; Bredemeier and Schmidhalter, 2001; Schächtl, 2004). Thus, the N concentration of leaves is gained in an indirect way. As an enhanced N supply leads to an increasing N concentration, the values of N-Tester measurements are in accordance with mineral N dressings (Table 2). So N-Tester measurements enable the definition of N demand of plants.

Figure 4 SPAD-Meter (by courtesy of YARA GmbH & Co. KG, Dülmen, Germany). (For colour information, please see the colour plate section.)

Table 2 N-Tester values dependent on the nitrogen supply of two winter wheat cultivars (EC 37, Schächtl, 2004).

	N amount (kg N ha^{-1})				
Cultivar	0	60	120	180	Ø
Flair	509	584	623	658	594
Orestis	427	502	525	604	514

The results are independent of external conditions. So time of day as well as the detection of wet leaves display no problem. But an important effect is due to different cultivars. Varieties often differ in chlorophyll concentration and greenness, even though their values of N concentration are comparable (Maidl et al., 2001). Table 2 gives an example of a cultivar with dark-green coloured leaves (Flair, high chlorophyll concentration) and with light-green coloured leaves (Orestis, low chlorophyll concentration). The N concentration of both cultivars was comparable and increased with the amount of mineral N fertiliser. Without considering the cultivar effects, measurements with the N-Tester would recommend a comparable N application for un-fertilised cv. Flair and cv. Orestis that already received 120 kg N ha^{-1}.

A problem of SPAD-Meter and N-Tester measurements is the impossible differentiation between the lack of sulphur or nitrogen, as a shortage of both nutrients leads to a reduction in chlorophyll concentration. Also, water deficiency as well as drought stress impairs the derived measurement values (Martinez and Guiamet, 2004). However, nutrient deficiencies other than nitrogen and water stress influence similarly all non-destructive passive and active nutrient sensors. Both hand-held devices are only suited for point measurements on single leaves. Thus, a high areal solution within a heterogeneous field is very time-consuming.

LAI-2000 plant canopy analyzer

The LAI-2000 plant canopy analyzer (Figure 5) enables a detection of leaf area index in the field without destroying plants. For the passive method, a minimal intensity of irradiance is essential. Light intensity is measured at the top as well as the bottom of the canopy. The reduction of radiation on the way through the canopy is proportional to the number of leaf layers and correlated to the leaf area index. Two different measurement techniques are available. When using one sensor, the measurements have to be performed in a defined sequential course at the top and the bottom of the canopy. With two sensors, a simultaneous detection of radiation at the top and the bottom of the canopy is enabled. Approximately eight measurements are needed for robust values. Especially for plants with a

Figure 5 LAI-2000 plant canopy analyzer (by courtesy of LI-COR Biosciences GmbH, Bad Homburg, Germany). (For colour information, please see the colour plate section.)

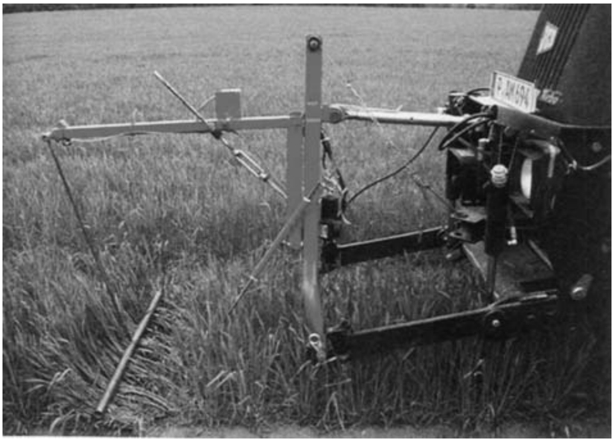

Figure 6 Crop-Meter (Ehlert, 2004; by courtesy of agrocom. GmbH & Co. Agrar-system KG, Bielefeld, Germany. (For colour information, please see the colour plate section.)

large row width such as maize, potatoes, and sugar beet, a systematic placement of the sensor is essential, between as well as within the rows (Figure 6). AQ2

The knowledge of leaf area index enables a derivation of biomass yield (Schächtl and Maidl, 2002; Figure 12). Nevertheless, the correlation between leaf area index and dry matter yield depends on the effect of canopy architecture with different cultivars.

The application of the LAI-2000 plant canopy analyzer is limited for defined external weather conditions. The readings are only valuable for situation with diffuse irradiance and no direct sunlight like in the early morning or late afternoon period or for cloudy conditions. Wet canopies should be avoided as raindrops on the lens lead to a refraction of light. The sensor is only suited to gain point information, thus the application is limited within heterogeneous fields.

Reflectance measurements

Reflectance spectra of canopies are detected with a spectrometer (Figure 7, hand-held device). The measurement method is an optical passive tool as direct sunlight or a minimal intensity of diffuse irradiance is required for deriving a reflection signature. In order to obtain the degree of reflection, the reflectance of the crops as well as the irradiance is gathered. Typical reflectance spectra of winter wheat canopies with different nitrogen supply are given in Figure 13. A characteristic feature for green plants is the trend in the visible (400–700 nm) and near-infrared (>700 nm) regions. Blxue (400–500 nm) and red (600–700 nm) wavelengths of the incoming light are highly absorbed by green plants, thus the reflection in these wavelengths is low. In these regions, plant pigments (carotinoids, chlorophylls) exhibit absorption maxima. The low absorption and therefore the higher degree of reflection at green wavelengths (500–600 nm)

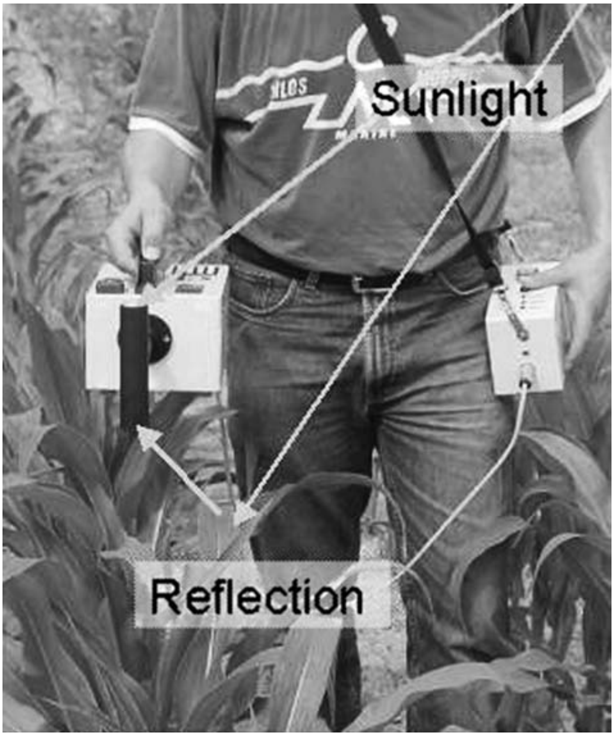

Figure 7 Hand-held spectrometer (by courtesy of tec5 AG, Oberursel, Germany).

lead to the typical green colour of the plants. In the near-infrared region (>700 nm), a steep rise in the reflectance spectra appears in the crossover between red and near-infrared wavelengths, leading to the so-called red-edge of reflectance spectra.

A varying N supply is associated with changes in reflectance signatures of plants (Figure 13), due to altered biomass yield as well as values of concentration of absorbing constituents. With increasing chlorophyll concentration, the intensity of absorption is reinforced in blue and red wavelengths, whereas the reflection is diminished. Furthermore, an enhanced amount of biomass leads to a higher intensity of reflection in the near-infrared spectral region. Accordingly, the local minimum in reflectance at about 670 nm is enlarged with increasing N supply, and the red-infrared edge of spectra shifts towards longer wavelengths (Liebler et al., 2001).

But numerous studies revealed the influence of diurnal variation of external effect such as weather conditions, cloudiness, and solar angle. As a result, the performance of a vegetation index is subjected to diurnal variation. A vegetation index, suitable for an application in plant production, should be sensitive to crop parameter and insensitive to environmental parameters. Sticksel et al. (2004) found that all vegetation indices varied significantly between morning, noon, and afternoon measurements (Table 3). RVI, IRG, and GR were more subjected to a diurnal effect than other indices. By far, REIP was least affected by a diurnal factor. N fertiliser treatment strongly affected all vegetation indices (Table 4).

In general, increasing amounts of applied N resulted in increasing index values. It is important to notice that REIP, IRG, and IRI differed significantly for all tested N amounts, while for NDVI, RVI, and GR, a saturation effect was observed at the highest level of biomass formation (Table 4).

Reflectance measurements are influenced by the external conditions. In contrast to handheld spectrometers, oblique oligo-view sensors such as

Table 3 Absolute and relative values (in brackets) of different vegetation indices as affected by time of day.

Time of day	Vegetation index					
	REIP	NDVI	RVI	IRG	IRI	GR
Morning	725.5 (99.9)	0.914 (98.4)	28.9 (92.6)	10.45 (96.3)	1.45 (100)	2.68 (97.1)
Noon	725.2 (99.9)	0.858 (92.4)	20.7 (66.3)	8.96 (83.3)	1.41 (97.2)	2.13 (77.2)
Afternoon	725.9 (100)	0.920 (100)	31.2 (100)	10.84 (100)	1.45 (100)	2.76 (100)

Table 4 Vegetation indices as affected by N fertiliser treatment.

N (kg ha^{-1})	Vegetation index					
	REIP	NDVI	RVI	IRG	IRI	GR
0	721.2 a	0.804 a	13.2 a	6.08 a	1.27 a	2.00 a
100	725.1 b	0.912 b	27.0 b	9.88 b	1.44 b	2.64 b
160	727.6 c	0.940 c	34.3 c	12.16 c	1.52 c	2.72 c
220	728.3 d	0.940 c	34.5 c	12.49 c	1.53 c	2.79 c

Values followed by different letters in a column are significantly different at $p < 0.05\%$.

the YARA N-Sensor allow for measurements being highly independent of daytime, azimuth angle, and cloudiness (Mistele et al., 2004).

Measurements, however, cannot be performed at very low zenith angles. Such limitations do not exist for the newly developed active principle implemented in the YARA N-Sensor *ALS*. This sensor has its own radiation source and measurements can also be conducted reliably at night.

Reflectance measurements are influenced by soil reflectance. Thus, at very early growth stages with a reduced ground cover measurements reflect a mixed signal between soil and plant. In contrast to reflectance measurements in the Nadir position, sensors with oblique oligo-view optics allow earlier measurements. Thus, reliable assessment of biomass and nitrogen content can be obtained as early as EC 28 in wheat and at the growth stage EC 14 in maize (Liebler, 2003; Schächtl, 2004; Mistele et al., 2004; Mistele, 2006). Structure and composition (leaves, stems, flowers, ears, awns, etc.) of a canopy may further influence reflectance measurements.

Calculation of vegetation indices allows reducing effects of influencing factors. These parameters are mathematical combinations of various wavelengths in different regions of the reflectance spectra. The vegetation indices show strong correlations to different parameters of biomass growth and nutrient status. An example is the vegetation index REIP ('red edge inflection point') that indicates the shifting point at the red-infrared of reflectance spectra. An increasing nitrogen supply of the canopy leads to a shift in REIP values towards longer wavelengths (Liebler, 2003; Figure 14). Nevertheless, sensor measurements have to be corrected for cultivar effects, mainly due to different canopy architecture. For cultivars with a planophile growth habit (e.g. cv. Pegassos), REIP values reach a saturation level at a lower biomass yield than when measuring varieties with a more erectophile growth habit (e.g. cv. Xanthos).

The principles of passive and active reflectance measurements are already available in a commercially available product, the 'N-Sensor' of the company YARA (Figure 8). The device is mounted on the roof of a tractor. Simultaneously, the canopy is scanned in four vertical directions at an

Figure 8 N-Sensor on tractor roof (by courtesy of YARA GmbH & Co. KG, Dülmen, Germany). (For colour information, please see the colour plate section.)

oblique view from the top of the tractor and an additional sensor detects the incoming irradiance in vertical direction. The N-Sensor is applicable for on-the-go measurements of nutrient status within heterogeneous fields. The plant information can be used to guide amount and distribution of nitrogen fertiliser dressings in an online-mode (Reusch, 1997; Link et al., 2002).

Fluorescence measurements

Another technique to monitor the nutritional status of plants by means of non-destructive and remote measurements is based on the fluorescence of plant pigments such as chlorophyll. The use of chlorophyll fluorescence in plant physiology studies in not new, since this method has been used for many years as a tool for photosynthesis research and for stress detection in plants. Laser-induced chlorophyll fluorescence is the optical emission from chlorophyll molecules that have excited to a higher energy level by the absorption of electromagnetic radiation. Changes in the chlorophyll concentration can be detected on the basis of changes in the plant's fluorescence spectra. FAM tested newly developed sensors to describe the nitrogen content and biomass of crop stands under field conditions.

The fluorescence sensor MiniVeg N (Figure 9, hand-held device; Figure 10, tractor-mounted sensor) is an active optical sensor using the measuring principle of laser-induced chlorophyll fluorescence. Core of the device is an internal laser diode (red light laser), inducing the chlorophyll molecules in plant cells to emit fluorescence light. The intensity of fluorescence light is detected with highly sensitive optical components at the wavelengths of 690 nm (red; F690) and 730 nm (near-infrared; F730) and the vegetation index ratio is calculated (F690/F730).

Figure 9 Hand-held fluorescence sensor (by courtesy of Fritzmeier Umwelttechnik GmbH & Co., Germany).

Figure 10 MiniVeg N (by courtesy of Fritzmeier Umwelttechnik GmbH & Co., Germany).

The emission of fluorescence light is due to the induction of chlorophyll molecules by laser light leading to an excessive level of energy. Nevertheless, other chlorophyll molecules may selectively re-absorb the emitted fluorescence light during the path through a leaf (Agati et al., 1993). Owing to the partial overlapping of absorption spectra and fluorescence spectra of chlorophyll at about 670 nm, the degree of re-absorption is maximised in the red region and of minor importance in near-infrared wavelengths. Thus, red fluorescence light is highly re-absorbed, whereas the radiation in the near-infrared region passes the leaves nearly uninfluenced. The degree of re-absorption depends on the chlorophyll concentration. At higher values of chlorophyll concentration, the re-absorption at 690 nm increases disproportionally. Thus, the intensity of detected chlorophyll fluorescence at 690 nm (F690) decreases with augmenting chlorophyll concentration, whereas in the range of 730 nm (F730) only small changes are detected. Therefore, the vegetation index ratio is negatively related to the chlorophyll concentration of plants (Sticksel et al., 2001; Figure 15). Owing to the strong correlation between chlorophyll concentration and N concentration (Ercoli et al., 1993), the ratio describes the N supply of plants.

Very recently, a fluorescence sensor is available as tractor-mounted device in the front of a tractor (Figure 10). The laser-induced chlorophyll fluorescence readings of canopies can be performed independent of external conditions, even during the night (Schmidhalter et al., 2004; Schächtl et al., 2005). As only chlorophyll molecules are induced to emit fluorescence light, no effects of soil reflection have to be considered. Thus, the application of the sensor is already practicable at the tillering of cereals, under conditions with low LAI ground cover of plants. Furthermore, a detection in row cultivars such as maize, potatoes, and sugar beet seems promising.

