

Chapter 9

Site-Specific Fertilizing

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Abstract Fertilisation aims at providing soils with nutrients for high crop yields without adversely affecting the environment. Since in most cases the properties of soils as well as of crops vary within individual fields, site-specific fertilization is needed. The challenge is to find **sensing methods** that provide suitable signals for the site-specific control of fertilizer application. Feasible approaches to meet this challenge are based on

- recording the yield of previous crops and the nutrient removal derived from it
- electrochemical indication of nutrients in soils by ion-selective electrodes
- sensing the nutrients either in soils or in crops via optical reflectance.

The best choice depends on a variety of factors such as *e.g.* nutrient type, properties of soils, properties of crops and climate. The last listed method – sensing via optical reflectance – can be used in a proximal mode from farm machines or also in a remote mode from satellites provided clouds do not obstruct the radiation. Its use for in-season nitrogen application with proximal sensing from farm machines is becoming a leading technology.

Keywords Bending resistance • Benefits • Control algorithm • Crop-reflectance • Fluorescence • In-season crop properties • Ion-selective electrodes • Nutrients removed • N-sensor • Reflectance of soils

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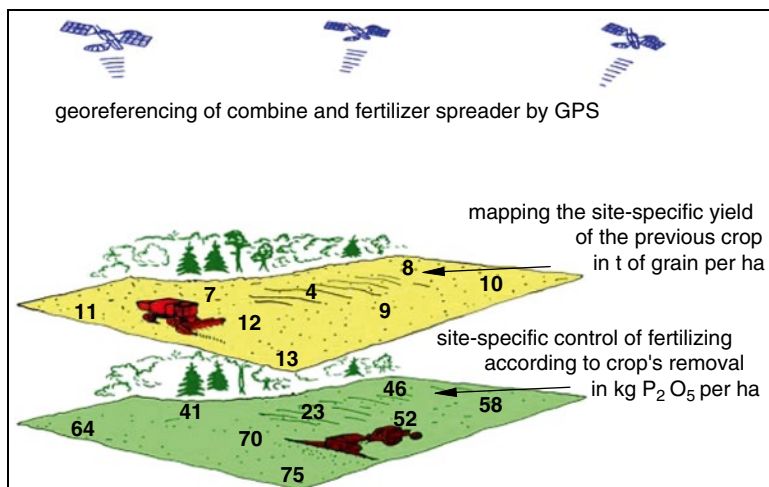


Fig. 9.1 Concept of site-specific fertilizing according to nutrients removed in the previous harvest. The *inserted numerals* are based on the harvest of wheat in tons of dry matter – straw not considered – as well as on a removal of 5.8 kg of P_2O_5 per ton (From Swedish Institute of Agricultural Engineering 1988/89, supplemented and altered)

9.1 Fertilizing Based on Nutrient Removal by Previous Crops

Harvesting crops always results in a removal of mineral nutrients from fields. The concept that these nutrients should be replaced in order to avoid depletion of soils has been accepted in the agricultural sciences since long. However, in the past, removal and replacement respectively referred to whole fields. The yields as well as the fertilizing had a whole field basis.

Modern georeferencing, fertilizing and harvesting techniques (see Chap. 12) have changed the situation. If during harvesting, the yields in units of mass are recorded and georeferenced with a high spatial resolution for *e.g.* grid areas of 100 m^2 , the **removal of nutrients** for these small areas can be determined. Because knowledge about the gravimetric nutrient content of the harvested products is available. Consequently, a georeferenced distribution of the fertilizer for the next crop can be controlled in such a way that precisely this amount of nutrients is applied in a site-specific way (Fig. 9.1). The result is a **site-specific maintenance application**, since the nutrients removed by the harvest are replaced.

This concept for detecting the site-specific nutrient need is reasonable if the supply of the previous crops was adequate, hence the soil not deficient in nutrients. A second prerequisite is that the removal by the plants is the only factor or at least the dominating criterion for the nutrient depletion of the soil.

The first prerequisite mentioned above can be met approximately by starting the system with careful conventional manual sampling, traditionally analysing the supply

in a laboratory and providing soils with nutrients in such a way that a rather uniform level of supply is obtained. It might require some efforts and costs to do this preparatory first step in a site-specific way. The needs can be somewhat eased if a small average oversupply – at least for the major nutrients phosphate and potash – is accepted.

The second prerequisite – the removal by the harvest being the main factor of changes in the nutrient level – implies that losses of nutrients by leaching, by runoff of water or by erosion do not occur. For well managed fields, losses via runoff or by erosion will be on the average rather small and will represent mainly exceptional cases that take place in situations of adverse weather. But this does not hold for **losses by leaching** that result from natural rain or irrigation. In many agricultural areas, these losses by leaching into the not-rooted subsoil and into the groundwater horizon can be substantial as well as rather unpredictable. Whether the losses via leaching still allow to rely on nutrient removal alone for a site-specific control of fertilizing, depends on the ions that are involved. The main point is whether the nutrients are absorbed by soil particles or bound within compounds that are not soluble in water and whether hence their leaching downwards is prevented.

The **nitrate** and **sulphate ions** hardly are absorbed by soil particles, they are easily dissolved in water and hence are disposed to leaching into the non-rooted subsoil and into the groundwater. The leaching of these ions occurs especially on sandy soils and somewhat less on soils with a higher clay content, however, soil texture alone cannot eliminate the problem. Another factor that considerably can reduce the leaching is nutrient uptake by growing crops in combination with precise fertilizing that is in line with the seasonal needs of plants. This is simply because ions that are taken up by the roots of crops cannot leach any more. Yet this fact can only help to diminish the leaching problem somewhat, it cannot do away with this problem in geographical regions where during winter there is no nutrient uptake. In short, for a site-specific control of nitrogen- and sulphur fertilizing, in most areas it cannot be expected that the concept of nutrient sensing via removal supplies reliable information.

The situation for fertilizing of **phosphate** is completely different. The phosphate ions are very immobile within soils. Leaching of these ions does not occur. This is mainly due to fixation in calcium-, aluminium- and iron phosphates that are not soluble in water. Hence sensing the removal of phosphate via yield recording can be regarded as a good choice for mapping the site-specific removal. In a subsequent operation, the map can be used to control the spreading. The information about the removal is obtained by simply applying a factor to the site-specific yield.

Potash ions again present another situation. They do not leach anything as fast as nitrate- or sulphate ions do. Yet they do not possess the immobility of phosphate ions either. Potash that is not taken up by the crop can be held in the soil by clay minerals or by organic matter. However, in order to prevent leaching in humid areas and when no crops are growing, a clay content of 5 % or more is needed (Potash Development Association 2006). And for a site-specific concept, this minimum in clay content is needed for about all cells within a field. So for sensing the potash supply via removal by crops, restrictions in the soil texture must be considered.

For **calcium** and **magnesium**, depletion of reserves within soils due to removal by crops seldom is a problem. Thus sensing the removal by crops hardly is

Table 9.1 Removal of phosphate and potash per ton of dry matter of harvested crop parts^a

| Crop | Phosphate in kg P ₂ O ₅ | Potash in kg K ₂ O |
|---------------------------------|---|-------------------------------|
| Winter wheat, only grain | 5.8 | 7.6 |
| Winter wheat, straw plus grain | 4.0 | 18.6 |
| Winter barley, only grain | 6.5 | 8.8 |
| Winter barley, straw plus grain | 4.6 | 19.7 |
| Maize, only grain | 6.8 | 4.8 |
| Soybeans, only grain | 14.0 | 22.0 |
| Rape or canola, only grain | 18.4 | 9.2 |
| Grass, leys, parts aboveground | 8.0 | 30.0 |

^aExtracted from International Fertilizer Use Manual (2007) and Soil Science Society of America (2008), data partly converted

necessary. But large amounts of fertilizers that contain these chemical elements might be needed to maintain a specific acidity level of soils (pH value) that promotes growth. Site-specific sensing of this acidity level is dealt with in Sect. 9.2.2.

In principle, also the removal of **micronutrients** such as copper, zinc, manganese, boron and molybdenum by the harvest can be recorded via yield sensing. For doing this, the information about the micronutrient content within crops and parts thereof is available (International Fertilizer Association 2007; Osmond and Kang 2008). Especially for micronutrients, recording the site-specific situation via removal by yield sensing appears highly attractive, since no other methods are available. Because the laborious traditional soil sampling plus analysing in laboratories is by far too expensive on a site-specific basis. However, with micronutrients – as with macronutrients – sensing the situation via removal might not be the only factor that defines the need of a crop. Leaching as well as the release of micronutrients by soils must be considered. Both might depend on the respective ion and the pH of the soil. Up to now, recording the removal of micronutrients via site-specific yield sensing is not state of the art. Research directed to this topic is urgently needed.

Summing up, phosphorus as well as of potash – with exceptions in the latter case (see above) – are candidates of application. Removal rates of these nutrients are listed in Table 9.1. They depend on crop species and on the harvested crop parts. The more the harvested crop parts are composed of vegetative- instead of reproductive plant matter, the higher the ratio of potash units to phosphate units is.

It should be noted that the **removal rates** in Table 9.1 are per ton of dry matter. Removal rates per ton of harvested product that are based on moist plant material and not on its dry matter can be very misleading since the water content can vary widely with most crops. As an extreme example: when forage is harvested from grasslands or leys, the water content of fresh material can be 85 %, but with dry hay it may be 15 %. With all crops, the water content of the harvested product changes steadily due to varying weather. And the water does not contain any nutrients.