An alternative laser-induced chlorophyll fluorescence sensor is the tractor-based Planto N-Sensor (Figure 11). The principle is similar to the MiniVeg N-sensor. However, whereas the MiniVeg N-sensor measures in close contact with the plant canopy, the Planto N-Sensor is mounted on the roof of the tractor and measures at about 3 m distance from the plant canopy (Schmidhalter et al., 2004). The Planto N-Sensor has a scanning function that allows to scan the biomass independent of the detection of the chlorophyll content and augments the detected area. The unique system allows to determine independently biomass and chlorophyll density (Bredemeier and Schmidhalter, 2003, 2005). The scanned area, however, is considerably smaller for laser sensors as compared to that of reflectance-based sensors. Fluorescence measurements are influenced by temperature. An integrated temperature sensor, however, allows considering such an influence (Bredemeier and Schmidhalter, 2003; Schächtl et al., 2005). Although light intensity seems to have little influence on laser-induced chlorophyll measurements particularly under controlled conditions (Bredemeier and Schmidhalter, 2003), such an influence has to be considered, particularly at clear sunny days (Blesse and Schmidhalter, unpublished; Maidl and Limbrunner, unpublished) (Figures 12–15). AQ3

Figure 11 Laser-induced chlorophyll fluorescence sensor Planto N-Sensor (Planto GmbH, Leipzig, Germany, by courtesy of Technical University of Munich). (For colour information, please see the colour plate section.)

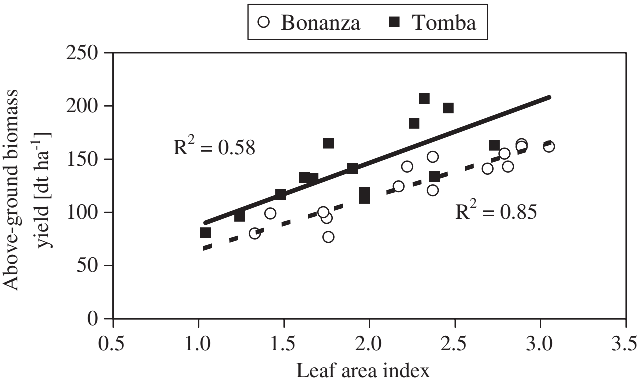

Figure 12 Correlation between leaf area index and above-ground dry matter yield for two potato cultivars (Schächtl and Maidl, 2002).

Yield measurement systems

To detect the yield of agricultural crops, measurement systems working directly on the harvesting equipment have been developed and evaluated. To realise local yield detection, continuously working measurement

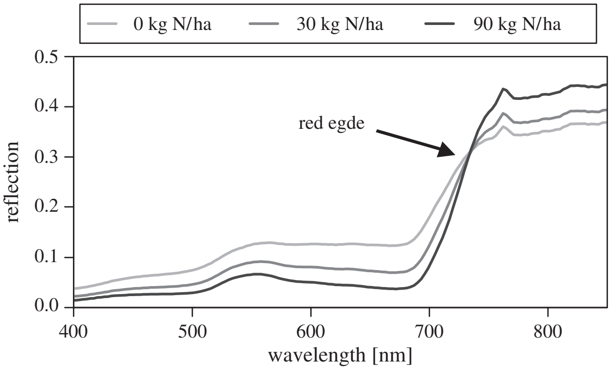

Figure 13 Reflectance spectra of wheat canopies (EC 32) with different N supply (Liebler et al., 2001).

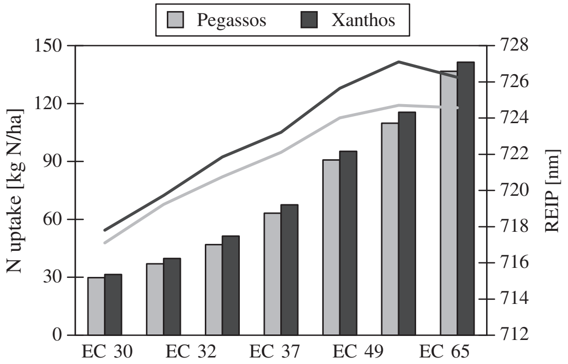

Figure 14 REIP (lines) und N uptake (bars) for two winter wheat cultivars during vegetation period (Liebler, 2003).

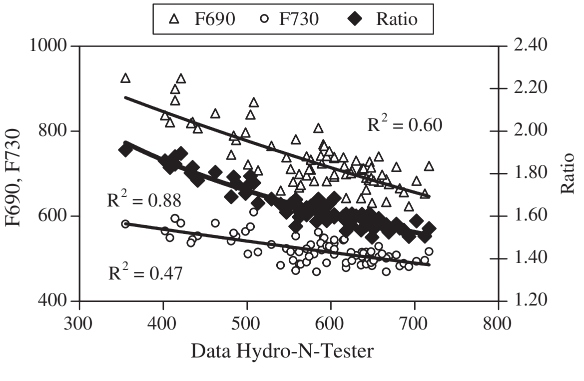

Figure 15 Correlation of F690 (triangles), F730 (circles), and ratio (squares) on chlorophyll concentration (Sticksel et al., 2001).

systems are necessary. Counter weighing of the total mass of crops harvested on a field can be used to calibrate and control the systems.

Components for most local yield measurement systems include (Figure 16):

- Mass flow sensor
- Sensor for working capacity (speed and working width)
- Position detection system (usually DGPS)
- Processing, monitoring, and data storing unit
- Data transfer to office computer

The mapping process of geo-referenced yield data is normally realised on the office computer with analysis and mapping software.

Yield detection for combinable crops

For yield measurement within the combine harvester, several meters, also referred to as yield sensors, have been developed and introduced into practical use. They work on the continuous flow principle and are installed in the upper part or on the head of the clean grain elevator. The available measuring systems are based upon two different measuring principles (Figure 17).

With the *volume measurement principle*, the corn flow is registered according to its volume via the specific weight (hl-weight or density) into mass flow. The volume is registered by determining the corn volumes on the elevator paddles.

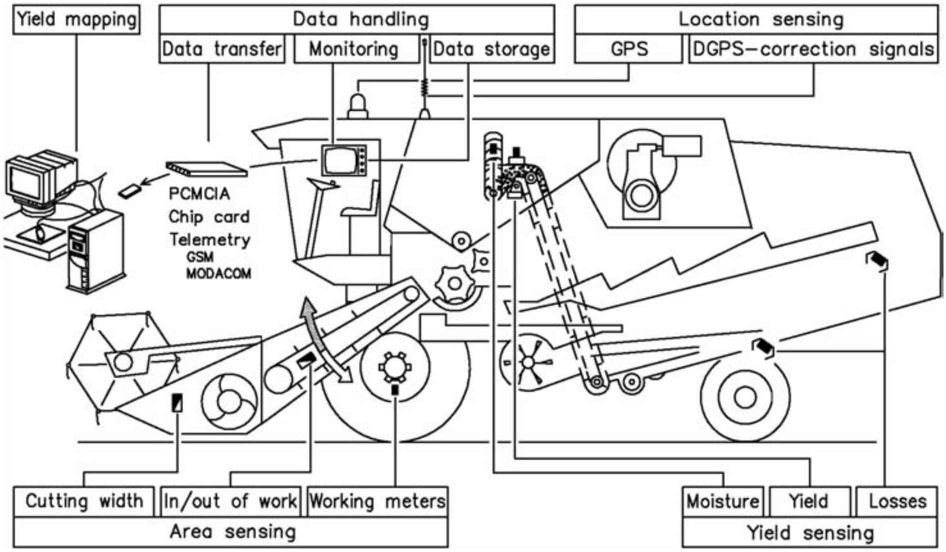

Figure 16 Components for local yield detection in a combine harvester.

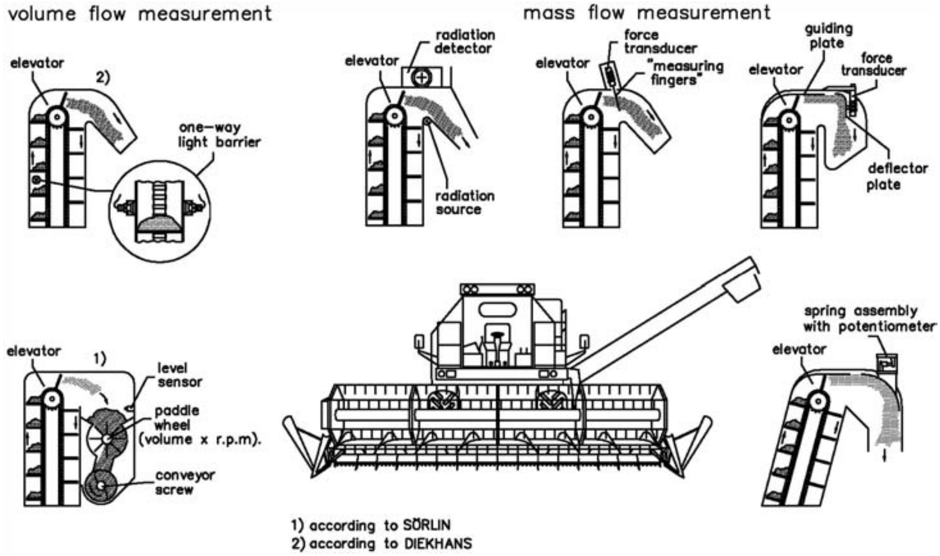

Figure 17 Yield measurement systems for combine harvesters.

Two systems on the market (Quantimeter of Claas and Ceres 2 of RDS) operate with a light barrier in the upper part of the feed-flow side of the grain elevator (left side of Figure 17). The corn conveyed by the elevator paddles interrupts the light beam. From the length of the dark phase and from calibration functions, the height and hence the volume of the corn charge on the paddles are calculated. The zero tare value is served by the darkening rate when the elevator is running empty. A tilt sensor is designed to compensate the influence of a non-uniform loading of the elevator paddles on a side slope. The hl-weight, which has to be determined with a beam balance, is used by the evaluation electronics to deduce the mass flow (t h^{-1}). As in all other measuring systems, this is converted into the area yield (t ha^{-1}) by being offset against harvested area produced from entered cutting width and measured threshing distance (wheel sensor). In addition, the harvested area is used to determine the area output (ha h^{-1}). Like with all other systems, the mass flow and the yield can be adjusted to standard moisture through the use of a continuously working moisture sensor.

In *determining the mass* of the corn flow, one relies on either the force/impetus measurement principle or the absorption of gamma rays by mass in a radiometric measuring system.

One measurement system on the market (Massey Ferguson Flowcontrol) operates according to the radiometric principle. The corn discharged from the elevator paddles passes through the region between a weakly radioactive source (Americium 241, activity 35 MBq) and a radiation sensor. As it does so, radiation is absorbed. The degree of absorption corresponds to the areal weight of the corn in the region of the measuring window. The material velocity, which is deduced from the elevator speed, is used to calculate mass flow. Today similar systems are also used in food processing.

A number of yield measurement systems developed in the USA use the force/impetus measurement and is likewise fitted on the elevator head in the discharge path of the corn. The sensor consists either of a baffle plate, which is fitted to a force-measuring cell (AgLeader, Case, Deutz-Fahr, picture top-right), or of a curved plate fitted to a spring element measuring the displacement way (John Deere), or of a curved plate mounted in patented geometry to a force measurement cell to compensate varying friction force (New Holland). Corn hitting the baffle plate or the curved plate causes a force effect to the bending bar, the spring element or the load cell, which is electrically sensed with strain gauges or the displacement sensor. Since this impetus is the product of mass and velocity, it is possible to calculate the mass flow. The material velocity is deduced, in turn, from the elevator velocity.

Besides the sensor element, all systems consist of processing, monitoring, and data storage units in the cab and have the possibility to integrate a moisture sensor. Most of the systems are factory-installed accessories; some products can be retrofitted to a selection of combine types (Demmel, 2001).

Yield detection for forage crops

Typical crop rotations in many regions of the world, especially in Western Europe, do not only consist of combinable crops. To get information on the variability of yields of different kinds of crops, yield measurement systems for other harvesting equipment than combine harvesters is necessary.

Since 1990, research on mass flow sensors for forage choppers have been reported. First results were published by Vansichen and De Baerdemaeker (1993). In 1995, Auernhammer et al. presented the results of a comparison of mass flow measurement systems based on the clearance between upper and lower feed rolls (volumetric), the power consumption of the cutter drum, the power consumption of the blower, and a radiometric measurement system (mass flow) in the spout (Figure 18).

As in yield measuring systems for combines, the mass flow is converted into the area yield (t ha^{-1}) by being offset against harvested area produced from entered cutting width and measured harvesting distance (wheel sensor). In addition, the harvested area is used to determine the area output (ha h^{-1}). Continuous yield sensor readings (often 1 Hz) are combined with information from the satellite positioning system for geo-referencing.

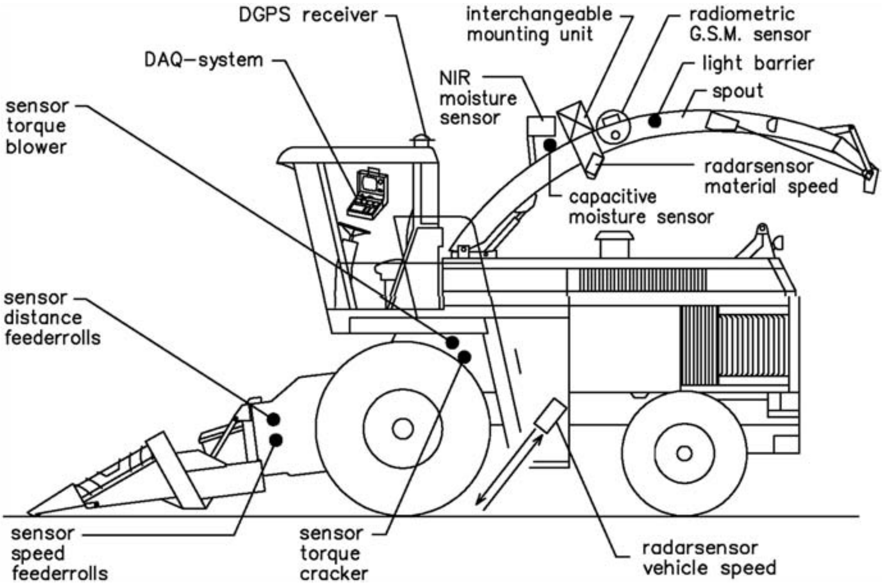

Figure 18 Possible sensor configuration for mass flow detection in a forage chopper.

As an alternative for mass flow detection in the forage chopper, Missotten et al. (1997) developed and evaluated the friction-compensated curved plate in the spout.

Since 2005, Claas and John Deere have been selling mass flow and yield detection systems based on the measurement of the displacement of the feeder rolls (volume flow system) as options for their self-propelled forage choppers.

Research and development on systems for local yield detection in round balers, square balers, and self-loading trailers did not result in products on the agricultural equipment market (Auernhammer and Rottmeier, 1990; Behme et al., 1997).

Since 2000, three research groups have published their work on the development of mass flow measurement technology for tractor-mounted grass mowers. The systems were based on belt weighing technique, force, and torque measurement. Until now, none of the developments is available on the market (Kumhala et al., 2001; Demmel et al., 2002; Wild et al., 2004).

Yield detection for root crops

To determine the geo-referenced yield of root crops such as potatoes and sugar beet, different measurement principles have been integrated into harvesting equipment, tested, and evaluated (Figure 19).