Hence for exact records, the respective **site-specific dry matter** content at harvest time must be taken care of. For several crop species, yield sensing instruments

in harvesting machines that record the respective dry matter situation and simultaneously supply site-specific maps about this are state of the art.

Hence the logical procedure for defining the nutrient removal is:

- harvested wet crop mass times dry matter content = harvested dry crop mass
- harvested dry crop mass times removal per dry mass unit = nutrient removal.

As for the units:

In Table 9.1 the nutrient removal is expressed per ton of dry matter of the harvested crop parts. A harvested wet crop mass per site-specific cell in t would have to be multiplied by the dry matter content on the wet basis in decimal fractions and not in %. The final nutrient removal would then be defined in kg of P₂O₅ or K₂O per site-specific cell in the field.

9.2 Fertilizing Based on Soil Sensing by Ion-Selective Electrodes

9.2.1 Basics

This method of detecting the site-specific nutrient supply of the soil relies upon the **electrochemical series of potential** (voltage) that holds when chemically different conductors of electricity get into contact. As a result, the difference in potential can cause a flow of electrons in case of metals or alternatively of ions in case of liquids or slurries. The function of galvanic cells is based on this phenomenon.

However, with ion-selective electrodes the objective is not to produce electricity, but just to use the indicated voltage for detecting specific ions. And in order to get information about specific ions – such as those of the nutrients – the respective electrodes contact the soil or the soil: water mixture via a **membrane** (Fig. 9.2). The function of this membrane is to transmit only the respective ions that are to be sensed. So in case of soil sensing, membranes are selected that just transmit either

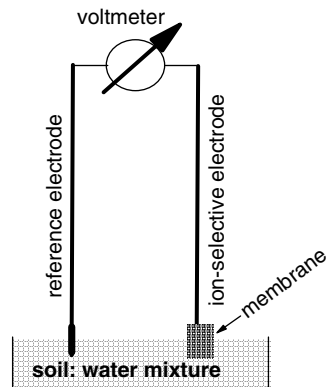


Fig. 9.2 Operating principle of electrochemical sensing by ion-selective electrodes. Both electrodes can be within one probe (simplified and not to scale)

H⁺ or NO₃⁻ or K⁺ *etc.* ions. The main objective in the development of ion-selective electrodes has been to find membranes that effectively prevent the passage of unwanted ions and just let pass specific ions of mineral nutrients or of water for the recording of soil pH.

Presently, ion-selective electrodes are used in numerous laboratories for analysing soils, foods, water and for clinical chemistry. They are widely employed for measuring the pH of soils either via portable handheld instruments or in a stationary mode in laboratories. Despite this, the ability to precisely just let pass ions of the nutrient that is to be sensed and to retain all other ions with other chemical formulas still is a topic of efforts and research. The question is how well membranes – which consist of various materials – are able to separate ions that have different formulas so that interferences are avoided.

The **voltage output** of ion-selective electrodes generally is proportional to the logarithm of the measured specific ion activity. This relation must be included in the data processing program if it is targeted at the active ions.

As for site-specific fertilizing, the challenge is online and on-the-go sensing by ion-selective electrodes. Up to now, these instruments cannot record in a continuous mode in a similar way as implements that sense soil properties via electrical conductivity do. The present procedure is to use on-the go operations, during which periodically small samples of soil or mixtures of soil and water are prepared and brought into contact with ion-selective electrodes. In order to avoid incorrect measurements, the electrodes must be cleaned by rinsing with water following each contact. The cleaning process and sometimes also the sample preparation necessitate an **intermittent sensing operation**.

Selecting the best membrane for the respective ion is a crucial point. Due to the many applications in various laboratories, ion-selective electrodes with a variety of different membranes are commercially available. Some recommendations are to use (Adamchuk et al. 2005; Kim et al. 2007a, b; Lund et al. 2005):

- electrodes with glass- or antimony membranes for sensing pH
- electrodes with polyvinyl-chloride membranes for potassium and nitrate
- electrodes consisting of cobalt rods for phosphates.

The polyvinyl-chloride membranes may be treated with special chemicals in order to improve the performance. Electrode aging and mechanical wear due to abrasion by soil still are problems, especially with membranes based on glass or polyvinyl-chloride. For sensing of pH, the wear problem can be reduced by using antimony instead of glass for the membranes (Adamchuk 2008).

9.2.2 Sensing pH and Nutrients in Naturally Moist Soils

An important point is the preparation of the soil samples. The traditional procedure of stationary sensing via ion-selective electrodes in laboratories has been to do this based on **solutions** or **slurries** of soil samples. On-the-go operation from farm vehicles is facilitated if **naturally moist soil** samples can directly be sensed. However,

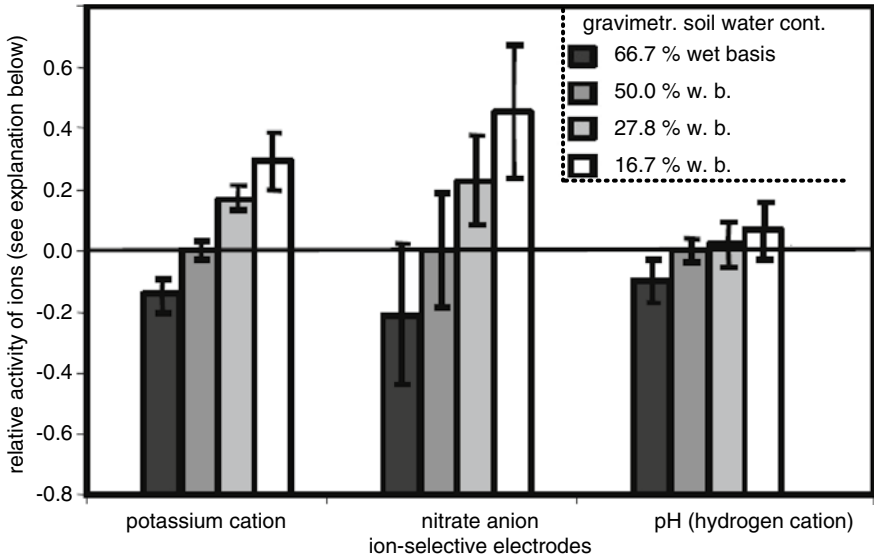


Fig. 9.3 Relative activity of ions and the water content of the soil samples. The ion-selective electrodes that were used correspond to the recommendations mentioned in the previous section. The results have been standardized by subtracting the respective average records for 27.8 % water content from each measurement. The bars on top of the columns indicate standard deviations (From Sethuramasamyraja et al. 2007, altered)

sensing the soil as it presents itself in the field implies that the moisture varies to some extent. This holds between different fields and times as well as within a field when site-specific sensing takes place.

Experimental results for sensing of soil samples with varying water content did reveal that the ions react on this differently (Fig. 9.3). If hydrogen ions are sensed when mapping the pH of soils, there hardly is an effect of varying soil water content. Contrary to this, the results for sensing of nitrate- as well as of potash ions do depend on the soil: water ratio. Especially with nitrate ions, the effect is obvious (Fig. 9.3).

The technique as shown in Fig. 9.4 provides **pH readings** from naturally moist soil samples in cycles of about 10 s. This means that with a travel speed of 2 m/s (= 7.2 km/h) and a transect distance of 20 m, a reading is obtained for successive cells of 400 m². So compared to the conventional method of taking one sample per ha for analyzing in special laboratories, the **spatial resolution** is 25 times better.

In non-uniform fields, this is a substantial improvement. Because in most cases, it is not possible to solve the site-specific problem that is associated with the conventional sampling resolution by **interpolation** between the mapped points. Any interpolation method can only help to alleviate the problem if the adjacent points are spatially related. Yet with a sampling cell size of 1 ha, the distance between neighboring locations is about 100 m. For the pH situation of most fields, this is well beyond the range of semivariance (Mulla and McBratney 2000). This means that any interpolation is useless (see Sect. 2.3).

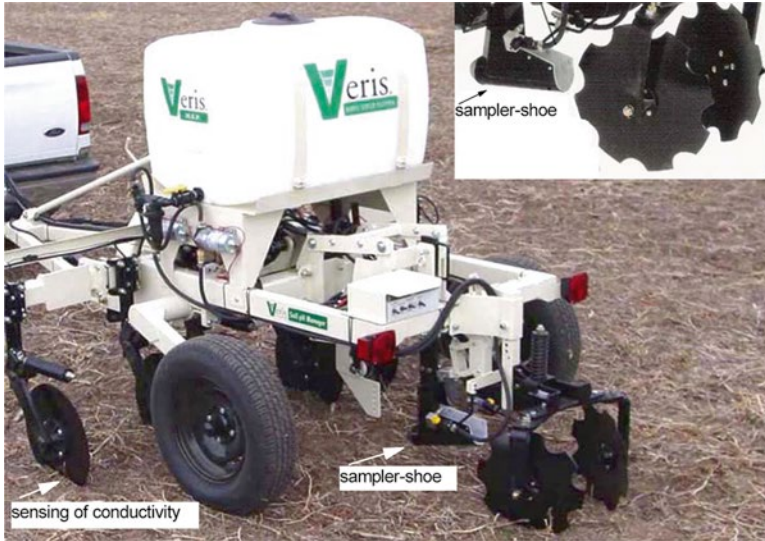


Fig. 9.4 Implement for simultaneous sensing of pH and electrical conductivity of soils. For pH sensing, a horizontally oriented sampling shoe (*insert top right*) is periodically lowered into the soil and when lifted pushes a naturally moist soil sample against ion-selective electrodes. After this, the electrodes are rinsed with water. Crop residues – if present – are swept aside by a row cleaner. Calibrating of the electrodes is essential for precise sensing (From Veris Technologies, Salina, USA, altered)

On the other hand, solving the problem with a substantially better resolution while using the conventional method of analyzing in laboratories is economically not possible. Because for the traditional laboratory method, the costs rise almost proportional to the number of samples. Whereas with modern proximal or remote sensing methods, the number of samples hardly affects the costs.

It is important to differentiate between **soil water pH** on the one hand and **soil buffer pH** on the other hand. Ion-selective electrodes that sense hydrogen cations indicate via their voltage output only the soil water pH, which reflects what the plants experience. But the soil water pH explains nothing about the ion absorbing capacity of the soil particles. This **ion absorbing capacity** results in reserve- or exchange acidity that is indicated by the soil buffer pH. When conventional soil laboratories analyze soil in order to present recommendations for liming, both soil water pH as well as soil buffer pH are measured. The soil buffer pH is not an *a priori* existing feature of the soil, it is generated in the laboratory. Basically, soil buffer pH is the resulting pH that develops after in the laboratory there was added a defined amount of liming material. In the laboratory, the difference between the original soil pH and the final pH that is created by the liming material, a buffering solution, is recorded. This difference depends heavily on soil properties. It indicates how much lime is needed to raise the soil pH to the level that is aimed at.

So for recording the **liming requirement** in a site-specific manner by on-the-go sensing, the “buffering capacities” of the soils need to be taken care of in addition to

the soil water pH. This means either a procedure for sensing pH buffer in a similar way as in conventional laboratories must be developed or – instead of this – soil properties that can act as suitable **substitutes** must be used. The first procedure – sensing pH buffer directly in the field – has been studied, but not yet realized in an on-the-go mode (Viscarra Rossel and McBratney 2003). As for substitute soil properties, the **cation-exchange-capacity (CEC)** is a prime candidate. It predominantly depends on the clay and organic matter in soils. Both clay and organic matter particles have a net negative electric charge. Hence the higher the clay and organic matter content is, the more cations can be absorbed and thus also be exchanged with the soil water.

The cation-exchange-capacity and the clay content have rather high correlations to the electrical conductivities of soils (see Sect. 5.2.2.1). And the organic matter content can quite precisely be sensed via infrared reflectance (Sect. 5.3). Hence, substituting the traditional buffer pH measurements by techniques that can be recorded on-the-go and thus provide site-specific information is feasible. It probably is reasonable to concentrate on the cation-exchange-capacity alone as a substitute property for the buffer pH. Because this soil property includes already effects of the clay and of the organic matter.

Concerning the spatial resolution, the advantages of on-the-go sensing of soil water pH are obvious. Yet measurement errors might occur. Assuming that the soil water pH indications from conventional laboratories are precise, the question is, how well the on-the-go sensed records of ion-selective electrodes compare to these.

The comparison in Fig. 9.5 is based on the commercialized sensing technique of Fig. 9.4 and furthermore to georeferenced points in fields where exactly samples for analysing in laboratories were taken. This means that the advantages of on-the-go sensing in the spatial resolution are not considered. The on-the-go recorded data that were used without any further processing (Fig. 9.5, top) were only fairly correlated to the soil water pH from the laboratories. The correlation was considerably improved by field-specific data shifts in such a way that a regression slope of 1 was obtained (Fig. 9.5, bottom). This **post-calibration** removed field specific biases. However, for the time being, these data shifts still require a few georeferenced laboratory measurements from each field. So calibration is an important point.

Simultaneous sensing and mapping of several ions that are essential for crop nutrition in the same field operation would be an interesting and challenging objective. Experiments in this direction by using different ion-selective electrodes in **naturally moist soil** samples at the same time were simulated in a laboratory by Adamchuk et al. (2005). The ion-selective electrodes corresponded to those listed in Sect. 9.2.1. After converting the voltage output of the electrodes to the respective ion activities, the results were compared to those from methods of conventional soil laboratories. The average correlations of 15 soils from sandy, loamy and clayey fields were:

- for soil water pH $r^2 = 0.93 - 0.96$
- for available potassium $r^2 = 0.61 - 0.62$
- for nitrate nitrogen $r^2 = 0.41 - 0.51$

Since all experiments were conducted in naturally moist soils, it was assumed that primarily the low water content resulting from this caused the less successful

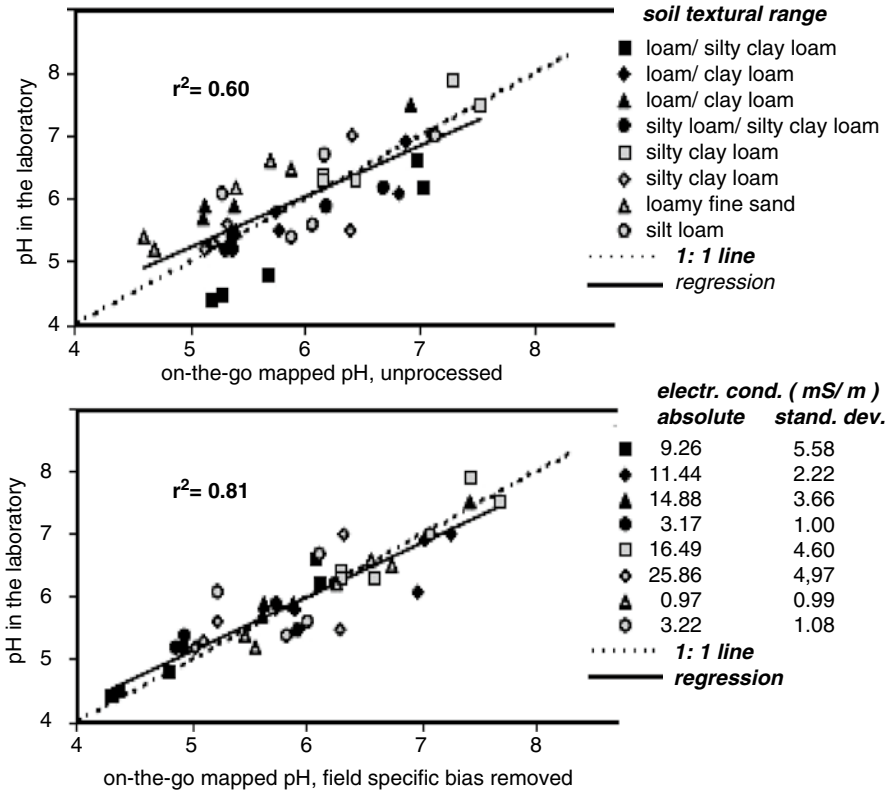


Fig. 9.5 Comparison between water pH measured conventionally in laboratories or sensed by ion-selective electrodes on-the-go (Fig. 9.4) using naturally moist soil samples. The graphs are based on records from eight fields within six states of the USA. The data in both graphs are from the same fields, but differ in the processing as explained in the text (Extracted from Adamchuk et al. 2007, altered)

results for potassium and nitrogen. From Fig. 9.3 it can be seen that potassium and especially nitrate nitrogen react on the water content in the samples. But the coefficients of determination (r^2) for the soil water pH were even better than those in Fig. 9.5.

In all these experiments, soil phosphorus was not included. Up to now, sensing this nutrient with ion-selective electrodes has not been successful. Reasons for this are dealt with later.

9.2.3 Sensing Nitrate in Slurries of Soil

Sensing in slurries or in liquid extractions of soils by **ion-selective electrodes** is being practiced in laboratories. In an on-the-go operational mode, up to now neither

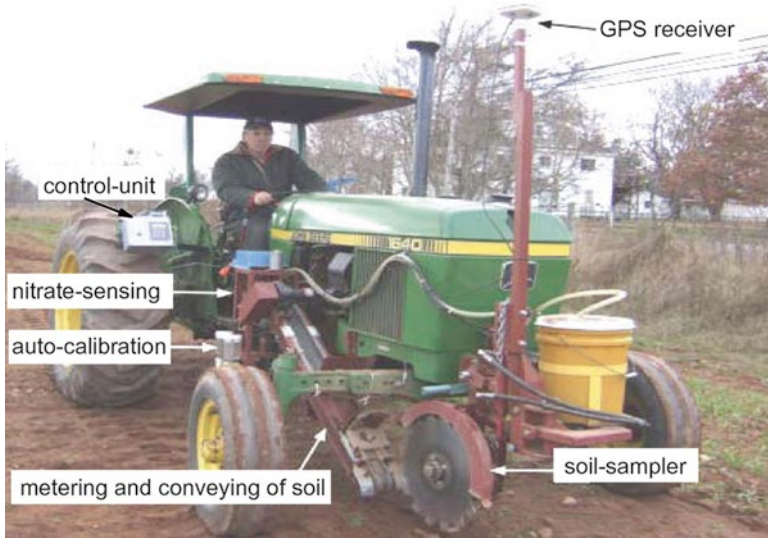


Fig. 9.6 Technology for sensing of soil nitrate in slurry samples on-the-go by ion-selective electrodes. The soil sampler is in a lifted position (From Sibley et al. 2010, altered)

the use of slurries nor of liquid extractions from soil samples are state of the art in site-specific farming. The reason for this is probably the more complicated sensing procedure compared to direct sensing of naturally moist soil. However, prototypes that can be used to sense nitrate by ion-selective electrodes in soil slurries in an on-the-go mode have been developed (Fig. 9.6).