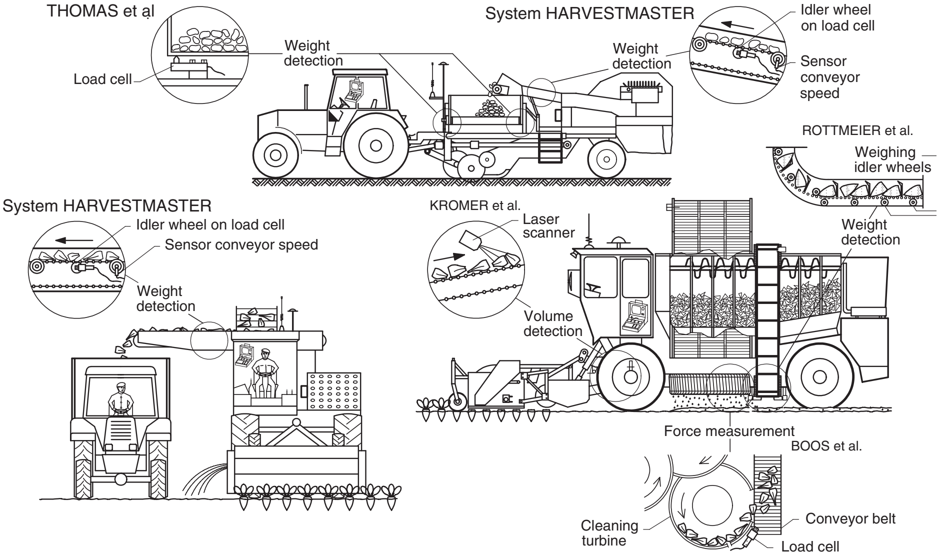

Figure 19 Sensor applications to determine mass flow and yield in root crop harvesting equipment.

A number of authors report that they have successfully developed and evaluated conveyor belt weighing systems combined with GPS positioning systems and data processing units (Campbell et al., 1994; Walter et al., 1996; Demmel and Auernhammer, 1999).

Godwin and Wheller (1997) used a trailer equipped with load cells to obtain yield data based on the mass accumulation rate.

Kromer and Degen (1998) tried to deduce sugar beet yield by estimating the volume of the beet using a laser scanner.

Hennes et al. (2002) adapted the friction-compensated curved plate principle to the conditions at a rotating cleaning turbine of a sugar beet harvester.

In the USA a number of potato custom harvesters are using the commercially available Harvestmaster HM-500 yield measurement system (conveyor weighing principle) to control the load of the transport trucks to avoid fines for overload.

Yield detection for other crops (not common to Western Europe)

Also for crops not common to Western Europe, continuously working mass flow and yield measurement systems able to deliver data for georeferenced yield detection and yield mapping have been developed.

In the USA and Australia, yield measurement systems for self-propelled cotton pickers and cotton strippers have been intensively developed and evaluated. The cotton flow is determined with optical or microwave sensors and the sensor readings are converted into mass flow by calibration algorithms (comparable to optical mass flow measurement systems in combines; Durrance et al., 1998; Searcy et al., 1989). First systems are available commercially (John Deere, AgLeader, Microtrac, Farmscan, AGRIplan).

Further sensor research and developments tried to make systems available to continuously detect mass flow and yield of sugar cane (Cox et al., 1998; Benjamin et al., 2001), peanuts (Perry et al., 1998), grape (Tisseyre et al., 2001), pea (Glancey et al., 1997), and tomato (Pelletier and Upadhyaya, 1998).

Accuracy of yield detection in harvesters

Combinable crops: Extensive studies on the measuring accuracy of the individual measuring systems were carried out in the years 1991–1995 (Demmel, 2001). They were supplemented by joint test bench trials of all four systems in 2000 and 2001 (Kormann et al., 1998; Demmel, 2001).

The level of accuracy in practical use was determined by counter weighing the grain tank loads on calibrated platform scales. The measuring systems were examined, in part, on different combine harvester models with different grain types in lightly to medium cropped land (Table 5).

The mean relative error represents the measure of the calibration quality. It should ideally measure zero, or at least close to zero. This requirement

Table 5 Errors of yield measuring systems for combine harvesters in practical use (Demmel, 2001).

Meter manufacturer	Period of study, total area, number of grain tank loads	Combine harvester models, grain types	Relative calibration errors (%)	Std. dev. of the relative error (%)
CERES 2 RDS	3 years, 140 ha, 179 tank loads	3 combine models, 4 grain types	−0.14	±3.43
FLOW CONTROL MASSEY FERGUSON	2 years, 140 ha, 132 tank loads	2 combine models, 2 grain types	−1.01	±4.07
YM 2000 AGLEADER LH565 LH AGRO	3 years, 130 ha, 182 tank loads	3 combine models, 4 grain types	−1.83	±4.06

Table 6 Errors of yield measuring systems for combine harvesters at different throughputs – 2000/2001 test bench studies, flat-standing position, 10, 15, 20, 25, and 30 t h^{-1} throughput, 5 repetitions/variant, $n = 25$/m, reference mass/variant 1 t, winter wheat (Demmel, 2001).

Meter manufacturer	Relative calibration error (%)	Std. dev. of the relative error (%)
CERES 2 RDS	−0.57	±5.50
FLOWCONTROL MASSEY FERGUSON	−1.64	±3.02
YM 2000 AGLEADER LH 565 LH AGRO	−1.71	±3.65
QUANTIMETER CLAAS	−2.71	±1.72
PRO SERIES 2000 RDS	−3.89	±5.54
GREENSTAR JOHN DEERE	−2.89	±2.81
FIELDSTAR (Force) DRONNINGBORG/AGCO	−0.22	±1.52

was successfully achieved by all meters. The standard deviation (s) is the measure of the measuring accuracy. It indicates the range of error within around two third of all measurements lie. Despite the different measuring principles, all measuring systems are characterised by approximately equal ranges of error between ±3.5 and ±4%.

In the test bench studies, the accuracy of the measuring systems was intended to be determined under identical, clearly defined conditions. Particular considerations were given to the effect of different throughput levels and of transverse and longitudinal tilts (Table 6).

When the measuring accuracy of the various yield measuring systems is checked in the test bench under flat conditions at different throughputs, mean calibration errors $<3\%$ are obtained. Only at lower throughputs (10 t h^{-1}) do occur larger deviations (3–10%). This indicates that the calibration curves plotted in the instruments are not yet optimally matched to low throughputs.

The standard deviations vary at the individual throughput levels between 0.5 and 3%, across all throughputs they varied between 2 and 6%.

Lateral and longitudinal tilts of the combine harvesters at constant throughputs (20 t h^{-1}) exert a very much greater influence upon the accuracy of the meters (Table 7).

The least reaction to tilt influences is exhibited by the radiometric measuring system. The two volumetric measuring systems are equipped, for compensation of this influence, with one or two axle tilt sensors. Nevertheless, the errors caused by lateral and longitudinal tilts cannot successfully be compensated under all conditions. In this regard, the force measuring systems occupy a middle position between radiometric and volumetric meters.

Table 7 Errors of yield measuring systems for combine harvesters at different tilts – 2000/2001 test bench studies, 20 throughput, 5, 10, and 13° of lateral tilt to the left and to the right and longitudinal tilt forward and back, as well as combinations thereof, 5 repetitions/variant, $n = 60/\text{m}$, reference mass/variant 1t, winter wheat (Demmel, 2001).

Meter manufacturer	Relative calibration error (%)	Std. dev. of the relative error (%)
CERES 2 RDS	−3.38	±8.07
FLOWCONTROL MASSEY FERGUSON	−1.11	±2.17
YM 2000 AGLEADER LH 565 LH AGRO	−0.24	±4.31
QUANTIMETER CLAAS	−0.91	±3.74
PRO SERIES 2000 RDS	−0.90	±11.73
GREENSTAR JOHN DEERE	−1.36	±3.37
FIELDSTAR (Force) DRONNINGBORG/AGCO	−0.02	±2.38

Table 8 Accuracy of mass flow and yield measurement systems for forage choppers.

Measurement principle	System placement	Author	Evaluation extent	Measured accuracy
Gamma ray absorption	Spout	Auernhammer et al. (1997)	24 field, 416 loads	Avg = −0.5%, SD = 3.3%
Friction compensated curved plate	Spout	Missotten et al. (1997)	1 field, 9 loads	Avg = +0.0%, SD = 2.7%
Force measurement	Blower wall	Barnett and Shinners (1998)	n.c.	Avg = n.c., SD. =<12%
Ultrasonic absorption	Spout	Barnett and Shinners (1998)	n.c.	Avg = n.c., SD. =n.c.
Feeder roll displacement	Feeding rolls	Ehlert (1999)	1 field, 41 loads	Avg = −1.0%, SD = 8.2%
Laser surface scanning	Spout	Schmittmann et al. (2000)	n.c.	n.c.

Forage

Based on a very high number of control weights of trailer loads during the evaluation of the gamma ray absorption-based measurement system for a self-propelled forage chopper, Auernhammer et al. (1997) reported on an accuracy (standard deviation of relative error) of ±3.3% after optimisation of the meter in 1993 and 1994. Table 8 contrasts the results of the evaluation of different measurement principles to detect mass flow and yield in forage choppers published by different authors.

Root crops

The compilation of publications about studies on the accuracy of measurement systems for root crops show that the majority of the authors have used the conveyor weighing system HM 500 from Harvestmaster (Table 9).

Although integrated in very different harvesting equipment, the error level seems to be similar. Demmel and Auernhammer (1999) tested this particular meter in a trailed one-row bunker hopper potato harvester and in a self-propelled six-row side loading sugar beet harvester. They reported on an accuracy (standard deviation of relative error) of 4.9 and 2.2%, respectively.

Research and development needs

Continuously working mass flow and yield measurement systems able to deliver data for yield mapping are available or in development for most harvesting technologies and machines. Nevertheless, this first generation of sensors and meters are in most cases retrofit solutions for existing machine systems. Therefore, a number of compromises have been made to integrate them. In many cases these compromises negatively influence the operability and in some cases they also reduce the measurement accuracy.

One aim for the future must be to optimise the application of mass flow and yield sensors by integrating them in new machine designs. Second, the accuracy has to be increased and stabilised, especially under worse and changing operating conditions. At least the operability must be facilitated, especially calibration effort and complexity.

Detection/determination of site-specific soil variability

Soil variability can be determined by soil sampling and analysis, which cannot be the chosen method for site-specific farming (see above). Here, non-destructive principles to sense soil properties are introduced. They can be separated into proximal and remote sensing, for both of them two methods are outlined.

Electromagnetic induction measurements to survey the spatial variability of soils

Measurements of the electromagnetic induction by EM38 were calibrated and validated on different levels, on the field level and on the farm level (Schmidhalter et al., 2001b; Schmidhalter, 2001; Heil and Schmidhalter, 2003; Sommer et al., 2007, this issue), and a survey was conducted within geographic regions of various origins.

Table 9 Accuracy of mass flow and yield measurement systems for potato and sugar beet harvesters.

Measurement principle	Harvester type, Crop	Author	Evaluation extent	Measured accuracy
Mass accumulation system 'Silsoe'	Trailer sugar beet, potatoes	Godwin and Wheeler (1997)	1 field, 15 loads	Avg = −1.1%, SD = 4.0%
Basket weighing system 'Tifton'	Trailed two-row basket combine, peanuts	Durance et al. (1998)	2 fields, 40 loads	Avg = +0.2%, SD = 3.1%
Conveyor weighing 'Harvestmaster'	Trailed two-row side loading, potatoes	Rawlins et al. (1995)	1 field, 48 loads	Avg = n.c., SD = 4.9%
Conveyor weighing 'Harvestmaster'	Trailed six-row side loading, sugar beet	Hall et al. (1997)	1 field, 99 loads	Avg = −1.0%, SD = 2.2%
Conveyor weighing 'Harvestmaster'	Trailed one-row bunker hopper, potatoes	Demmel et al. (1998)	2 fields, 77 loads	Avg = −1.3%, SD = 4.1%
Conveyor weighing 'Harvestmaster'	Self-propelled six-row side loading, sugar beet	Demmel et al. (1998)	2 fields, 39 loads	Avg = +1.0%, SD = 3.7%
Conveyor weighing 'Rottmeier'	Self-propelled six-row tanker, sugar beet	Demmel et al. (1998)	5 fields, 23 loads	Avg = 2.1%, SD = 5.6%
Force curved plate system 'Leuven'	Self-propelled tanker loader, sugar beet	Broos et al. (1998)	1 field, 19 loads	Avg = 0.4%, SD = 1.6%
Laser optical volume system 'Bonn'	Self-propelled cleaner loader, sugar beet	Kromer and Degen (1998)	2 fields, 15 loads	Avg = n.c., SD = 4.0%

Calibration was performed for individual soil horizons with detailed investigations of soil texture, soil water content, and the electrical conductivity of the soil solution. Clay content and water content in 0–90 cm soil depth were the parameters most closely related to the apparent electrical conductivity with R^2 values between 0.31 and 0.67 for clay and 0.31 and 0.64 for water content. Other soil parameters such as silt and sand content or the electrical conductivity of the soil solution were in general not related to the apparent electrical conductivity. Values of the electrical conductivity in the horizontal and vertical modes correlated with each other ($R^2 = 0.93$). The results point out that relevant information for site-specific management can be obtained by this non-contacting method.

A further segmentation of the data in different soil groups improved the relationships significantly to R^2 values higher than 0.67 for clay, silt, and sand (Heil and Schmidhalter, 2003). By this way, soil water content at field capacity could be determined with adjusted R^2 values higher than 0.89.

Principles developed within the FAM project were further introduced and adopted to the German-wide precision farming project Preagro where 2800 ha of arable land in largely different geographic and climatic zones were mapped by electromagnetic induction. Data of the apparent electrical conductivity (ECa) were compared to various other information sources (national soil inventory, yield maps, and spectral information from airborne remote sensing) (Neudecker et al., 2001). Multi-temporal measurements showed comparable patterns in ECa over time. Zones of different soil substrates could be better delineated by electromagnetic induction than by the previously existing information from the national soil inventory. The latter information was related to ECa with R^2 0.01–0.71. The closest relationship was found at the more heterogeneous sites. On heterogeneous field sites, good correlation to yield could be found with R^2 up to 0.71. ECa measurements represent a fast technique to map soil heterogeneity and are useful to delineate different management zones.

Determination of soil texture and organic matter content by near-infrared spectroscopy

Spectra (1000–2840 nm) of dried and sieved (2 mm) soil samples were obtained by using a FT-NIR equipped with a PbS detector (Vector 22N, Bruker, Ettlingen, Germany). Multivariate calibrations were developed with PLSR and cross-validated using OPUS 4.0 (Bruker, Ettlingen, Germany).

Results of the cross-validation confirm the potential of NIRS models to accurately predict clay, silt, and organic matter content in soil. The corresponding regression coefficients were 0.91, 0.91, and 0.9 with prediction errors (RMSECV) of 11, 15, and 12% (Wagner et al., 2001). These results are in line with a more recent investigation (Sorensen and Dalsgaard, 2005) and indicate the feasibility of near-infrared spectroscopy for rapid non-destructive prediction of soil properties.

Remote sensing – Spatial detection of topsoil properties using hyper spectral sensing

The spatial variability of topsoil texture and organic matter across fields was studied using field spectroscopy and airborne hyper spectral imagery with the aim of improving soil-mapping procedures (Selige et al., 2006). Organic matter and clay content were correlated with spectral properties. Topsoil reflectance (330–2500 nm) was measured in the field using a GER 3700 field spectrometer and a Lambertian Spectralon reference panel of known reflectivity. The airborne HyMap sensor was used at an early flight campaign in May for recording hyper spectral images (420–2480 nm, 128 channels) of bare soil fields. PLSR was applied to develop and calibrate a model that establishes a quantitative relationship between the spectra and soil parameters.

Organic matter and clay content could be determined simultaneously from a single spectral signature since organic carbon largely responds to wavebands in the visible range and clay responds to wavebands in the near-infrared region (Selige and Schmidhalter, 2001). Complexity and auto-correlation between the soil parameters led to the use of multivariate calibration techniques, particularly PLSR. PLSR estimates of the organic matter content and the clay content of topsoils indicated R^2 values of 0.82–0.92 with prediction error values (RMSECV) of 0.4% for organic matter and 4–6% for clay content. It is shown that the clay and organic matter content can be predicted quantitatively using hyper spectral sensing (Selige et al., 2006).

Characterising soils for plant-available water capacity and yield potential using airborne remote sensing

Multi-spectral airborne remote sensing was used to improve the inventory of soil heterogeneity at the field level. Ground measurements of crop parameters were collected from representative soil sites. Spectral information at visible, infrared, and thermal wavebands was recorded from the airborne scanner Daedalus AADS 1268 at 11 spectral channels (Selige and Schmidhalter, 2001). The spectral information was transformed into soil information using bio-indicative transfer functions, based on cause and effect relationships of the soil–plant system. Soil properties, plant development, and crop stand conditions were measured on the ground at representative soil sites. The available water storage capacity and the rootability were derived from soil texture and texture changes within the soil profile. Grain yield and biomass of each soil site were determined. Relationships between the investigated parameters were established.

The variability of the plant-available water storage capacity of the rooting zone accounted for 93% of the variability of winter wheat biomass at the development stage BBCH 77 (milk ripeness) when the leaves started to become yellow (Selige and Schmidhalter, 2001). The biomass at this development stage also indicated the pattern of the later harvested grain yield. The crop stand condition at this development stage accounted for 96% of the grain yield variability of winter wheat. This result also suggests that the crop stand condition can be used to forecast yield and its pattern across fields. The correlation between plant-available water capacity and grain yield underlines the importance of soil water availability. The thermal emission and its relationship to the transpiration of crops were recognised as most suitable to detect quantitatively soil properties via crop stand conditions of winter wheat.

Detection of spatial crop heterogeneity – Yield data processing and yield mapping

During the harvesting process, data from different sensors are permanently stored on a yield monitor. Apart from yield sensor and position information provided by GPS receivers, yield monitors also read data from moisture and speed sensors. Some yield monitoring systems also use tilt sensor information in order to correct for tilt-induced errors in yield sensor readings.

The information that is contained in the yield data files varies depending on the yield monitoring system. Almost all sensors provide information on position, time, and yield. Depending on the yield monitoring system, additional information on the quality of GPS, grain moisture content, ground speed, tilt, cutting width, header status, and swath number is stored in the yield data files.

Data stored in yield monitors have been pre-processed to a different extent depending on the yield monitoring system. The calculation of yield at a current position as described above is already a form of pre-processing. Results from investigations made with different yield monitoring systems installed on one combine harvester to measure the same grain flow indicate that the yield measurements from some systems have been filtered or averaged before storing (Steinmayr, 2002; Noack et al., 2003). The results suggest that rapid changes in yield grain flow cause different responses in the yield data.

However, on a load basis the absolute amounts of grain yield match very well when compared to the results obtained with scale weights (Auernhammer et al., 1993).

Yield data filtering

Yield data files logged with yield monitors contain erroneous measurements as the sensors are operating in harsh environments. Also, different factors such as unknown crop width entering the combine, the time the grain travels from the header to the sensor, and tilt of the combine affect the reliability of yield measurements. Errors occurring during the process of yield data collection have been very well described and classified by Blackmore and Marshall (1996).

The removal of potentially erroneous measurements from yield data files is a prerequisite for the creation of meaningful yield maps. Simplistic approaches use upper and lower threshold values to filter yield datasets. The threshold values are either fixed or based on the standard deviation of the dataset. Global threshold filtering does not account for the local variance of yield and its spatial distribution and may therefore fail to remove erroneous measurements or even remove reliable data.

Different authors have presented expert filters for filtering yield data files. Some of these filters rely on information that will not be available in all data file formats (Rands, 1995; Blackmore and Marshall, 1996; Beck et al., 2001; Taylor et al., 2000; Thylen et al., 2000; Steinmayr, 2002).

Noack et al. (2001) have developed a method that compares yield measurements in tracks with those in neighbouring tracks also taking into account the standard deviation of yield within the tracks. It tries to use both the temporal and the spatial relations between yield measurements. This method has been tested on datasets collected with three yield-mapping systems installed on one combine. By filtering with the H method (Noack et al., 2001) the comparability of the resulting yield maps from the different yield mapping systems was notably increased.

Yield map creation

A yield map is the visual representation of yield variation within a field. One form of yield maps shows the GPS positions where the yield data were ranged and printed as coloured posts (Figure 20, *right*). *Post maps* are simple to create, but they have several disadvantages when they are used as input for spatial analysis: Yield information is only available for discrete positions and is not related to neighbouring yield values. Post maps do not allow to distinguish areas with similar yield and to use these in order to classify a field into higher and lower yielding zones.

Grid yield maps (Figure 20, *left*) are composed of tiled rectangles. A yield value is assigned to each rectangle (grid cell) so that yield information is available for any position within the field boundaries.

Grid yield maps can be created with different methods, inverse distance interpolation and Kriging interpolation being commonly used for yield mapping.

For the estimation of grid cell values, several other parameters apart from the grid cell size (‘C’ in Figure 21, *right*) have to be specified. The search radius determines the maximum distance that a data point may have from the centre of the grid cell in order to be included in the estimation of the grid cell value (‘S’ in Figure 21, *right*). The weight determines the weighting of each single data point in the estimation of the grid cell value. Generally, the weighting is decreasing with increasing distance from the centre of the grid cell (‘D’ in Figure 21, *right*). The estimation of a grid cell value appreciates all data points within the search radius according to their weight.

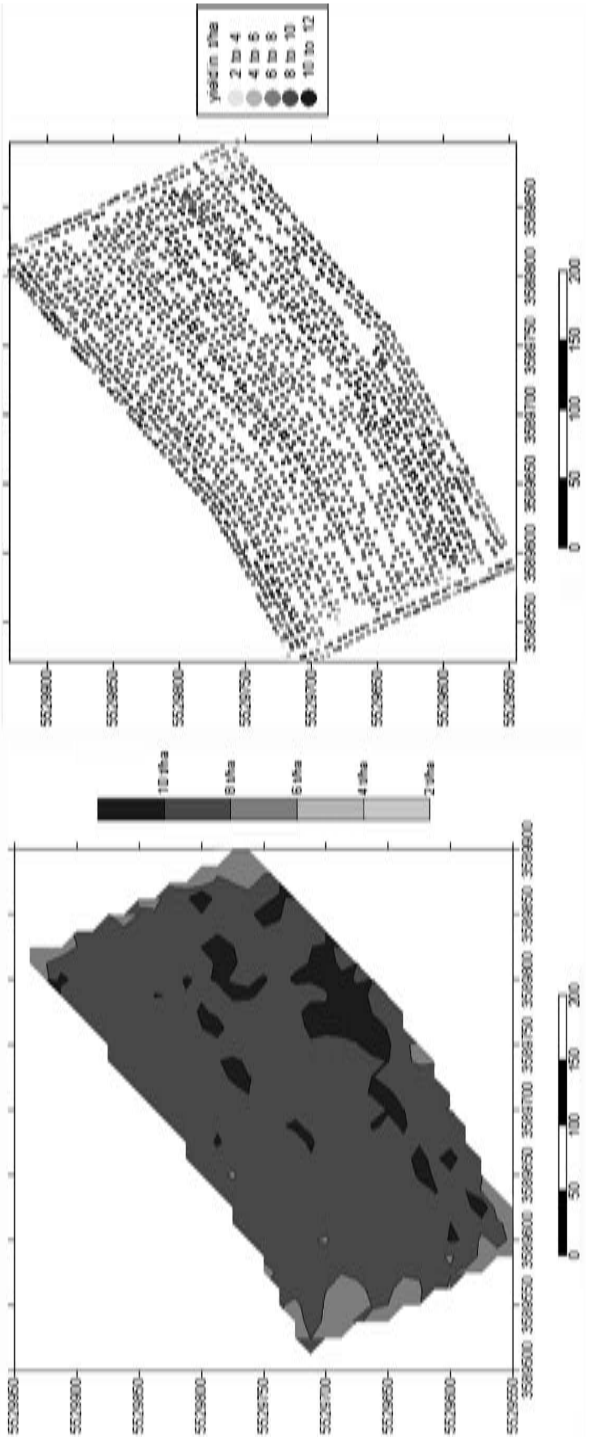

Figure 20 Different kinds of yield maps (*left:* grid yield map, *right:* post yield map).

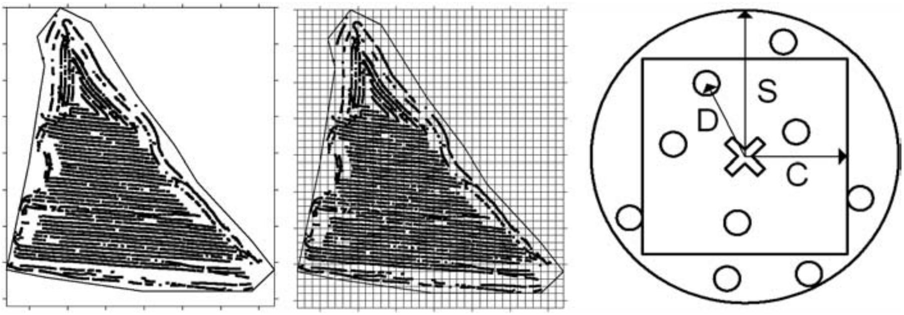

Figure 21 Steps during grid yield map generation (*left:* clipping, *middle:* grid creation, *right:* grid value calculation).

The inverse distance interpolation uses fixed values for the search radius and weight. The weight is expressed as the power of the inverse distance (e.g. weight 2 assigns the weight $1/D^2$ to each value).

The Kriging interpolation requires the calculation of a semivariogram before the interpolation itself. Semivariograms show how the variance of spatial data is related to the distance of data points. Semivariograms may be calculated either for the whole dataset (global semivariogram) or for a subset of data in the neighbourhood of the grid cell centre (local semivariogram). Fitting an appropriate model to the empirical curve is the most delicate step in Kriging interpolation: The model determines the search radius and the distance weighing for the grid cell value estimation.

The results of Kriging interpolation, especially Block Kriging (local semivariograms), are generally considered to be superior to the results from inverse distance interpolation. However, Kriging is very delicate due to its dependency on the choice of the curve model and can hardly be automated effectively. Minasny et al. (1999) have developed a very useful program for Kriging Interpolation of yield data.

Tractor-based non-destructive sensing of biomass and nitrogen status – Reflectance measurements

A tractor-based spectrometer was used to measure the reflectance in field-grown wheat and maize plants. The experimental design included different nitrogen applications (0, 90, 130, 170, and 210 kg N ha^{-1}). Individual plots were 15 m wide and 50–60 m long (Mistele, 2006). The spectrometer contained two units of Zeiss MMS1 silicon diode array with a spectral detection range from 400 to 1000 nm and a spectral resolution of 3.3 nm. One unit was linked with a diffuser and measured the sun radiation as a reference signal. Simultaneously the other unit measured the canopy reflectance with an oligo-view optic (Lammel et al., 2001). The spectrometer was connected with a four-in-one light fibre and the signal was optically averaged. The optical inputs were positioned with an azimuth angle of 80° between the front and rear side and 100° between the right and left side of the tractor. The zenith angle was set at 58 ± 6° to minimise the influence of the tractor (Reusch, 2003).

In front of the tractor the sensor system was mounted 1.90 m above the canopy. The field of view consisted of four ellipsoids with 1.23 m in length, together around 4.5 m^2. The reflectance was measured at five wavelengths, which were at 550, 670, 700, 740, and 780 nm. Various reflectance indices were calculated including the REIP, NDVI, IR/R, IR/G, and G/R.

Spectral indices were related to measurements on biomass and nitrogen content plants that were cut shortly after the spectral measurements. Small plots on both sides of the tractor were harvested, 1.5 m in width and around 8 m in length, matching exactly the measured area. A plot chopper equipped with a weighing unit was used for this purpose. A separate subsample was removed and dried after weighing to estimate the total dry matter. The dried samples were milled and analysed for total N content with an elemental analyser (Macro N, Varian).

The sensor was used to test the reliability of the 'YARA N-Sensor' to detect spatial differences in N status and biomass of crops in field experiments of 3-year duration. As judged against validations performed on harvested areas of 25 m^2, which varied in nitrogen supply, the results showed that strong correlations exist between reflectance indices and N uptake from the end of tillering to flowering ($R^2 = 0.90$) (Mistele et al., 2004; Mistele, 2006). Close relationships between spectral indices and biomass, nitrogen content, and particularly nitrogen uptake ($R^2 > 0.85$) were determined in four seasons from 2001 to 2004 for wheat (Schmidhalter et al., 2001a, 2003; Mistele et al., 2004). A good correlation between spectral indices and the final yield was observed as well. Reliable estimates could already be obtained at the 4-leaf stage of maize plants. Consistency in data normally requires that reflectance be measured only when the solar zenith angle provides sufficient irradiance, when sky conditions are uniform and bright, and when the sensor view angle is close to nadir (Major et al., 2003). The oligo-view optic tested outperformed existing techniques by enabling non-nadir measurements at solar zenith angles with reduced irradiance and non-uniform sky conditions. As such, the tractor-based passive sensor represents a fast and highly suitable means to measure the nitrogen status and biomass of wheat crops.

Laser-induced chlorophyll fluorescence measurements

The reliability of proximal remote-sensing measurements of the laser-induced chlorophyll fluorescence to determine chlorophyll and nitrogen content as well as biomass production in field-grown maize and wheat plants was determined with a newly developed sensor. A tractor-mounted fluorescence sensor developed by Planto GmbH company (Leipzig, Germany) was used that detects the fluorescence emitted at 690 and 730 nm. The sensor was mounted at the rear of the tractor at a height of around 3 m above the plant canopy. A laser beam stimulates the emission of fluorescence, which is detected at a distance of approximately 3.3 m between the canopy and the sensor. The canopy is scanned in a 0.5 m wide strip. Strips of approximately 15 m in length were measured and the total area sensed was around 6–7 m^2. The relationship between the ratio of laser-induced chlorophyll fluorescence intensities at 690 and 730 nm (F690/F730) and nitrogen supply in winter wheat was characterised (Bredemeier and Schmidhalter, 2005). The chlorophyll fluorescence ratio F690/F730 was then calculated. Destructive harvests for biomass and nitrogen content were done as described for the reflectance measurements by spatially matching sensor measurements and harvested area.

The fluorescence ratio F690/F730 and the biomass index were well correlated with shoot biomass and nitrogen uptake across different developmental stages. Similar relationships were found in wheat and maize. The fluorescence intensity at 690 and 730 nm increased as shoot biomass and SPAD values increased, while the ratio F690/F730 was inversely correlated with N uptake, shoot biomass, and SPAD values. The goodness of linear fits between nitrogen content, biomass, nitrogen uptake, and SPAD values to fluorescence ratio mean was as follows: 0.78, 0.87, 0.87, and 0.88 (Bredemeier and Schmidhalter, 2003). N fertilisation levels in the field could be differentiated by means of fluorescence ratio measurements. Shoot dry biomass could be determined by means of biomass index measurements independent of leaf chlorophyll content.

These results indicate that nitrogen uptake and biomass can be detected reliably through chlorophyll fluorescence measurements under field conditions (Bredemeier and Schmidhalter, 2005). In contrast to point data measurements, the establishment of scanning field fluorescence sensors opens new possibilities for N status and biomass measurements. Moreover, because the signal comes from green plant parts only, it has a very low background and is little affected by soil reflectance. Furthermore, the system allows the independent determination of biomass and chlorophyll density already at the seedling stage (Blesse and Schmidhalter, unpublished).