The soil samples are collected by means of a hydraulic-powered wood saw blade. This device cuts an about 15 cm deep slot into the soil and throws a spray of fine soil onto a belt conveyor. The belt of this conveyor is provided with pockets of an oblong shape. These pockets in the belt thus receive samples from the soil. A scraper above the belt levels all soil samples to the same height. When the belt passes around the tail end roller of the conveyor, the pockets are stretched lengthwise. This stretching of the pockets facilitates their complete emptying and the precise delivery of the samples into a small container, that houses an **electrochemical cell**, the nitrate sensing unit.

Just prior to the discharge of the soil sample, water for the extraction of the nitrate ions is pumped into this container, where the ion-selective electrodes are located. A stirrer within this container is activated and creates a **soil slurry**. And consequently, the nitrate in the soil is rapidly extracted into the watery fraction of the slurry. The ion-selective electrodes sense the activity of the nitrate ions via the voltage, and the georeferenced result is recorded. This design provides an unchanging ratio of naturally moist soil to water (Sibley et al. 2008), which is important for accurate measurements of nitrate ions (see Fig. 9.3). In gravimetric terms, about four times as much water as naturally moist soil is in the slurries (Sibley et al. 2009). Because of the intermittent operation, a sensing signal is obtained every 10 s in a similar way as with soil water pH sensing.

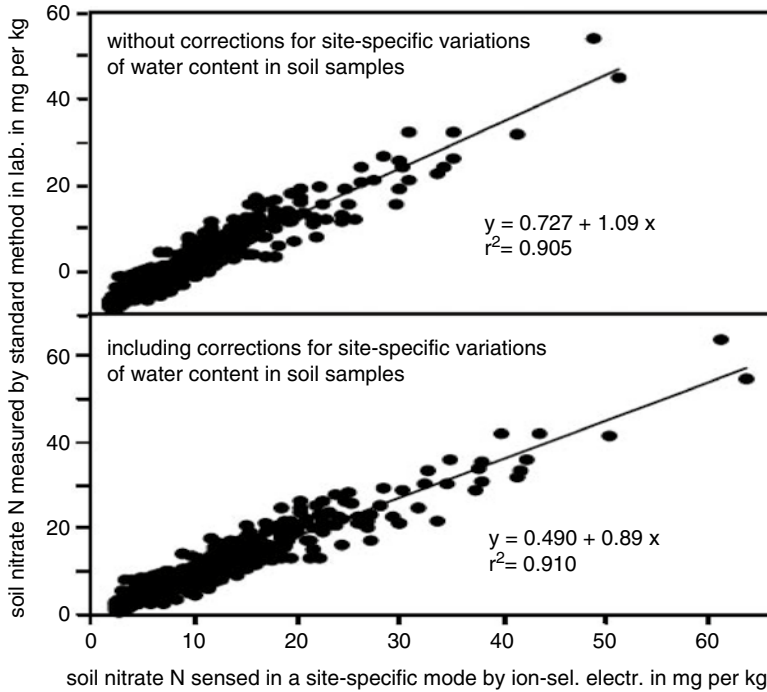


Fig. 9.7 Soil nitrate N sensed in a site-specific mode either electrochemically or by a standard method in a laboratory. The soil samples came from the same site-specific locations of several fields in Nova Scotia, Canada (From Sibley et al. 2010, altered)

The operation implies that the natural moisture content of the soil samples can vary depending on the location in the field. With a fixed ratio between the naturally moist soil volume and the amount of water added, this also means that small variations in the final water content of the slurry in the electrochemical cell can result. However, these rather small variations in the water content of the slurry due to differences in the moisture of the soil do not deteriorate the **accuracy of sensing**.

This can be seen from comparisons of soil nitrate N that was sensed in a site-specific mode either electrochemically by ion-selective electrodes or by standard methods in a laboratory. These comparisons were made with or without corrections for the varying natural moisture of the soil samples. Both cases resulted in very high correlations to the findings for the same site-specific locations from the standard laboratory methods. Differences that might be due to the corrections for the respective soil moisture of the samples do not show up (Fig. 9.7, top and bottom). This is probably because the water that is added for preparing the slurry counts much more than the natural soil moisture. Yet this does not alter the fact that substantial changes in the water content of the sensed soil have an effect on the output of ion-selective electrodes (Fig. 9.3).

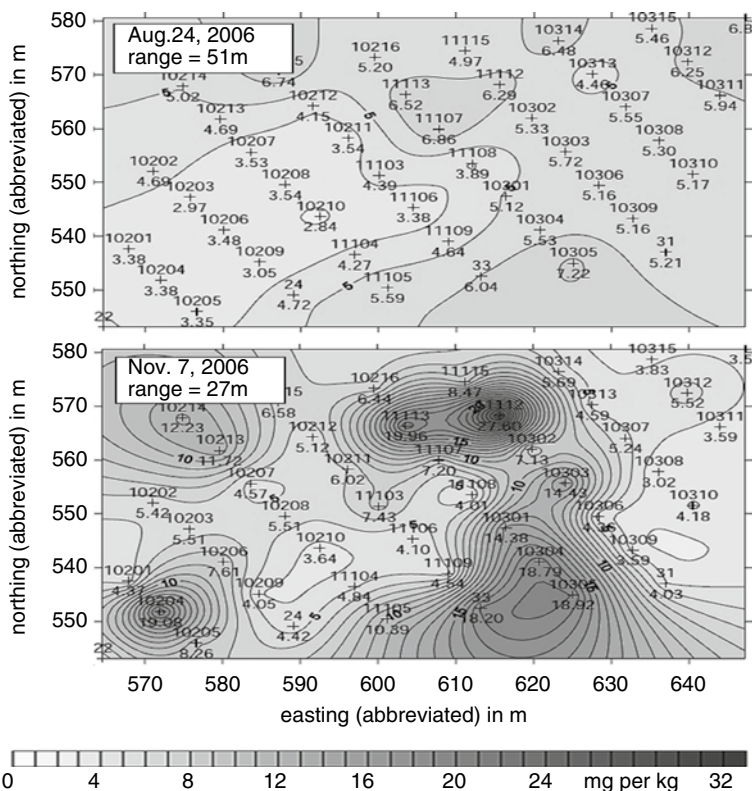


Fig. 9.8 Contour lines of nitrate-N in a field at the date of wheat harvest (*top*) and about 10 weeks later (*bottom*) as created by the sensing technique shown in Fig. 9.6. Darker colors indicate higher amounts of soil nitrate N. For details see the scale. The *plus signs* designate the respective sample locations, the *numbers above them* stand for the identification of samples and the *numbers below them* indicate the respective nitrate N level in mg per kg. The first four numbers of the northings and eastings have been deleted (Extracted from Sibley 2008, altered)

The soil minerals can store a variety of plant nutrients. But there are no minerals that contain nitrate N. Reserves of nitrate N in soils primarily depend on the decomposition of organic matter and the conversion of ammonium that results from this. For the actual plant supply, the main **reserves** of nitrate N are in the soil water. And since the soil water is a very **transient property**, so is the nitrate N in the soil. When soil water moves away from the rooted soil zone – *e.g.* into the groundwater region – the nitrate N goes with it.

On-the-go soil nitrate sensing allows to track the supply in a site-specific mode, at least for the depth range from which samples are taken. Based on the technique of Fig. 9.6, contour lines about the site-specific nitrate N supply of a field in Nova Scotia, Canada, were mapped several times during the year (Sibley 2008; Sibley et al. 2010). Figure 9.8 shows an extract of the results from the time of wheat harvest to late autumn.

There is on the one hand a **spatially** highly variable nitrate supply within the field, yet in addition on the other hand also a **temporally** rather fast changing situation. At harvest time, the nitrate supply is rather low – probably because of the previous uptake by the crop – and it is fairly uniform. Some weeks later in late autumn, the nitrate content in some parts of the field is much higher. Any similarity in the spatial pattern of the two maps is difficult to detect. The temporal increase in the nitrate content is probably due to mineralization of crop residues. But this increase varies very much spatially. This can result from locally changing amounts of crop residues or from varying conditions for the decomposition. Nitrogen uptake by bacteria that decompose straw may be important. In case much rainfall had taken place in autumn, the nitrate content at the second date probably would have been lower because of leaching. In short, the situation for soil nitrate N is very difficult to predict, spatially as well as temporally.

An adequate response to the spatial problem is site-specific sensing. The best solution for the temporal problem, however, is sensing and controlling in real-time. Up to now, this is not possible with remote sensing. Hence doing this in a proximal way from vehicles and in an on-the-go operational mode is the logical consequence. Yet an important point is that using ion-selective electrodes allows for on-the-go operations, but not in real-time. This is because presently all ion-selective electrodes (Figs. 9.4 and 9.6) rely on intermittent operations with an average time of about 10 s between successive signals. And if a spreader or sprayer of farm chemicals is to be controlled on-the-go with sensing during the same operation, the **time span** before a signal has its effect on the distribution of the fertilizer is even longer than these 10 s. Because the actuator – the device that steadily readjusts the spreader or sprayer based on the signals – in addition needs a fraction of this time interval of 10 s to get effective. So the time interval of 10 s between the signals to get effective can be taken as an absolute lower limit.