Nitrogen fixation of legumes and legume content of clover grass

Because N supply in organic farming mainly relies on symbiotic N_2 fixation, growth of the legumes is the Achilles' heel of this land use system. Therefore, a sufficient description of the reasons for variation in N_2 fixation does arouse much more interest than for the variation of crop yield in general. In organic farming, the main gateway for N to enter the crop rotation are legume–grass mixtures, because the N fixed by pulses is typically sold. Our research focused (i) on the development of a method to describe variation of N_2 fixation of legume–grass mixtures and (ii) to derive parameters that determine the observed variation in field. By combining data about the variation of N_2 fixation and the variation of the yield of non-legumes, options for site-specific farming in organic farming can be lined out.

Nitrogen fixation and therefore its variation are basically determined by two parameters: the N yield of the legumes and the proportion of N derived from atmosphere (N_{dfA}).

In general, N_2 fixation can be calculated as follows (Eq. (1)):

$$N_2 \text{ fixed } [\text{g/m}^2] = \text{total yield } [\text{g/m}^2] \times \text{leg } [\%] \times N_{\text{leg}} [\%] \times N_{\text{dfA}} [\%] \qquad (1)$$

where total yield is the dry matter produced by the whole stand during the investigated time frame (i.e. the sum of shoot, roots, nodules, litterfall, and rhizodeposition); leg, proportion of the legumes within the dry matter production of the whole stand; N_{leg}, concentration of N in the total dry matter of the legume; and N_{dfA}, proportion of N derived from atmosphere within the total amount of N taken up by the legume during the investigated time frame.

Although the equation looks very simple, lots of pitfalls appear if N_2 fixation has to be calculated. In general, data of the actual shoot yield can be determined. The determination of N in litterfall, stubble and root residues, and rhizodeposition is difficult because these data typically remain in secrecy. On the basis of published data, Høgh-Jensen et al. (2004) derived an empirical model to calculate total N_2 fixation only based on shoot yield data of grass–clover mixtures. All the other data necessary to calculate total N_2 fixation are estimated via ratios to the shoot data. The model requires only data about shoot dry matter yield of the mixture, the proportion of legumes in the mixture, the concentration of N in the shoot dry matter of the legume, and N_{dfA} in the shoot-N. But, even then the determination of N_2 fixation is still challenging.

Total yield of legume–grass mixtures is rarely measured and on-the-go measurement systems are not yet available on the market (see above). Further on, the determination of the proportion of legumes within mixtures with non-legumes is simply laborious, because reliable data are only gained by hand sorting. For pulses, which are regularly grown in pure stands, the seed yield is usually measured. But this is not a sufficient indicator for N_2 fixation, because the ratio between seed and straw yield strongly varies (Beck et al., 1991), and in pure stands of legumes N_{dfA} may vary considerably at short distances (Mahler et al., 1979; Stevenson et al., 1995; Walley et al., 2001). So far there is no simple method available to determine N_{dfA} in field. However, at generally N-limited conditions and if legumes are grown in mixtures with non-legumes they will regularly reach high N_{dfA} values ($>90\%$), because the non-legumes take up almost all plant-available soil N. Therefore, under such conditions the N yield of the legume will be closely correlated to their N_2 fixation (Boller, 1988;

Peoples et al., 1995). Such conditions were expected at the FAM research farm. Therefore, first of all, a method was needed to determine easily the proportion of legumes within a mixture.

During the past 20 years several papers have shown the potential of near-infrared reflectance spectroscopy (NIRS) to determine legume content in legume–grass mixtures. It is an easy-to-use technique, which can even be mounted onto harvesting machines (Dardenne and Féménias, 1999). However due to the dominant absorption of water within the spectral range of 0.9–2.5 μm, the determination of constituents other than water in fresh green plant samples is difficult. That is why determination of legume content in ground samples was so far tested with dried forage mixtures, binary (Petersen et al., 1987; Pitman et al., 1991; Shaffer et al., 1990; Wachendorf et al., 1999), and more complex mixtures of several legumes and grasses (Coleman et al., 1990; Pitman et al., 1991). However, there was still no study that showed the capability of NIRS in predicting legume content of multi-species legume–grass mixtures in widespread use in Western Europe, i.e. with white clover (*Trifolium repens* L.), red clover (*T. pratense* L.), and lucerne (*Medicago sativa* L.) as dominating legumes in varying proportions. Additionally, method development as published so far was mostly based on samples from well-defined plot experiments and the methods were not tested for their performance in real stands. But, an adequate validation is the most crucial aspect during the development of a NIRS method.

Therefore, three NIRS methods were developed based on samples taken from the fields of the FAM research farm (Locher et al., 2005a). Crucial aspects of calibrating a NIRS method (composition of the standards, measurement conditions, influence of the homogeneity in particle size within each sample, and the spectral range used for the estimation) were tested for their effect on precision and accuracy of the prediction of legume concentration in dried and ground mixtures. All of it proved to be of minor relevance presumably because of the overall diversity already inherent in the samples used for calibration. In contrast to the vegetation indices as introduced above, NIRS models that determine legume concentration require a broad range of the measured spectral information (in our case 75–90% of the recorded 1.0–2.86 μm range). However, comparing all six models only 70% of the selected spectral ranges were in common. Most likely this part of the spectral information describes the difference between the grasses and legumes in the samples (Figure 22). Reducing the models to this range slightly increased the standard error of prediction from less than 4% to less than 4.5% legume content (Locher et al., 2005a). Attempts to further restrict the spectral information failed, which is not surprising because the determination of complex parameters such as legume concentration will combine information about several constituents, which in principle are found in both grasses and legumes.

Finally, the applicability of the models to predict independent samples of legume–grass mixtures were broadly tested with samples from other

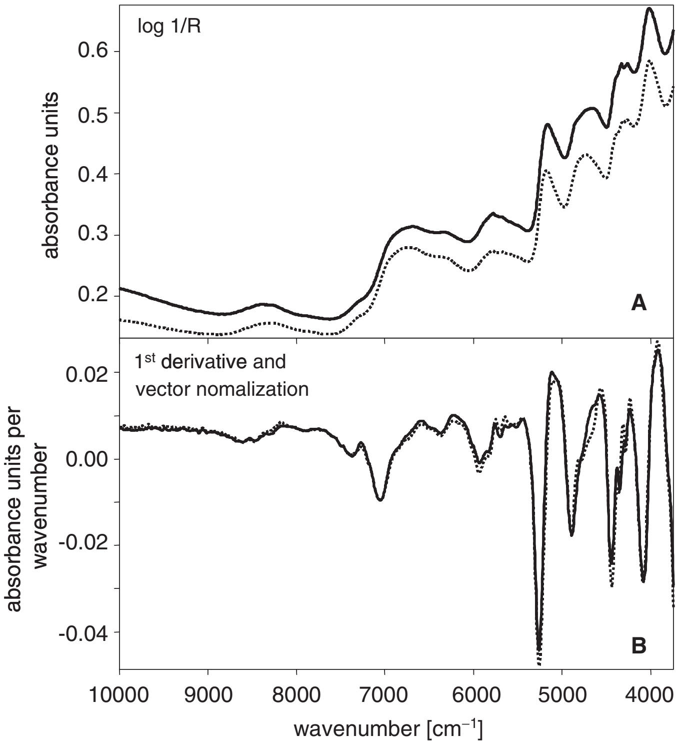

Figure 22 NIR spectra of a legume sample (solid line) and a grass sample (dotted line): original absorbance spectra (A), vector normalised first derivative spectra (B) (Locher et al., 2005a).

regions in Germany (Locher et al., 2005b) and at a small set of samples from Finland (Nykänen et al., 2005). With any of the test sets the calibrations proved to predict well legume content in dried ground mixtures. Instead of a strong linearity of the predicted to the real values (slope 0.93–1.09; $R^2 > 0.92$) standard error of prediction ranged between 3.3 and 12.5% legume concentration. Most of the errors were caused by a systematic bias of up to 10%, which was frequently observed but did not affect linearity. If estimates were bias corrected, the prediction error fell below 5% legume concentration, which is presumably well below any sampling error. It was concluded that without bias correction the NIRS values are already precise and can be compared within one field. For accurate values to compare fields or to calculate N_2 fixation, a bias correction is advised (Locher et al., 2005b).

The extensive validation done proved the capability of NIRS to precisely determine the proportion of legumes in dried legume–grass mixtures. However, the determination of legume content in fresh green plant samples remains an open task. A first test under lab conditions was promising, even by using the methods for dried samples a determination seemed to be possible (Locher, personal communication). However, for the purposes of precision farming a method is needed that already determines the proportion of legumes during harvesting. Nowadays several plot choppers use the NIRS technique (Dardenne and Féménias, 1999; Welle et al., 2003), but still analysis of data offers lots of pitfalls (Paul et al., 2002). The key problem is that the water status of the measured material strongly varies and therefore the spectral information representing water. If this problem can be solved it will be only a technical detail to install a NIRS system on a mower as used by Demmel et al. (2002) and Wild et al. (2004) (see above). Then on-the-go measurements of total yield of forages and several constituents will be possible.

At the FAM research station, the NIRS method was used to determine the in-field variability of legume proportion in multi-species legume grass, finally to determine the variation of N_2 fixation. As stated above, N_2 fixation of a legume–grass mixture is defined by four factors: dry matter yield of the mixture, the proportion of legumes therein, the N concentration of the legumes, and their fixing activity (N_{dfA}). Detailed investigations were carried out at the FAM research farm on different fields at different harvests and years (Locher, 2003). Results supported the expectation that only dry matter yield and the proportion of legume determined the variation of N_2 fixation of the investigated multi-species legume–grass. Measurements done in the fields confirmed earlier reports in the literature (Peoples et al., 1995; Weißbach, 1995; Boller, 1988; Lopotz, 1996) that N_{dfA} did not considerably vary under the conditions at the FAM research farm (Heuwinkel et al., unpublished). However, one should be aware that small increases in N availability may reduce N_{dfA} (Mallarino et al., 1990; Heuwinkel et al., 2005a). In field, variation of the N concentration of the legume dry matter was negligible, but not the variations between harvesting dates (Locher, 2003).

Strong in-field variation was observed for legume dry matter yield, which is the product of the total dry matter yield and legume concentration of the legume–grass mixture (Heuwinkel et al., 2005b). Additionally both parameters showed a strong seasonality, with the highest total dry matter yield at the first or second harvest. The proportion of legumes in the shoot dry matter yield steadily increased from moderate values in spring (30–70%) to high values in the following harvests (>70%) as shown for field A12 of the FAM research farm (Figure 23) (Locher, 2003; Heuwinkel et al., 2005b). Correlation analysis between total dry matter yield and proportion of legume done with the single data of all the 19 harvests revealed that both parameters were independent from each other in 15 of the 19 studied cases (Locher, 2003). It was concluded that in-field variation of N_2 fixation of legume–grass mixtures was determined by both the dry matter yield of the mixture and the proportion legumes therein (Heuwinkel et al., 2005b). This is visualised by one dataset of one harvest on field A09 of the FAM research station (Figure 24). Another striking

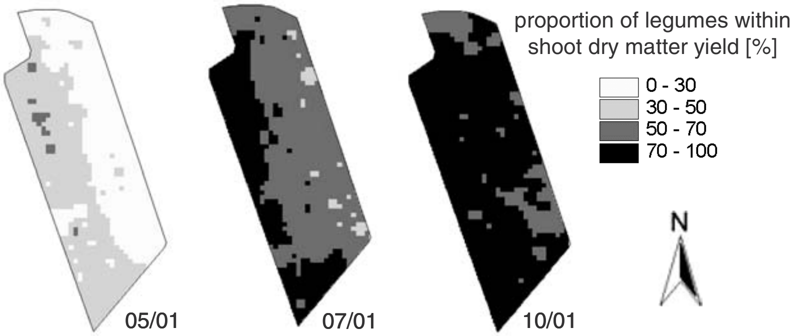

Figure 23 Variation of the proportion of legumes within the dry matter yield of a multi-species legume grass mixture grown at field A12 of the FAM research station. Data of all three harvests in May, July, and October 2001 are shown.

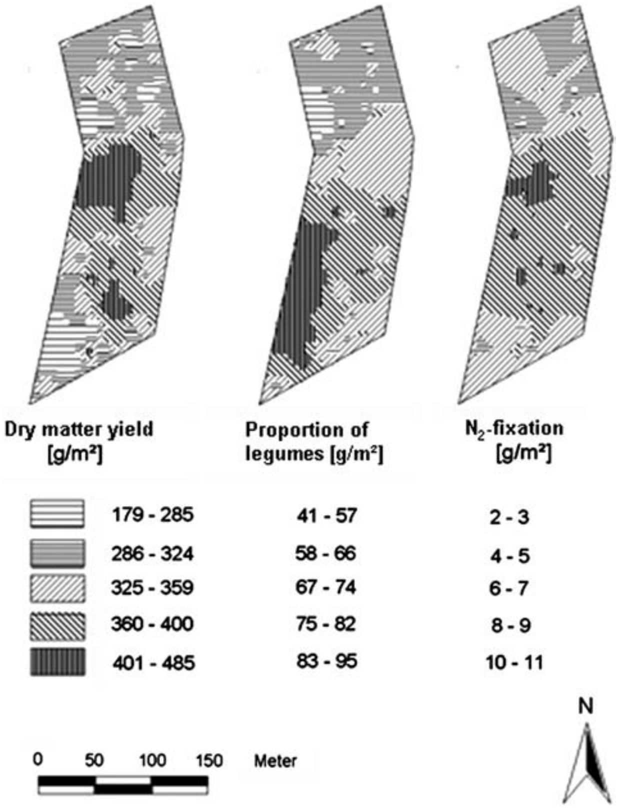

Figure 24 Variation of shoot dry matter yield, proportion of legumes, and N_2 fixation of the multi-species legume grass grown in field A09 of the FAM research station. Data are from the third harvest in 1999.

result is demonstrated by this figure: the strong variation of N_2 fixation within one field. Within all the 19 studied cases the coefficient of variation of shoot dry matter yield of the mixtures ranged from 14 to 55%, while this figure of the proportion of legumes ranges from 10 to 39%. The additive effect of both parameters on N_2 fixation resulted for 17 out of 19 datasets in a clearly higher coefficient of variation of this parameter (Locher, 2003).

2.3.3 Development of site-specific crop production strategies

As a consequence of the knowledge of the spatial variability of soils, crops and yield site-specific production strategies have to be developed and evaluated.

Principles of site-specific farming

Three major concepts based on mapping systems, on real-time sensor-actuator systems, and on a combination of both are known (Auernhammer and Schueller, 1999).

Map-based systems

Map-based systems are using satellite navigation systems such as GPS NAVSTAR (or other positioning systems) to establish a geographic basis for site-specific crop production (Figure 25).

Components of map-based systems include:

- Positioning systems to establish equipment location
- Sensors for yield detection and soil measurements
- Mapping software
- Controllers for map-based applications
- Actuators to perform the control

Map-based systems try to integrate information from different sources. Control maps have to be generated to execute field operations such as variable seeding, fertilisation, or pesticide application.

Real-time systems

Real-time systems use the actual information on a soil or plant parameter detected by a sensor system to deduce and take an appropriate action. They do not require positioning or mapping systems except for record of the action (‘as applied map’). An example is the application of nitrogen fertiliser based upon sensing chlorophyll intensity and biomass quantity of the crop (Figure 26).