Yet spreaders or sprayers operate with travel speeds between 2 m/s (= 7.2 km/h) and about 4 m/s (= 14.4 km/h). The minimum time interval of 10 s hence corresponds to a distance in the direction of travel of 20–40 m. This range is much longer than the conventional distance between the front of a tractor – where the samples might be taken – and the distributing devices of spreaders or sprayers. Of course, these limitations do not hold if mapping takes place and maps are used for controlling subsequent operations.

9.2.4 *General Prerequisites and Prospects*

The **first prerequisite** for sensing by ion-selective nutrients is that the respective ion must exhibit an electric potential in a solution or in a slurry. This potential of either cations or of anions depends – among others – on the well known **Hofmeister series**, which ranks the ions according to their hydrophilic or conversely their hydrophobic properties. Within the respective Hofmeister series for anions or for cations, the nitrate anion as well as the hydrogen- and potassium cations are located rather centrally. Thus these ions do not present unusual situations.

But the plant available orthophosphate ions do. These anions stand at the far end of the Hofmeister series, they are strongly hydrophilic. Hence these anions are heavily hydrated. And in turn, the consequence of this is that their electric potential largely has been taken away by hydrogen ions, and thus their free energy is rather small. This makes the sensing of phosphate ions more difficult compared to those from hydrogen-, potassium- and nitrogen, however, not impossible (Kim 2006).

A **second prerequisite** are suitable ion-selective electrodes. The general design is as outlined in Sect. 9.2.1, but differences exist in the treatment of the membranes with special chemicals in order to improve the ability of separating specific ions (Kim et al. 2006, 2007a, b, 2009). The need for frequent calibrations and the wear of some membranes must be considered.

A **third prerequisite** are appropriate extractants that provide for the targeted ions in slurries or solutions from the soil sample. The simplest situation is when water can be the extractant and the content within a naturally moist soil suffices. This situation holds for sensing of the soil water pH. For nitrate, the situation is that water too can be used as an extractant, however, some is added to naturally moist soil to create a slurry. Kim et al. (2007b) searched for an extractant that can be applied to **simultaneously** sense the ions of the three macronutrients nitrate-N, plant available phosphate (orthophosphate) and plant available potassium. The Kelowna extractant – a mixture of acetic acid and ammonium fluoride – can be used simultaneously for all three macronutrients. This solution is employed as a multi-ion extractant in laboratories in British Columbia. It should be noted that the simultaneous sensing of different ions implies that the electrochemical cell is provided with a separate ion-selective electrode for every nutrient.

A **fourth prerequisite** is that there should be no interference between different ions. Theoretically, the composition of the ion-selective electrodes or its membranes aims at excluding any interference. However, there still are limits in this respect. Figure 9.9 shows the situation for simultaneous sensing of the three macronutrients. The respective ion-selective electrodes that were used complied with those mentioned in Sect. 9.2.1 and their membranes – when necessary – were prepared with suitable ligands. The Kelowna solution (see above) was used for extracting the ions. The results are based on 37 different soils located in Illinois and Missouri, USA.

For each of the three graphs in Fig. 9.9, the respective **primary ion** that is to be sensed is on the axis along the bottom. In case of cation sensing (Fig. 9.9, bottom), the voltage rises when the concentration increases – as must be expected. Contrary to this, for the anions, the voltage mainly goes down (Fig. 9.9, top). For the electrodes that pick up nitrogen and potassium as primary ions (top left- and bottom graph), there was no interference by phosphate ions. Furthermore, the nitrate and potash electrodes were not sensitive to potassium and nitrate ions respectively (these graphs are not shown). But the responses of the phosphate electrode were influenced by concentrations of nitrate ions (graph top right) as demonstrated by the changing colour. Even more important probably is the fact that the voltage induced by the phosphate ions did not change unidirectionally when the concentration increased. Simultaneous sensing of several macronutrients in electrochemical cells in an on-the-go mode without doubt is worth to strive for, but it is not yet state of the art in precision farming.

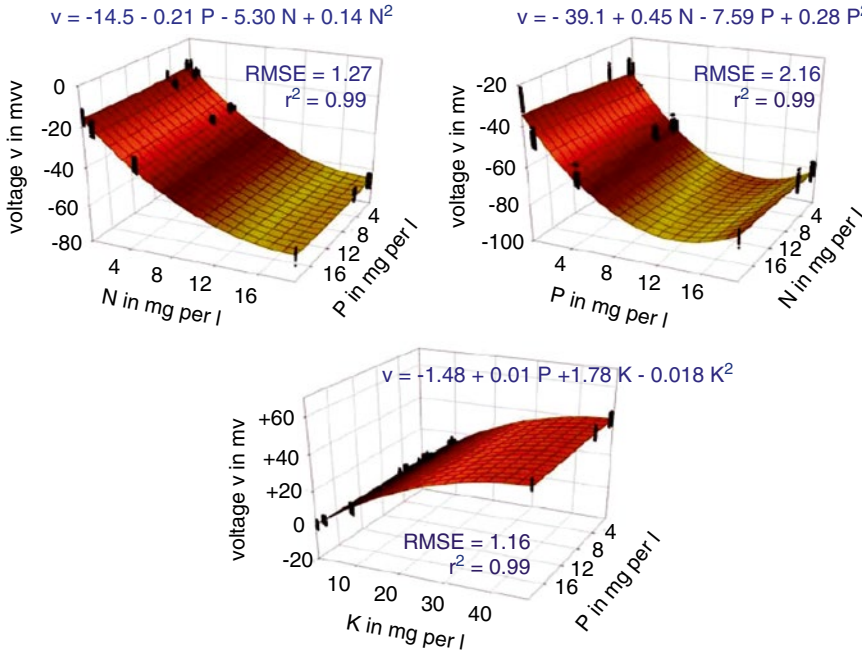


Fig. 9.9 Simultaneous sensing of ions from nitrate, from plant available phosphate and from plant available potassium by an electrochemical cell with ion-selective electrodes in a laboratory. For each graph, the respective primary ion that is to be sensed is on the front axis along the bottom. And the interfering ion is on the respective right axis of the bottom (From Kim 2006, altered)

Summing up: within the near future, the best prospects in practical applications probably exist for on-the-go soil water pH sensing. The reason for this is not only the fact that this can be done using naturally moist soil and that – contrary to sensing of nitrate – no technique for the creation of a slurry is needed. An additional fact is that recording of the soil water pH is **temporally** simpler than the sensing of nitrate by ion-selective electrodes. Because the soil pH hardly changes over months, but the nitrate content can vary within some days. And the more short-termed the situation is, the more a control system is needed that operates in real-time. Consequently, for the application of nitrogen, a real-time control system is much more important than for the spreading of lime. Yet none of the present sensing systems that use ion-selective electrodes allow real-time control because of the time intervals between the signals.

As for potash and phosphates, the former nutrient is easier to sense by ion-selective electrodes than the latter. However, the site-specific situation for phosphates can – after some preparations – very well be mapped via sensing of the nutrient removal by the previous crop (Sect. 9.1). On soils with clay the same might hold for potash. So it is reasonable not to use the same sensing method for all nutrients.

9.3 Fertilizing Based on Reflectance of Soils

9.3.1 General Remarks

Using signals that are derived from optical reflectance and not from the electrochemical potential in soils has distinct advantages for real-time control of fertilizing. Because these signals are almost **immediately available**. The reflectance signals are transferred from the soil to a sensor with the speed of the light. Instead of a signal interval of about 10 s, as with ion-selective electrodes, several signals within 1 s can easily be recorded by a sensor. In practice, some time for processing of the signal and for actuating the control of a spreader or a sprayer must be considered. Yet the operating speed of modern computers and actuators is such that process control within **real-time** for site-specific fertilizing or spraying is feasible and for some applications already is state of the art. This is an important criterion when the situation for the supply of crops varies not only spatially but temporally as well. A prime example for this is the supply of crops with nitrogen, which requires rather fast control responses.

However, the situation for sensing via reflectance in case of **soil nutrients** is not the same as with natural soil properties such as texture (sand, clay, loam), organic matter and water. This is – among others – because the respective amounts differ substantially. In rough gravimetric terms, the constituents that stand for the natural soil properties mentioned above account for many tons per ha, whereas the macronutrients at stake can easily be expressed in kg per ha. This is at least the situation if the macronutrients that are available to crops are considered. With micronutrients, the amounts required might be even below 1 kg per ha.

The **coefficients of determination** between optical reflectances and various soil properties in Table 9.2 are based on **full spectra regression analyses** of soil samples collected either in several areas of the United States (Chang et al. 2001; Lee et al. 2009) or in the Zhejiang province of China (He et al. 2007). The natural soil properties listed are rather well correlated to the spectral data. This is in line with some results in Sect. 5.3. About the same applies to the properties that are related to soil pH. But most of the soil nutrients listed in Table 9.2 show a rather poor correlation to the reflectance.

An important point in this respect is, which soil constituents can be regarded as nutrients that are available for plants. A prerequisite is that the respective nutrients are either solvable in water or at least in a chemical **extractant** (Table 9.2) that approximately removes from soil samples the plant available nutrients and hence is used in the laboratories as a standard.

The total N in soils cannot be regarded as being plant available since generally a large part of it is fixed in organic matter. The mineralization of this part can take years or even decades. Most of the mineral N is taken up by crops as nitrate ions, however, plants may also absorb ammonium ions. Up to now, soil sensing methods concentrate on recording the nitrate ions.

The rather discouraging results for spectroscopic sensing of soil nutrients as presented in Table 9.2 should not be regarded as a proof of perpetual failure.