Real-time systems with maps

These systems combine the capabilities of map-based and real-time systems. Maps of yields, soil types, and nutrients can be used with real-time

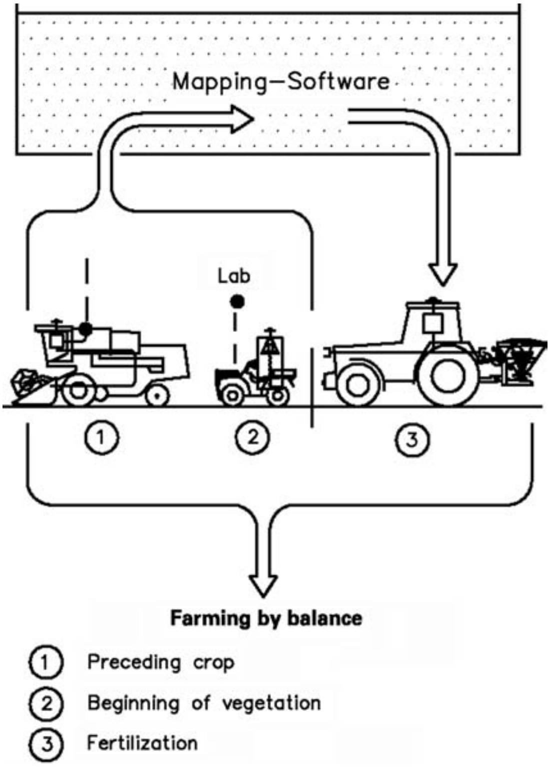

Figure 25 Components and structure for map-based systems (Auernhammer et al., 1999).

sensors of plant growth, soil moisture, and weed infestation to control field operations. Because such systems require all components listed previously, they are very complex. But they allow the optimisation of field operations, especially of fertiliser and pesticide application (Figure 27).

Problems coming up with real-time systems with maps come from the fact that more than one information source lead to a decision. Therefore, an information command structure or a sensor fusion model has to be applied to the system (Ostermeier et al., 2003).

Detection/determination of management zones – Causes of yield variability

Spatial variability of soil properties as a result of abiotic and biotic factors, as well as of considerable small-scale variations in topography and climate, has long been recognised. With the introduction of statistical analyses and global positioning systems, systematic recording and analysis of soil properties has become possible. The inherent high variability of

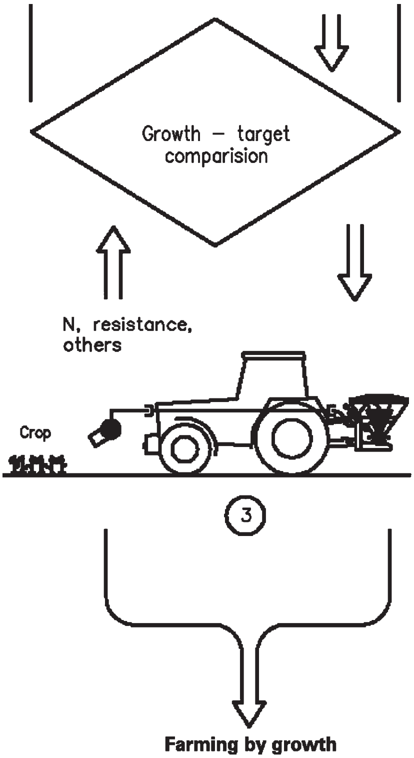

Figure 26 Components and structure for real-time systems (Auernhammer et al., 1999).

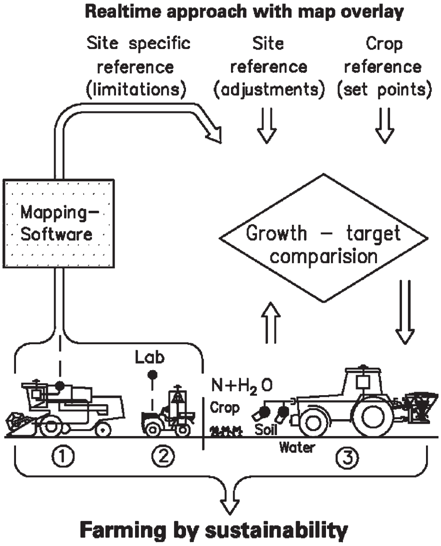

Figure 27 Components and structure for real-time systems with maps (Auernhammer et al., 1999).

inorganic and organic nitrogen in soils has been illustrated repeatedly (e.g. Van Meirvenne et al., 1990). As is the case for nitrogen, plant-available soil water varies frequently as a consequence of the variability of soil texture and is the norm rather than the exception in most fields. Precipitation variability is often no less important than that in soil, and its effect on the crop yield can often be even more considerable than that of spatial variability. In many areas of the world, available soil water and precipitation or irrigation amount and distribution are among the primary factors determining yields of crops.

To evaluate the interaction between plant-available soil water, precipitation (or irrigation), and nitrogen, fertilisation experiments were conducted over two consecutive years with winter wheat with two different N fertiliser treatments (180 and 120 N kg ha^{-1}) and three different water supply treatments (stress by rain sheltering, irrigation, and rain-fed only) on sites of different plant-available soil water.

Among the three factors (i.e. site, precipitation, and N fertilisation), site was the most important one influencing variability in grain yield, whereas precipitation, and in particular its distribution during the growing season, influenced the overall yield level in a given year. Increased N fertilisation generally increased yield, but its efficiency was low on lower yielding sites such as sandy soils if climatic conditions were unfavourable, thereby advocating reduced N fertilisation application on sites of lower plant-available soil water. This result also underscores the importance on such sites of sufficient water supply for efficient N use as already reported by others (Eck, 1988). For the maximum benefit, crop management should consider annual variability in yield in addition to soil conditions, and site-specific N fertilisation should be adapted to the actual plant growth.

At the FAM research farm the major sources of infield variability were soil depth and clay content, soil texture and shallowness, and soil texture and topography. Soil fertility levels except for nitrogen were adequate such that they were not yield limiting. Potassium and phosphorus removal by crops was regularly replaced. Soil physical and chemical properties of all sites were previously intensively characterised. This together with concomitant measurements of soil matrix potentials and previous more mechanistic investigations of the relationship between yield and varied water supply allow identifying water and nitrogen supplies as yield-limiting factors (Geesing et al., 2001).

In the organic farming the varied effect topography and N-mineralisation potential of the soil may have on different crops was investigated. Usually in hilly landscapes foothill positions are expected to be more fertile, i.e. their soil-N release will be higher. If legume–grass mixtures are grown in fields with a marked topography, one may expect changes in N_2 fixation as already shown for pulses (e.g. Stevenson et al., 1995). If legume–grass is frequently cut and removed, the amount of plant-available soil-N should decrease from harvest to harvest. In two of the four intensively investigated fields, the legume–grass strongly reflected this effect of N availability on species composition. At field A12 (Figure 23) foothill positions are along the east side of the field while the west represents hilltop positions. At each harvest the highest proportion of legumes was found in the west of the field and the lowest along its east border. Additionally, a strong increase over time was observed at any place in the field.

Field A09 (Figure 24) was taken for more detailed investigations. Because of a grassland history prior to the FAM study, its northern third had increased levels of organic matter (1.8% C as compared to 1.4% in the rest of the field), which can effect availability of soil-N. In this part of the field a much lower proportion of legumes was observed as compared to the remaining field at any sampling date (q.v. Figure 24). In this field, correlation analysis revealed a significant linear relationship of the proportion of legumes on the uptake of soil-N by the mixture at all seven harvesting dates (R^2 = 0.19–0.75; Heuwinkel et al., 2005b). This was found for the other fields as well, but the coefficient of determination was mostly low (0.3; Locher, 2003). In all datasets the regression had a negative slope and the intercept on the *Y*-axis was mostly close to the theoretically expected value of 100, i.e. at no N uptake from soil-N only legumes can grow.

In the year 2000, undisturbed soil samples were taken at six selected sites of field A09 and incubated in lab to determine the specific potential for N release. These data were correlated to field data about the uptake of N from soil by the legume–grass mixture and to the grain yield of the two following grains, wheat and rye (Figure 28). Surprisingly, legume–grass reflected much better the potential differences in N release from soil-N than the grains although their growth was clearly N limited. The most likely explanation for this are lateral fluxes of mineral N in field. With legume–grass these can be expected to be of minor importance because relevant amounts of mineral-N are seldom found with legume–grass. For the grains, higher concentrations of mineral-N will accumulate during winter, especially for winter wheat following the legume–grass. This N may move downward or lateral with the water. At the field A09 relatively high grain yields were found at two sites with a medium N release, but which are located right below a site with a relatively high N release in lab that was not reflected by grain yield in field. Other effects (i.e. water supply) are less likely, because the N uptake by legume–grass was high in both years. However, further research is needed to verify this explanation.

Strategies for precision farming in organic farming should be aware of any kind of varied interactions between crops and topography because they have to address much more effects on the crop rotations than for integrated farming.

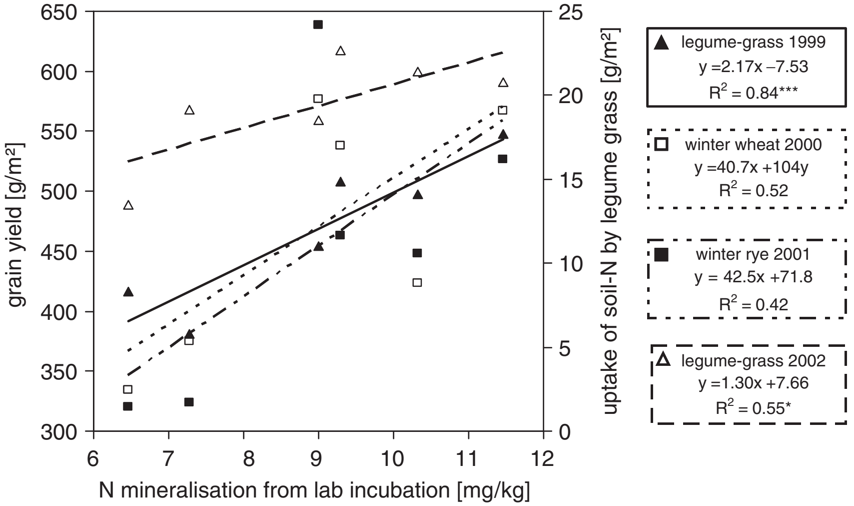

Figure 28 Correlation between N release from undisturbed soil cores incubated in lab and the uptake of soil N by legume–grass or the grain yield of winter wheat and winter rye grown at the sites in field A09 of the FAM research station (Heuwinkel et al., 2003).

Delimitation of management zones

Results from our studies indicate that zones of similar relative yield productivity can be precisely delineated using remote or proximal sensing information (Selige and Schmidhalter, 2001; Schmidhalter et al., 2001a). The information obtained from yield monitoring will reflect the yield more absolutely. The possibility for developing maps of classified management based on similar quality yield maps as obtained from farmers appears limited because of the high frequency of erroneous datasets, systematic errors in the recorded data, and their restricted yield predictive ability (Joernsgaard and Halmoe, 2003). More consistent information reflecting yield zones was obtained in this study and a previous one (Schmidhalter et al., 2001a) from the combination of several years of yield mapping and spectral information. Gaining information from proximal or remote sensing is considered to represent a powerful approach for the future for the delimitation of relative yield productivity areas. Remote sensing is especially appealing to identify management zones because it is non-invasive and low in cost. It also seems likely that further improvements can be obtained by combining mapping and sensor approaches. Combining the use of management zones with crop-based in-season remote sensing is suggested by others as well (Schepers et al., 2004).

Development of management strategies – Current N fertiliser recommendations

Different methods for deriving a N recommendation in winter wheat are available for farmers. Five strategies were tested in a 3-year field trial on several sites in Southern Bavaria (Hege et al., 2002). The strategies used various data for calculating N fertiliser doses. The strategies Expert-N and Hermes resulted from simulation models for estimating plant development and N release from soil. The strategy TUM relied on actual plant status. DSN as well as EUF used soil test data in order to adapt mineral N doses in winter wheat.

The strategy using actual plant information (TUM) proved to be valuable in achieving a high kernel yield as well as a pronounced quality of wheat kernels (Figure 29). The results were evident for the different trial sites. As only low N dressings were applied, N use efficiency was quite good. EUF reached the highest protein concentration of all strategies with 12.7%, but this was due to relatively high N dressings, leading to a reduced N use efficiency. Despite N use efficiency was highest for the strategies Expert-N and DSN, both fertilisation regimes were associated with a lower kernel yield and a lower kernel quality in relation to TUM.

For a strategy of site-specific N fertilisation, an adaptation of N doses to the heterogeneous conditions within agricultural fields is evident. Nevertheless, simulation models as well as soil test recommendations lose their importance in this context. Soil analysis in a small-scale resolution is cost-intensive, time-consuming, and not feasible. Input data for simulation models are often missing or not available in the required high-areal

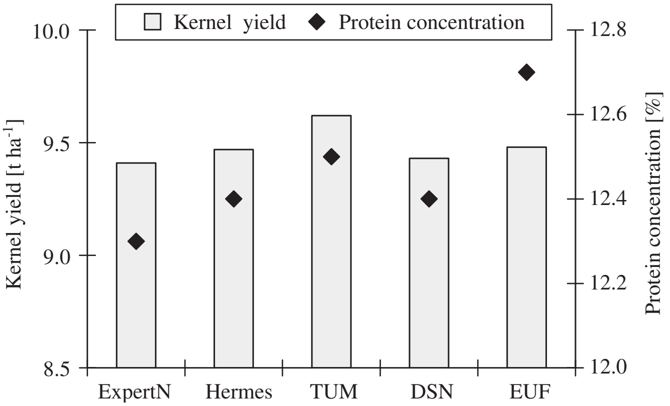

Figure 29 Kernel yield and protein concentration for different strategies of N fertilisation in winter wheat (adapted from Hege et al., 2002).

resolution. Nevertheless, plant information can be received on a small-scale mode, not via destructive biomass sampling and laboratory analysis, but by using sensors for online-detecting of N status of plants (see the sub-section "Tractor-based non-destructive sensing of biomass and nitrogen status – Reflectance measurements").

Strategies for site-specific N fertilisation

The 'on-the-go' information about biomass and nitrogen status obtained using the sensing methods can be combined with a fertilising algorithm to control the amount of N fertiliser being applied. Unfortunately, however, nutrient recommendations corresponding to within-field site-specific characteristics are rarely available (Robert, 2001). This is true not only for the sensor-based approaches but also for mapping approaches that largely report results from short-term studies. Universal nitrogen fertiliser application strategies for heterogeneous fields do not exist. Furthermore, there is no current consensus as to how lower or higher yield productivity zones should be treated. Increasing nitrogen input to weaker crop stands would enhance yields, but is not particularly environmentally friendly. Alternatively, it has been variously argued whether higher yield productivity areas should receive higher nitrogen inputs. The situation becomes even more complicated in trying to generalise the strategies for regions that differ in climate and, even more so, in trying to account for any annual variation in climate, which might also interact differently at different locations.

In the FAM research project, site-specific management of agricultural fields was performed for the cultivars wheat and maize. In this chapter, some exemplary results are presented.

The heterogeneous fields of the research station Scheyern were divided into sub-parts according to their yielding potential:

- High Yielding Zone (HYZ): $>$ 105% average yield
- Medium Yielding Zone (MYZ): 95–105% average yield
- Low Yielding Zone (LYZ) $<$ 95% average yield

For winter wheat, strip trials were conducted in order to compare different strategies of site-specific N fertilisation. In this context, the fertilisation practise within several repeated strips with a width of 7.50 m was set to uniform (UA) or variable application (VA) of N fertiliser. Beside the homogeneous application of mineral N fertiliser for a whole strip, three strategies of variable application of mineral N fertiliser have been executed:

- Mapping approach
- Online approach
- Online with map-overlay.

The mapping approach usually relies on deriving an application map prior to the fertiliser application. Thus, mainly historic data is used, e.g. yield maps and maps of soil parameters such as texture and electric conductivity. In the FAM research project, the trial sites were divided into sub-parts with different yielding potential. For this purpose, 3-year data of combine harvester measurements (2 years with winter wheat and 1 year with maize) were used.

For each yielding zone, the potential yield and quality were assessed at the start of vegetation in spring. Mineral N fertiliser doses within the different yielding zones were calculated according to the expected N uptake at final harvest. Thus, N fertiliser doses were in accordance with the yielding potential of the sub-parts: High yielding zones received more mineral N fertiliser than middle yielding zones that exceeded the low yielding zones. Timing of mineral N doses was set to the three most sensitive growth stages during winter wheat development (Figure 30): start of vegetation in spring, EC 32, and EC 49. The definition of growth stages followed the scheme of Tottman (1987). Partitioning of N doses at the growth stages was 30, 40, and 30% for start of vegetation, EC 32, and EC 49, respectively.

In contrary to the mapping approach, the strategy Online used actual information about growth and nutrient conditions of the plants when applying mineral N fertiliser. Thus, sensors are necessary for determining biomass and nitrogen status of the canopy in an online mode. Up to now, different sensors are available as tractor-mounted tools (see the subsection “Tractor-based non-destructive sensing of biomass and nitrogen status – Reflectance measurements”). The active chlorophyll sensor uses a laser beam as excitation source for performing laser-induced chlorophyll

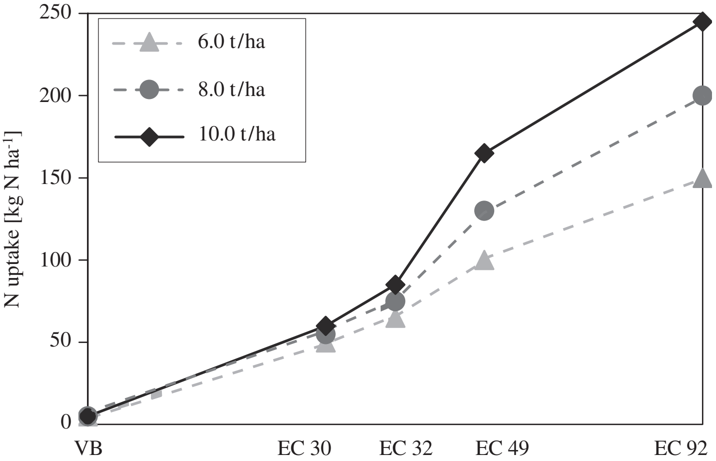

Figure 30 N uptake (kg N ha^{-1}) of winter wheat dependent on the kernel yield at final harvest (adapted from Diepolder, 1994).

measurements (Schächtl et al., 2005), whereas passive sensors rely on the reflection of sunlight. Such a reflectance sensor, the N-Sensor (YARA, Norway), is available as tractor-mounted mode (Link et al., 2002). We used this sensor for deriving our site-specific N recommendation in the online approach. For the first mineral N application at start of vegetation, N-Sensor values were influenced by soil reflectance and not reliable in deriving a N recommendation. Thus, a homogeneous and moderate amount of mineral N fertiliser was spread within the fields in order to enable a reaction with sensor measurements in EC 32.

For the second (EC 32) and third (EC 49) N application, wheat canopies were scanned with the N-Sensor (Co. YARA) and N fertiliser was applied according to these measurements. Core of the strategy was the establishment of homogeneous canopies. Thus, sub-parts of the field with an actually high biomass production and N supply received low mineral N doses in order to avoid lodging. In contrary, zones with an actually low biomass yield and N status of wheat plants received high dressings of mineral N doses.

The third examined site-specific N fertilisation regime 'online with map-overlay' combines the mapping approach with the online approach (Diepolder, 1994; Maidl et al., 2004). Our procedure in deriving an application map for this strategy was divided into two parts: First, the canopy was scanned with a reflectance sensor (2000: hand-held device, 2001: tractor-mounted N-Sensor), then mineral N doses were adjusted in relation to the site-specific yielding potential, i.e. core of the adaptation was the knowledge of optimal N supply of plants according to the yielding potential of the site (q.v. Figure 30).

An example for the derivation of mineral N application at EC 49 is given in Figure 31. The sensor value (REIP) indicates the N uptake of the canopy.

Effects of site-specific crop management in winter wheat – Influence on yield and quality

The fertiliser strategies lead to variable doses of N fertiliser applied to the wheat canopies (Table 10) at the three yielding zones. For uniform application of mineral N doses, all received 170 kg N ha^{-1} (2000) or 180 (2001) kg N ha^{-1}. The mapping approach was characterised by increased N dressings in the HYZ and reduced N doses in the LYZ. This effect becomes clear considering the high yield level and N uptake in the HYZ. Nevertheless, average values over yielding zones indicated a comparable amount of N fertiliser as with uniform application. For the online approach, N partitioning changed between the yielding zones and as expected, the LYZ received more N fertiliser than the HYZ.

For the strategy online with map-overlay, N partitioning was 195, 190, and 170 kg N ha^{-1} (2000) and 200, 205, and 170 kg N ha^{-1} (2001) at the

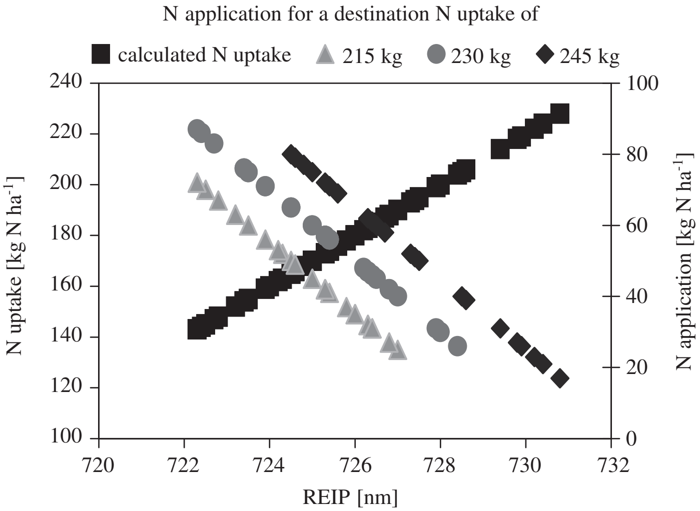

Figure 31 Online detection of N status at EC 49 with REIP values and corresponding N fertiliser application rates for the yielding zones HYZ, MYZ, and LYZ.

Table 10 Amount of N fertiliser for the strategies uniform application (UA) and variable application (VA).

Year	Yielding zone	UA (kg N ha^{-1})	VA (kg N ha^{-1})		
			Mapping	Online	Online map
2000	HYZ[a]	170	205	–	195
	MYZ[b]	170	170	–	190
	LYZ[c]	170	135	–	170
	Average	170	170	–	187
2001	HYZ	180	200	185	200
	MYZ	180	180	210	205
	LYZ	180	160	220	170
	Average	180	180	203	191

[a] HYZ = High Yielding Zone.
[b] MYZ = Medium Yielding Zone.
[c] LYZ = Low Yielding Zone.

HYZ, MYZ, and LYZ, respectively. The average values exceeded the uniform application by 10% (2000) or 6% (2001) due to an adaptation of N fertiliser doses to actual plant status. The same was evident for the online approach. Reasons for this can be found in the calibration procedure of the

N-Sensor (YARA, Norway) as the respective amount of N fertiliser was adjusted at a sub-part of the field. Maybe this zone was not as representative for the whole field as expected.

Average kernel yield for uniform N application amounted to 10.0 and 9.9 t ha^{-1} in 2000 and 2001, respectively (Table 11). In 2000, site-specific differences between the yielding zones were negligible (0.4 t ha^{-1}). Thus, the strategies of variable N application reached comparable yield results of 9.8 and 9.9 t ha^{-1}. Nevertheless, the low amount of N fertiliser with the mapping approach in the LYZ lead to a small reduction in kernel yield, whereas increased doses of mineral N in the HYZ had no effect on yield formation.

In 2001, the HYZ reached a kernel yield of 11.0 t ha^{-1}, 1.8 t ha^{-1} superior to the LYZ. As for the first year, the mapping approach increased these site-specific differences between the yielding zones to 2.4 t ha^{-1}. The reduced amount of N fertiliser in the LYZ impacted kernel yield, whereas increased N doses in HYZ had no effect.

The contrary was remarkable for the online approach where site-specific differences between the yielding zones diminished. This result is not surprising due to the aim of the online approach in gaining a more homogeneous plant stand within a heterogeneous field (Link et al., 2002).

The average yield of mapping approach was significantly increased when combining with sensor measurements in the strategy online with map-overlay. This is in accordance with Welsh et al. (2003) who showed that the actual situation of the plant is a better indicator of N demand

Table 11 Kernel yield for the strategies uniform application (UA) and variable application (VA).

Year	Yielding zone	UA (t ha^{-1})	VA (t ha^{-1})		
			Mapping	Online	Online map
2000	HYZ[a]	10.2 a	10.2 a	–	10.3 a
	MYZ[b]	9.7 a	9.7 a	–	9.6 a
	LYZ[c]	9.8 a	9.6 a	–	9.6 a
	Average	10.0 a	9.8 a	–	9.9 a
2001	HYZ	11.0 a	10.9 a	10.8 a	11.1 a
	MYZ	9.5 b	9.5 b	10.6 a	10.5 a
	LYZ	9.2 b	8.5 c	9.5 b	10.2 a
	Average	9.9 b	9.5 c	10.3 ab	10.6 a

Different letters in a line indicate significance at $p = 0.05$.

[a] HYZ = High Yielding Zone.

[b] MYZ = Medium Yielding Zone.

[c] LYZ = Low Yielding Zone.

than historic yield data. Regarding the results of both years, mainly the kernel yield in the LYZ was affected by the different strategies of variable N fertilisation.

The first year was characterised by a higher protein concentration in wheat kernels of 12.7% than the following growth period with 10.8% (Table 12). For uniform N application, lowest value of N concentration in kernels was achieved in the LYZ in both years. The mapping approach led to a further reduction of this quality parameter in the LYZ due to the low amount of N fertiliser. Nevertheless, an enhanced amount of mineral N in the HYZ enhanced protein concentration.

Protein concentration in the LYZ was increased when augmenting N doses in the online approach (Table 10). Thus, this strategy leads to a higher average protein concentration for the whole field as well as to a more homogeneous wheat quality. A comparable effect was observed for the strategy online with map-overlay. These results are not surprising as Reckleben and Rademacher (2004) point at the importance of giving high doses of mineral N to wheat canopies with a high yielding potential in order to obtain an increase in wheat quality.

Influence on the environment – N use efficiency

Regarding the implications of N fertiliser applications, not only the effects on kernel yield and kernel quality are of importance. N use efficiency (NUE) indicates the amount of N uptake of the kernels in relation to the amount of mineral N: NUE = N uptake × (N rate)$^{-1}$.

Table 12 Protein concentration of wheat kernels for the strategies uniform application (UA) and variable application (VA).

Year	Yielding zone	UA (%)	VA (%)		
			Mapping	Online	Online map
2000	HYZ[a]	12.6 b	12.7 b	–	13.4 a
	MYZ[b]	12.8 b	12.8 b	–	13.1 a
	LYZ[c]	12.4 a	11.8 b	–	12.5 a
	Average	12.7 ab	12.4 b	–	13.1 a
2001	HYZ	11.6 b	12.3 a	12.2 a	11.7 b
	MYZ	10.2 b	10.2 b	11.4 a	11.7 a
	LYZ	10.4 b	9.7 c	11.4 a	10.9 b
	Average	10.8 b	10.8 b	11.7 a	11.4 a

Different letters in a line indicate significance at $p = 0.05$.

[a] HYZ = High Yielding Zone.

[b] MYZ = Medium Yielding Zone.

[c] LYZ = Low Yielding Zone.

First of all in 2000 the average NUE was always higher than 100% and always below in 2001. The amount of N fertiliser corresponded with N use efficiency for the mapping approach in 2000 (Table 13). High N dressings led to a reduction in N use efficiency in the HYZ, whereas low N doses increased N use efficiency in the LYZ.

The strategy online with map-overlay resulted in both years an average N use efficiency close to 100%. With the other strategies, average values of N use efficiency were lower or higher especially in the LYZ.

Static field trials of a long-term or multi-year character were further established to test whether targeted, site-specific nitrogen fertiliser application can enhance nitrogen use efficiency as compared to optimal uniform nitrogen application while still maintaining yields. Mapping and online (sensor) variable rate nitrogen fertiliser application strategies at several locations (Ebertseder et al., 2005; Schmidhalter et al., 2006). In general, high yields were found on field sites representing moderate in-field variability. Despite highly contrasting weather conditions between years, similar responses of lower and higher yield zones were observed, and the effects of the different strategies were found to be relatively consistent. The results indicate considerable potential to increase nitrogen use efficiency while simultaneously maintaining yields. Similar to the results reported above, the mapping approach, which considers the long-term yield potential, indicated substantial gains for the environment in areas of lower yield productivity and fertile colluvial deposit zones, whereas the sensor approach allowed for nitrogen use efficiency to be optimised in areas of higher yield productivity.

Table 13 N use efficiency for the strategies uniform application (UA) and variable application (VA).

Year	Yielding zone	UA (%)	VA (%)		
			Mapping	Online	Online map
2000	HYZ[a]	114 a	84 b	–	107 c
	MYZ[b]	110 a	110 a	–	100 c
	LYZ[c]	108 a	126 b	–	107 a
	Average	113 a	102 b	–	105 b
2001	HYZ	107 a	101 b	108 a	98 b
	MYZ	82 a	82 a	86 b	90 c
	LYZ	82 a	79 b	76 c	99 d
	Average	93 a	87 b	92 a	96 c

Different letters in a line indicate significance at $p = 0.05$.

[a] HYZ = High Yielding Zone.

[b] MYZ = Medium Yielding Zone.

[c] LYZ = Low Yielding Zone.

N balance

N balance was calculated as difference between N fertiliser rates and N uptake of wheat kernels at final harvest. Negative values of this parameter indicate that more N was removed from the field than the amount applied via N fertiliser. On the other hand, positive values show that N rates exceeded N transfer via wheat kernels, resulting in an accumulation of nitrogen in the field. This amount of nitrogen is potentially available for leaching hazard.

In 2000, positive values of N balance were only found for the mapping approach in the HYZ (Table 14). The high amount of N fertiliser in these parts of the field could not be removed with kernel harvest. The strategy online with map-overlay enabled values of –1 and –13 kg N ha^{-1}. Applying a homogeneous amount of N fertiliser within the whole field resulted in a N balance of −16 kg N ha^{-1}. Nevertheless, repeatedly high negative N balances may induce a decrease in soil fertility.

In 2001, all fertilisation strategies led to positive N balances regarding average values for the whole field. Nevertheless, the strategy online with map-overlay allowed the slightest value of 9 kg N ha^{-1}. Regarding the separate yielding zones, N balance was well adjusted using this strategy. The other regimes of site-specific mineral N fertilisation resulted in great differences of N balance within the yielding zones, ranging from –12 to +36 kg N ha^{-1}, for the uniform application, +1 to +36 kg N ha^{-1} for the mapping approach, and –14 kg N ha^{-1} up to +57 kg N ha^{-1}for the online approach. Whereas the HYZ was characterised by negative N balances,

Table 14 N balance for the strategies uniform application (UA) and variable application (VA).

Year	Yielding zone	UA (kg N ha^{-1})	VA (kg N ha^{-1})		
			Mapping	Online	Online map
2000	HYZ[a]	−23 a	+10 b	–	−13 b
	MYZ[b]	−17 a	−17 a	–	−1 b
	LYZ[c]	−13 a	−35 b	–	−11 a
	Average	−21 a	−13 b	–	−8 b
2001	HYZ	−12 a	+1 b	−14 a	+4 b
	MYZ	+34 a	+34 a	+28 b	+20 b
	LYZ	+36 a	+36 a	+57 b	+2 c
	Average	+19 a	+25 b	+22 b	+9 c

Different letters in a line indicate significance at $p = 0.05$.