Table 9.2 Correlations between optical reflectance and various soil properties from spectroscopic experiments in laboratories

| Soil property | Coefficients of determination (r^2) | | |
|---|---|-------------------------------|--------------------------------|
| | Chang et al. (2001) ^a | He et al. (2007) ^b | Lee et al. (2009) ^c |
| Natural properties | | | |
| Water | 0.84 | – | – |
| Organic carbon | 0.60 | 0.92 | 0.80 |
| Total N | 0.85 | 0.88 | 0.53 |
| Clay | 0.67 | – | 0.76 |
| Silt | 0.84 | – | 0.79 |
| Sand | 0.82 | – | 0.79 |
| Properties related to pH (extractants in brackets) | | | |
| pH (water) | 0.55 | 0.87 | 0.68 |
| Ca (ammon. acetate) | 0.75 | – | 0.80 |
| Mg (ammon. acetate) | 0.68 | – | 0.73 |
| Nutrients, plant available (extractants in brackets) | | | |
| K (ammon. acetate) | 0.55 | 0.58 | 0.13 |
| P (Mehlich, Olsen) | 0.40 | 0.29 | – |
| Cu (Mehlich) | 0.25 | – | – |
| Mn (Mehlich) | 0.70 | – | – |
| Zn (Mehlich) | 0.44 | – | – |

The wavelength ranges used were

^aChang et al. 2001: 1,300–2,500 nm

^bHe et al. 2007: 350–2,500 nm

^cLee et al. 2009: 350–2,500 nm

In theory, soil nutrients have an optical fingerprint that is expressed in its reflectance as well as other soil constituents have. However, it may be more difficult to detect their fingerprints because of **interferences**. In case these interferences result from other soil constituents, targeted processing of spectral curves might help to differentiate. However, in addition to interferences from other soil properties, there may be substantial data scattering or **signal noise** due to a too fast response, to inertial reactions in vibrating instruments or many other uncontrolled factors.

A vast number of different techniques for **removing noise** is available and can be used for online data processing such as

- computing weighted moving averages that create a new sequence of data
- smoothing and differentiating of data by simplified least squares procedures (Savitzky-Golay filtering)
- employing first- or second derivatives of full spectra for attenuating the influence of solar angles as well as of the viewing geometry
- using a Fourier analysis or -transformation of full spectra, which is a method of decomposing the signals into sine waves of different frequencies
- transforming a full or partial spectrum by wavelets (= small waves). This method is based on a frequency-time analysis, which supplements the general frequency-amplitude approach.

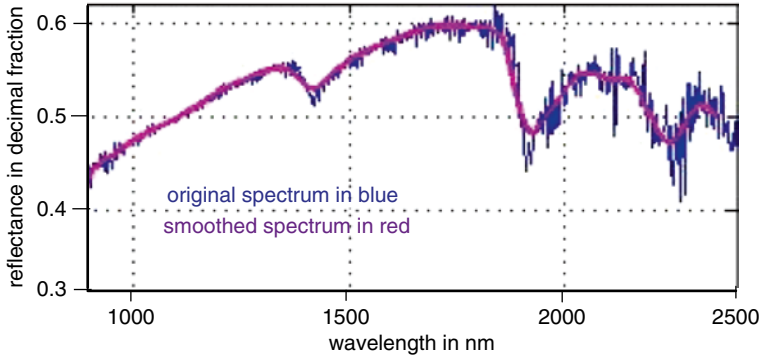


Fig. 9.10 Soil spectrum as originally recorded and after smoothing or removing noise by discrete wavelets. The three depressions in the spectral curve are caused by water absorbance (Extracted from Ge and Thomasson 2006, altered)

Removing noise can help substantially to get rid of unwanted influences (Fig. 9.10) but must be applied with care in order to avoid loss of important information. In addition to denoising methods, multiple regression analyses can substantially assist in extracting more information from the spectra such as

- partial least squares regressions
- principal component regressions
- stepwise regressions.

Denoising techniques and regression analyses cannot be dealt with here at length. In the future, these methods for processing the sensed data will probably often be used as “**black boxes**” in a similar way as present day computer programs. For details see Brandt (2011), Haykins and Van Veen (2003), Martens and Naes (1992) as well as Savitzky and Golay (1964). The important point is that a careful application of denoising methods and regression analyses makes it possible to extract from spectroscopic spectra exactly the information that is needed for site-specific precision farming.

The first step is using the relation between specific soil properties and the reflectance for the **calibration** of the sensor and its software. The reflectance that is detected in fields of a defined region thus helps to adjust the sensing equipment. The result can be that for soils that are located outside this defined area, the sensing device gets inaccurate. However, this is a matter of how much the soil properties vary geographically. An important question for the future will be, how much generalizing and standardizing of calibration is possible while attempting to use the same calibration for wide areas.

The calibrated sensing equipment can then be subjected to a **validation** process. This validation too is a comparison of soil properties as recorded by traditional procedures against the results that were detected by the spectroscopic sensing method. The difference is that now directly the calibrated instrument is used for the comparison.

Both the calibration as well as the validation can be based on **full reflectance spectra** or on **discrete wavebands**. In case of full spectra, the objective can be simultaneous sensing of several soil properties in one operation. Up to now, the results with simultaneous sensing of several soil properties via full spectra are good or satisfying with some properties, with others they are disappointing (Table 9.2). Possible reasons for this have been dealt with above.

An alternative is to base the first step – the calibration procedure – on full spectra but to extract from this information in a second step the knowledge for sensing single soil properties by discrete wavebands of small width. With this method, the searching of the correlations relies on a rather broad range, the validation is limited to one or a few narrow bands. And these narrow wavebands finally are used for sensing in site-specific applications. Because of the small bandwidths that are involved, this method improves the chance that interferences with spectral ranges that are affected by other soil properties can be avoided. It is probably for this reason that this method of **single property sensing** by discrete wavebands is dominating up to now in practical applications. However, the narrower the wavebands are on which the sensing relies, the more important get effective processing methods for removing noise and for smoothing the data (Fig. 9.10).

An interesting approach for the future might be simultaneous **hyperspectral sensing of several properties**. The term “hyperspectral” in this respect indicates too that only very distinct narrow wavebands are selected for every soil property and that spectral regions in between are disregarded in order to remove the probabilities for interferences.

9.3.2 Sensing the Lime Requirement

On-the-go sensing of the soil water pH by ion-selective electrodes in combination with electrical conductivity recording for indicating the buffering properties of soils and hence the lime required is state of the art (Sect. 9.2.2). Yet this method cannot be used to control the lime application in **real-time** because of the time delay that is associated with sensing by ion-selective electrodes. Sensing of the lime requirement by reflectance would remove this time problem.

Sensing the soil water pH alone by reflectance does not suffice. In order to account for the varying **buffering properties** of soils, Viscarra Rossel et al. (2006) used full spectra reflectance sensing techniques in laboratories for Australian soils and processed the data by multivariate analyses with partial least squares regressions. For the estimation of the lime needed, not only soil water pH was the subject of spectral sensing, but several soil properties as *e.g.* cation exchange capacity, organic carbon and texture were considered in the program as well.

The results that were thus obtained depended highly on the spectral range. When solely visible reflectance (400–700 nm) was used, the spectroscopic results were not reliable (Fig. 9.11). The near-infrared reflectance (700–2,500 nm)

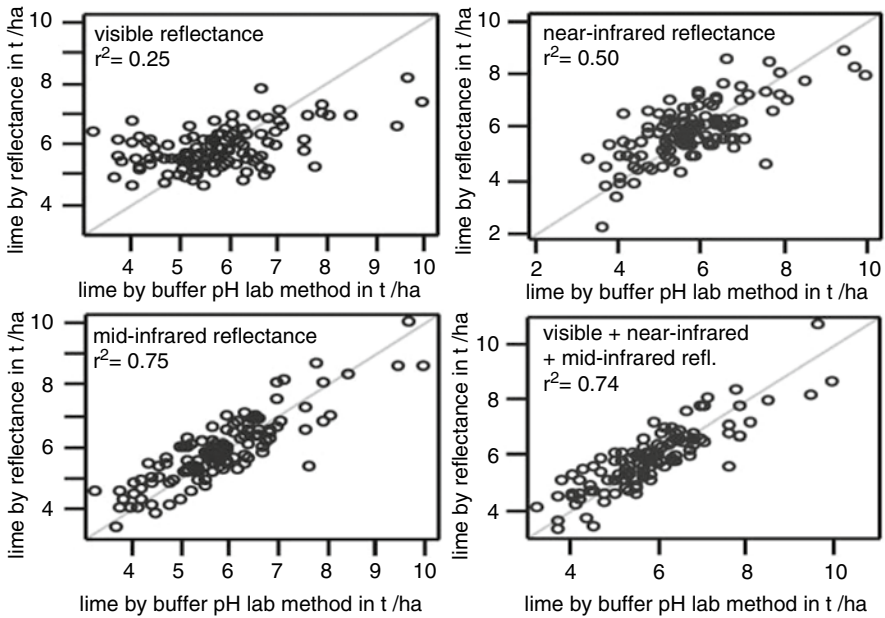


Fig. 9.11 Comparing the lime requirement as determined in laboratories either by standard methods or by reflectance of full spectra (From Viscarra Rossel et al. 2006, altered)

resulted in an improved yet still not satisfying correlation. But the mid-infrared spectroscopy (2,500–25,000 nm) finally supplied a coefficient of determination ($r^2=0.75$) that offered prospects for application. Using all these three spectral ranges in a combined manner together provided a similar result. Consequently, the mid-infrared region *per se* alone should be the best choice. This superiority of sensing in the mid-infrared range is in agreement with results that have been obtained with several natural soil properties (Sect. 5.3.2, Table 5.4). However, it is more expensive to sense in this spectral region than to use visible radiation or the near-infrared range. Even more important is that up to now mid-infrared reflectance needs rather dry soil, which prevents the application for proximal on-the-go sensing.

The soil properties that are important for the control of liming do not present the same conditions on a time scale. With professional farming, checking the soil water pH might be reasonable every 3–5 years. Compared to this, the soil properties that must be known in addition to define the **buffer situation** – like *e.g.* cation-exchange-capacity, texture and organic carbon – remain constant over much longer time periods. Hence a possible approach would also be to sense the soil water pH on a site-specific basis via reflectance in real-time while liming takes place, but to rely for the required buffer corrections on simultaneously used maps. These georeferenced digital maps with data about long-term soil properties

would need to be pre-processed for real-time site-specific buffer corrections. Such a combination of real-time sensing on the one hand and simultaneous use of pre-processed georeferenced maps with long-term soil properties on the other hand might be useful for an intelligent control of several field operations.

9.3.3 Sensing the Phosphorus Requirement

Phosphorus exists in soils within different compounds, especially in phosphates of calcium, aluminium and iron. These phosphate compounds are mainly a feature of natural soil properties, yet to some extent also originate from fertilizers, hence from human activities. In moderately acid soils as well as in alkaline soils, calcium-phosphates dominate. When the soil pH goes down, the proportion of aluminium- and iron-phosphates increases. All these phosphate compounds have very different optical spectra. They can be sensed spectrally rather easily with a very low classification error (Bogrekcı and Lee 2005).

This information, however, only indicates that there are calcium-, aluminium- or iron phosphates in a soil. It discloses nothing about the availability of phosphorus to plants. In fact, the important criterion for the supply of crops and hence for site-specific control of fertilizing is the **plant available phosphorus**. This exists in soil solutions either as hydrogen-phosphate anions (HPO_4^{2-}) or as dihydrogen-phosphate anions (H_2PO_4^-). The former anion dominates in weakly alkaline soil solutions, and the latter instead in slightly acid situations. Compared to the amounts of phosphorus in the soil phosphates, those of plant available phosphorus in the soil solution usually are very small. This is because phosphorus does not remain in solution for long in soils. The anions that crops extract from the soil solution are usually replenished from calcium-phosphates, provided the soil has a reservoir of these.

In soil laboratories, the plant available phosphorus is defined by chemical extraction. A standard extractant is the Olsen solution of sodium-bicarbonate, though also other extractants are used. For highly fertilized soils, sometimes simply water is recommended as an extractant (Finck 1991).

Sensing the plant available phosphorus by **reflectance** in laboratories traditionally has been done on the basis of **dried soil samples**. However, Maleki et al. (2006) and Mouazen et al. (2006) concluded that the spectral prediction of plant available phosphorus in **fresh, wet soils** is better than in dried samples whilst portending that the sensing takes place for anions in a soil solution. Their hypothesis is that hence this phosphorus fraction in the water phase of the soil correlates well with spectral signals and consequently more water implies also more plant available phosphorus.

The spectra in Fig. 9.12 are based on sensing of fresh, moist soil samples from several fields in Belgium. But since the water content of the sensed soil samples varied, the contents of available phosphorus were presented on the basis of dry soil in order to allow for a precise comparison. Yet this does not alter the original state of the soil samples at the time of sensing. The higher the soil content of available

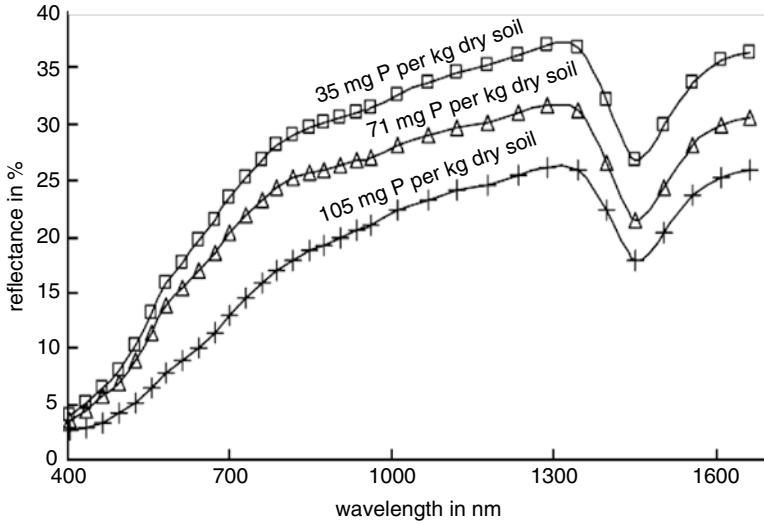


Fig. 9.12 Average reflectance of 30 spectra of soil samples for three levels of plant available phosphorus, defined by the Olsen extractant. Each sample contains diverse types of soil textures and different soil moisture contents (From Maleki et al. 2006, altered)

phosphorus, the lower the reflectance is. The courses of the spectra resemble those of water sensing by reflectance (see Sect. 5.3.2). More soil moisture also decreases reflectance in a similar way. Hence the question of autocorrelation between available phosphorus and water in soils deserves attention (Maleki et al. 2006). Nevertheless, the **coefficients of determination** (r^2) for the relation between the plant available phosphorus based on Olsen extractants and the **full spectra reflectance** from 400 to 1,660 nm were 0.73 and 0.75 and hence rather good. The small difference depended on the data smoothing technique that was used.

This method of sensing available phosphorus by visible and near-infrared spectra has been transferred from laboratory to field application for a site-specific on-the-go operation (Fig. 9.13). The spectral illumination is transferred by an optical fiber cable to the flattened soil underneath a cultivator sweep. A second optical fiber cable leads the reflectance back from this soil to the spectrometer. The cultivator sweep is adjusted for this flat surface sensing along its open bottom plane with a depth of about 15 cm from the soil surface.

For precise results, this **flat surface sensing** needs a very accurate guidance of the illuminating probe in order to get a high and rather constant part of the diffuse reflected light to the spectrometer. For this, the bottom edges of the subsoiler sweep must be held exactly parallel to the soil surface and the illuminating optical probe must be continuously sliding in a slanted position over the measured soil surface. In case the bottom edges of the sweep are not precisely parallel to the soil surface, the illuminating probe is guided somewhere above the sensed soil surface. But any increase in the distance between the illuminating probe and the soil surface reduces

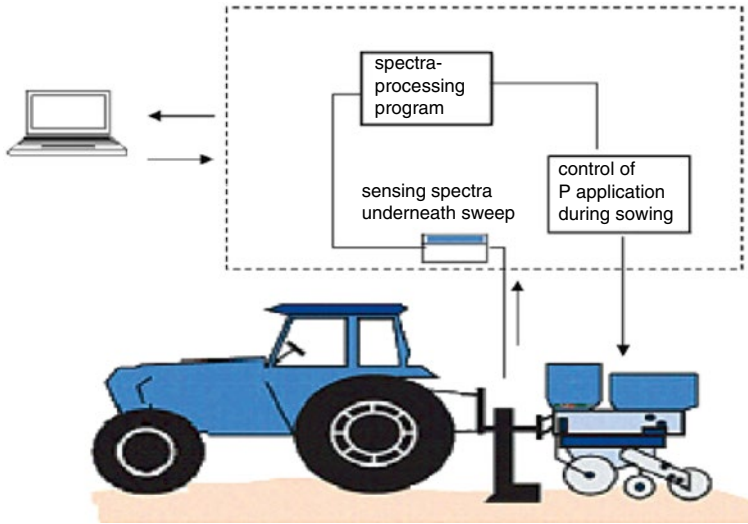


Fig. 9.13 Scheme for site-specific on-the-go flat surface sensing and control of phosphorus application during sowing (From Maleki et al. 2008a, altered)

the reflectance that is received by the spectrometer and thus impairs the sensing precision (Mouazen et al. 2009).

Furthermore, the **time lag** that is inevitable between the spectral soil scanning and the deposition of the fertilizer deserves attention. For accurate georeferenced site-specific operation, this time lag must be compensated for by a defined distance of the soil scanning device ahead of the fertilizer outlets. This time lag is generated by processes that successively take place, first the soil scanning, then the spectra processing plus signal transportation and finally the reaction of the fertilizer applicator due to the site-specific adjustments by the electric actuator. Each of these processes goes rather fast, but the total succession still takes between 1 and 2 s.

The offset distance in the direction of travel that is needed for the sensor position ahead of the fertilizer outlets in order to compensate for this time lag depends on the tractor speed. Maleki et al. (2008b) found that for each 1 km/h in tractor speed, an offset for the sensor ahead of the fertilizer outlets of 0.5 m was required. This means that the design as outlined in Fig. 9.13 would be adequate only for rather low speeds. For a speed between 7 and 8 km/h it is recommended to install the sensor in front of the tractor. In case this results in excess offset because then the overall time lag is not sufficient to compensate for the distance to the front of the tractor, an **artificial, additional time delay** in the signal transfer can easily correct the situation.

Time lags occur with all sensors that are used in on-the-go field operations. However, as long as the problems can be solved by spatially arranging the machine elements accordingly or by artificial time delays in the signal transfer – as shown above – the precision in the application of agrochemicals still can be good.