[a] HYZ = High Yielding Zone.

[b] MYZ = Medium Yielding Zone.

[c] LYZ = Low Yielding Zone.

high positive values in the LYZ display a great problem regarding the potential of N leaching hazard (Schächtl, 2004).

Transborder farming

In small-structured agricultural regions, many farmers have competitive disadvantages due to small-sized fields and a multitude of single plots resulting in extensive operation times and use of resources per area. An alternative for the time-consuming and expensive restructuring by regular land consolidation is the virtual land consolidation in terms of a transborder farming system. A transborder field is a number of adjoined plots, surrounded by natural borders or farm roads. Several single plots, cultivated by several farmers, can be farmed as one big field across the property borders. This requires cooperation of the participating farmers. Transborder farming means an enlargement of cultivation units and thus declining operation time and costs. At the same time, production methods can be better adjusted to ecological requirements.

In a transborder farming system, small fields situated side by side, are farmed together as one large field (Figure 32). Because of bigger cultivation units, farmers can realise increased gross margins through decreased labour and resource costs (Auernhammer et al., 2000a). Farmers have to agree on a common crop rotation on the transborder field and should use the best farming techniques and technologies that are available for each production process.

For evaluating the transborder farming system, as well as for accounting each individual farmer, a system for exact documentation of the field work for tractors and harvesters is essential (Rothmund et al., 2003a). Using these systems, yields can be allocated site-specifically by DGPS data. All process data, containing position information, can be allocated to known field boundaries of each farmer's property within the transborder field (Figure 33).

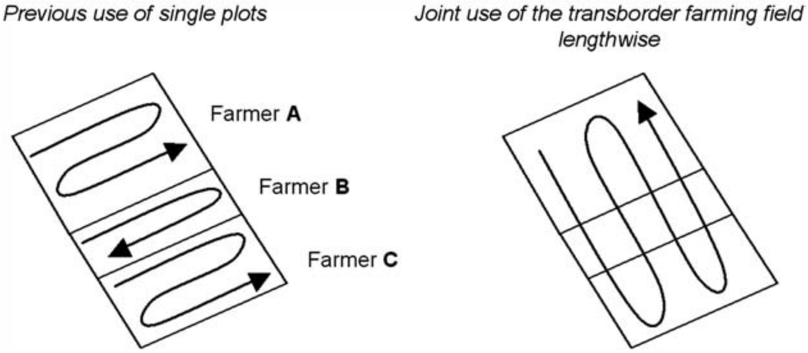

Figure 32 Changing of cultivation due to the formation of a transborder field.

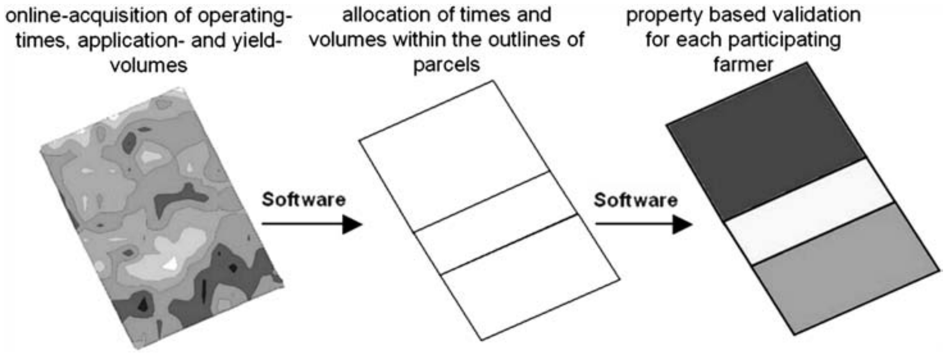

Figure 33 Specific accounting of mapped process data by boundaries within the transborder field.

The result of combining the automatic process data acquisition with an adjusted data management system is an 'Automated Documentation and Management System' for transborder farming. It allows field work on different plots, for instance in transborder fields, without paying attention to manual documentation. The high spatio-temporal resolution of GPS and attribute data from machines could never be realised by manual or just PC-supported systems. Using local or web-based software for allocating and validating field work data to each farmer's plots by a few mouse clicks, considerably reduces the time required for managing transborder farming.

Investigations in simulating the production on a virtual 'transborder farm' on 5–7 ha sized transborder fields instead of 1–2 ha sized fields resulted in a reduction of labour costs of about 30% and about 25% of machinery costs. There are some reductions of costs by sales discounts and there is a 'know-how effect', which can be from € 0 up to € 150 per hectare (Rothmund et al., 2002b). The results of a survey showed that the possible effects caused by specialised knowledge of single farmers in a transborder farming group could be more than 100% yield difference under equal soil conditions. Consequently, this 'know-how effect' can cause a big increase in yield for farmers with previous low yields and there will be no such effect for farmers with the previous highest yields. All in all, increases of gross margin from about € 100 up to more than € 300 per hectare and year are possible (Rothmund, 2006).

Both, in practical trials and in various simulations, the excellence of creating transborder farming systems in small-structured agricultural regions has been proved. Often this virtual land consolidation can be simply realised by working across the previous field boundaries without changing landscape or boundary ridges. Indeed, the realisation of a transborder farming system mostly fails due to another reason: the missing will for cooperation between the farmers. Even cognition of the economical facts cannot persuade, because farmers are afraid of losing their freedom of decision. Only economic forces combined with an increase in corporate thinking among the farmers can change this situation.

Documentation and traceability

Today site-specific acquisition of process data is enabled by a lot of sensors commonly integrated in modern tractors and farm tools combined with a satellite-based positioning system such as GPS. The automated and georeferenced acquisition of process data on agricultural machinery can be implemented easily, presupposed that a standardised electronic communication BUS system is available (Auernhammer et al., 2000a). By introducing the ISO 11783 standard (ISOBUS) for tractor-implement systems a widespread use of automated data acquisition in practice can be expected. Combined with an adequate data and information management it enables an automated documentation system. This is the base for a number of internal, inter-company, and external farm applications such as optimised farm management, site-specific crop management, machinery management for joint machinery use and contractors as well as the traceability of food and animal feed (Rothmund et al., 2003b). For these purposes, exclusively automated systems guarantee high quality of acquired information in a sufficient temporal and spatial resolution as well as adequate safety from falsification.

Some important components for an automated documentation system are already available, some however not yet. At the Technische Universitaet Muenchen an automatic process data acquisition system based on Agricultural BUS System (DIN 9684) has been developed (Auernhammer et al., 2000b). The new international standard for electronic communication systems ISOBUS (ISO 11783) is nearly accomplished (Böttinger and Autermann, 2003). The discussion on data interfaces and exchange formats based on the XML standard is on the way. To get a practical documentation system that produces additional benefits by using acquired information, missing components (i.e. data processing methods) have to be conceived and linked together with existing components (Demmel et al., 2001). The project's aim was to design an information management system, which starts with data acquisition and ends with the use of process information in different applications. The concepts have to include data storing, data transfer, and data processing up to providing information and diverse data interfaces.

Different information system models, which could be denoted as offline and online dataflow should be investigated and implemented in prototypes. For these models, advantages and disadvantages should be worked out and analysed. Especially data security and faultless data handling and processing a huge amount of data are points of interest. Accordingly, different types of use of information from automated documentation systems should be investigated. It was assumed that farmers, cooperatives, and contractors on the one hand and consumers or authorities on the other hand do not concern in the same information contents about agricultural production processes.

The following description is divided into three steps: first, data acquisition and transfer, then data processing and information providing and last but not least the information use.

Automatic process data acquisition within standardised communication networks

First of all, automatic data acquisition means that data recording is not affected by the driver. Starting the engine of a machine means starting data recording automatically. This approach differs from previous recording systems, which were operator or job orientated and data logging had to be started and stopped by pressing a button. In an automatic system the centre is a CAN-BUS that builds up a 'data transfer highway' for a number of connected electronic control units (ECUs), which are distributed on tractor and farm tools. These ECUs can deliver process data, like speed and hitch parameters of the tractor, working and application parameters of working implements, measurement values of crop sensors, and many more. An additional module called data recorder acts as a file server and inquires and stores the process data from different sources as shown in Figure 34. All the recorded data can be allocated to an exact position in landscape, assuming that a GPS receiver is connected to the system. The interoperability between different ECUs and the communication by the CAN-BUS is enabled by standardised data transfer protocols. Until today the German standard for agricultural BUS systems (LBS DIN 9684) had been used. It is now followed by the international standard ISOBUS (ISO 11783).

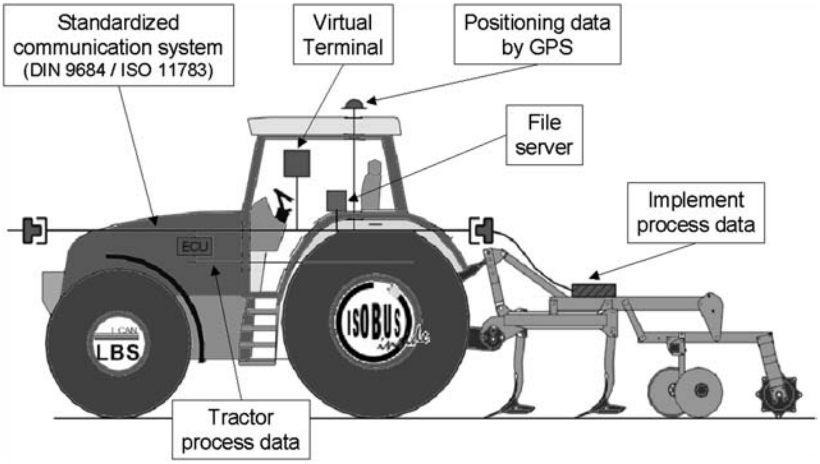

Figure 34 Configuration of automatic data acquisition in a standardised communication network (from Rothmund, 2006).

In the prototype conceived and realised at the Technische Universität München, all position and process data were stored once per second in a relational data model. For data storing and transfer PCMCIA memory cards and an ASCII format were used. In the current prototypes, data have to be transferred by reading out the memory cards to a local PC. For data transfer more advanced methods such as data synchronising using Bluetooth&macmillan; standard or connecting machines directly to the Internet by WLAN may be conceived. Transferring all process data via GSM (mobile phone standard) seems to be impossible at the moment because of the huge amount of data. As it is just being worked out in the ISOBUS standardisation process, the raw data transfer format will change to an XML-based data interface in the future.

Farm-based and web-based data processing methods

The new approach of fully automated data recording on agricultural machinery offers a new quality of data with a very high spatial and temporal resolution of information. But the huge amount of raw data requires sufficient data processing systems, database, and information management. Otherwise 'data graveyards' would be produced and the effort for data collecting would not be profitable. In principle there are two ways of data processing. The first way is farm-based data processing and storing using local software and database systems. This way could be called offline dataflow. The second way is a centralised data processing and data management for several or many farmers by external service providers. This also could be called online dataflow or web-based information system (Figure 35).

By conceiving, programming, and testing a prototype information system in each case – the offline and the online way – experiences for analysing problems and advantages of those methods could be gained. As a tool for local use on a farmer's PC, a Microsoft Access-based data evaluation tool was built. The complete functionality and the user interfaces for data processing, data keeping, and information providing were integrated within

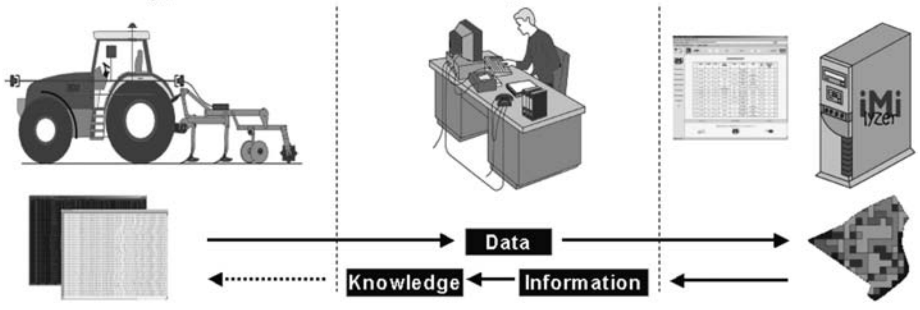

Figure 35 Scheme of online data and information flow in a web-based information system based on automated data acquisition systems.

the Microsoft Access database environment. For the online data processing a web-based information system using exclusively open source tools has been developed alternatively. The main components are a powerful database system and web developing tools such as mark-up and scripting languages. Data upload and information download by users occur by browser interfaces via Internet.

Demands on information contents for different user groups

The raw data from automated process data acquisition allows a big variety of different evaluation targets. It could be the base for classic farm software tools such as field books, machinery management, or invoicing software (Rothmund et al., 2002b). Furthermore, it can be the main data source for extended applications, which need detailed geographical information, like site-specific farming or inter-company farming (e.g. transborder farming systems in a virtual land consolidation). Regarding the target of information use, the requirements on processing algorithms and information structure can be very different, starting with simple aggregated schedular information or diagrams up to detailed maps and geo-statistical analyses. Beyond those mentioned internal or inter-company farm applications there is an important external use of information. Complete datasets of production processes enable documentation for the trace of products. This requirement of dealers, commercial processors, and consumers has to be fulfilled more and more by the farmers (Auernhammer, 2002).

To realise different information structures for different user groups considering data protection and privacy of information in a centralised database, variable aggregation levels and access authorisation structures have been modelled. Indeed those complex structures have not been fully integrated in the first prototype implementation yet.

2.3.4 Conclusions

Existing methods of soil and plant analysis are costly and time-consuming in delivering information on the actual and spatially resolved site-specific soil properties as well as the biomass and nutritional status of crops. Non-destructive techniques to sense soil and plant properties can contribute to improvements.

New developments of non-destructive techniques to sense soil and plant properties have been validated in the FAM project. Spatially resolved soil information can be gained by electromagnetic induction, near-infrared spectroscopy, and indirectly by correlating plant stands to soil properties. With such methods, soil texture, soil carbon, and plant-available water in the soil can be characterised. Derivation of relevant soil properties by non-contacting sensor techniques is highly effective and will provide long-term information for optimised management.

Remote and proximal sensing allows determining plant biomass, nitrogen content, and nitrogen uptake. The methods tested and further developed included aerial and ground-based reflectance-based measurements and tractor-based laser-induced chlorophyll measurements. Assessment of the nitrogen content, biomass, and nitrogen uptake of plants by contact less optical measurements is seen to be a promising technique for management decisions of farmers. These techniques have the capability of sampling a high number of plants in a short time rather than a single leaf point and allow a fast assessment of the spatial and temporal variability of plant growth.

Together such methods allow for optimised management to better adapt plants and inputs to heterogeneous field sites.

Site-specific agriculture aims at optimising inputs on the field and farm levels, and thus can benefit both the farmer (in terms of net return) and the environment (through lower emission levels). The results, derived from multi-year and multi-location field studies, recommend the adoption of variable rate nitrogen fertiliser application. A sensible increase in the already high yields by using site-specific farming is not possible. Site-specific farming can increase nitrogen efficiency and reduce environmental impacts. In general, it appears that potential benefits to the environment of site-specific nitrogen fertiliser application increase the higher the yield differences on a field are and the less favourable the weather conditions are. A combination of mapping and online approaches will further contribute to improvements. Techniques applied and newly developed within the FAM study offer a great potential for further applications. Promising fields are seen in site-specific soil cultivation, seeding, and plant protection. Both integrated and organic farming will benefit from such achievements.

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