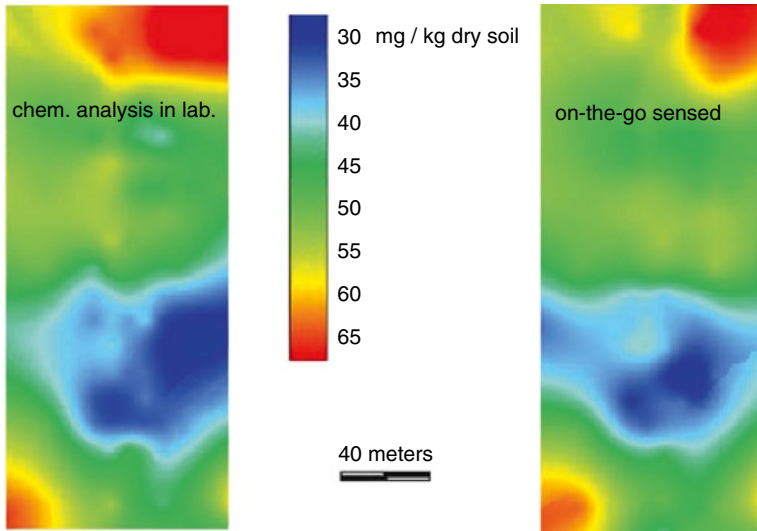


Fig. 9.14 Site-specific maps of plant available phosphorus for a field with silt loam in Belgium as obtained from chemical analyses in a laboratory (*left*) and from spectroscopic on-the-go sensing (*right*). The data for the chemical analyses as well as for the spectroscopic sensing were recorded at precisely the same georeferenced 126 locations. After that, the maps were created by kriging on a 1×1 m grid. So in effect, the two methods of analysing or detecting the phosphorus are only compared for specific spots in the field, they are not at all compared in their ability to resolve an area adequately at reasonable costs for site-specific farming (From Mouazen et al. 2009, altered)

If the soil phosphorus supply is mapped, the time lag situation would be somewhat different. The time lags that occur during the mapping process as well as those that result from the subsequent spreading operation together would have to be considered. In case the time lags, the travel directions and the operating speeds – from mapping and from spreading – are the same, the offset distances cancel each other. Yet there can be many different situations, and georeferenced path control is essential. For mapping, it seems reasonable to combine the flat surface sensing with a cultivating process.

The spatial comparison of detecting plant available phosphorus in Fig. 9.14 by spectroscopic sensing on the one hand and by conventional, chemical analysing in a laboratory on the other hand is based on specific spots in a field. It demonstrates that the spectral on-the-go method (Fig. 9.13) can provide for a similar result in the field as the chemical analysing can in the laboratory – for single spots. This principal precision in detecting the phosphorus is the prerequisite for using the high spatial resolution that is needed for site-specific application. It is obvious that in practice any analysing in laboratories never can provide this spatial resolution because of its high costs.

In field trials with maize in Belgium for which the phosphate fertilisers were either uniformly applied or distributed in a site-specific way according to the method in Fig. 9.13, the site-specific application resulted in a small saving of fertiliser of

4 %. Despite this small saving in fertiliser, the yield with the site-specific application was about 5.8 % higher. This difference in yields was significant (Maleki et al. 2008a).

It should be realized that the results of such field trials depend on many factors, especially in this case on the *a priori* existing supply of plant available phosphorus.

9.3.4 Sensing the Potassium- and the Nitrate Requirement

Potassium reserves exist in soils mainly in silicates or as absorbed ions of clay particles, and the amounts can vary greatly with the texture. For crop nutrition, the small amounts of **potassium ions** in the soil water solution or in a soil extractant of the laboratory are important. Detecting these ions by visible and infrared reflectance has been investigated in laboratories (Viscarra Rossel et al. 2006; Lee et al. 2009). Up to now, the results have not been very encouraging. And probably because of this, site-specific on-the-go sensing of plant available potassium has not yet been attempted. So for site-specific application of potassium – according to the present state of the art – either recording the situation via the removal by previous crops (Sect. 9.1) or sensing based on ion-selective electrodes (Sect. 9.2) should be considered as alternatives.

The soil nitrogen exists largely in compounds within the soil organic matter. Plants take up inorganic nitrogen that either results from decomposing of organic matter or from fertilizing as nitrate or as ammonium. Of these, nitrate is generally present in much higher concentrations and more mobile. Hence, nitrate ions are the dominant form of nitrogen used by plants. They exist mainly in the soil water and are not absorbed by soil minerals.

For a long time, sensing **nitrate ions** by soil reflectances in the visible and infrared range has not been successful (Viscarra Rossel et al. 2006). Solely the total N of soils was rather well defined by reflectance of this wavelength range (Table 9.2). But this is not surprising since the total N is highly correlated to the soil organic matter, which can be estimated accurately.

However, the perspectives for reliably sensing of nitrate ions by reflectance have been improved (Jahn et al. 2006; Jahn and Upadhyaya 2006). A combination of three steps has enhanced sensing of soil nitrate:

- using mid-infrared reflectance instead of visible and near-infrared reflectance
- smoothing and decomposing this reflectance by wavelets (see Sect. 9.3.1)
- in this way, detecting a narrow waveband in the mid-infrared range that is especially suited for sensing nitrate ions.

The described steps can be regarded as a **calibration procedure** that leads to a suitable selection, setting and adjustment of the spectroscopic technology. The first step – using mid-infrared reflectance instead of near-infrared reflectance – is a proven way for enhancing the estimation of various soil properties (see Sect. 5.3.2,

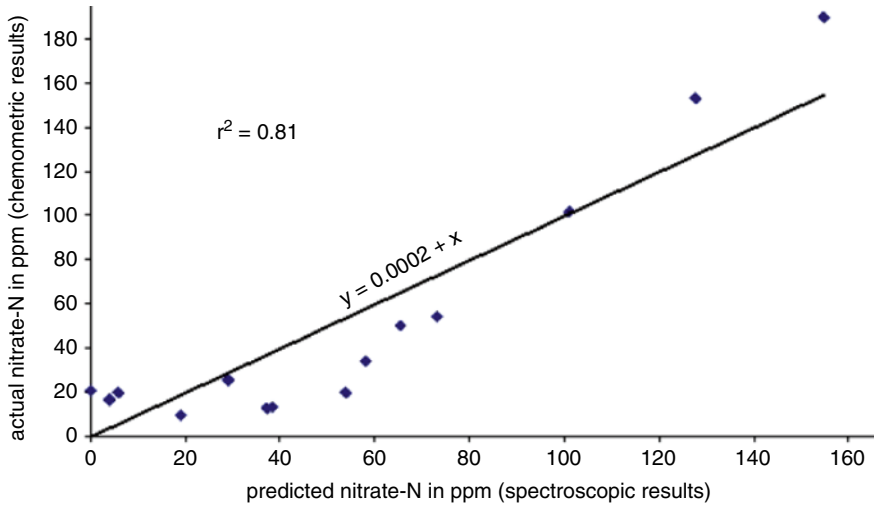


Fig. 9.15 Sensing nitrate-N in samples of soil paste by mid-infrared reflectance with 7,148 nm wavelength versus results from traditional analyses in a laboratory (From Jahn and Upadhyaya 2006, altered)

Table 5.4). The soil spectra in the mid-infrared range just have more distinct peaks and dips than those in the near-infrared region, and this improves the estimation results. However, a disadvantage is the higher investment for the sensing equipment compared to near-infrared spectroscopy. The second step pertains to the processing of the spectral data. This processing provides the means for the third step, finding the most effective wavelength for sensing nitrate ions.

So the procedure is that the calibration starts with the full mid-infrared spectrum from 2,500 to 25,000 nm wavelength, but the final validation is effected just by a discrete narrow waveband. For soil samples from several Californian fields, the result was a **wavelength of 7,148 nm**. The relation between the predicted nitrate from the spectral sensing with this wavelength and the traditional results from the chemometric analyses in a laboratory is shown in Fig. 9.15.

The relevance of this method of soil nitrate sensing rests not only on the reliability of the correlation between the spectral sensing and the traditional analyses in laboratories (Jahn et al. 2006). Important is also that it allows to simplify the sensing via mid-infrared radiation by employing a **discrete narrow waveband**, which in effect is a drastic reduction of the measuring range. This in turn can provide prospects to reduce the sensing cost for a final site-specific application of mid-infrared radiation.

However, site-specific spectral sensing of soil nitrate-N in an on-the-go manner has not yet been realized in practice. A question is at which **depth** from the soil surface the sensing should take place. Nitrate-N can be relocated rather fast within the soil profile since it moves with the waterfront. And it might be taken up by crops from depths well below the topsoil (Shanandeh et al. 2011). It is for this reason that

with the traditional soil analyses in laboratories for nitrogen – the Nmin method – in humid regions the samples are collected and averaged from a 90 cm deep profile (Marschner 2008). Since the relocation of nitrate-N will depend largely on the precipitation, site-specific spectral sensing should at least be adjustable for the depth from the soil surface.

For on-the-go sensing in fields, the mid-infrared radiation would also have to cope with varying soil moisture (Sect. 9.3.2). A discrete narrow waveband might be better suited for this than a full spectrum. However, the verification of this assumption has not yet been provided.

9.4 Fertilizing Nitrogen Based on In-Season Crop Properties

Basing the control of fertilizing on **past crop properties** instead of those of the soil is state of the art when the nutrients that were removed by the yields of previous crops are relied on (Sect. 9.1) However, because of the time scale involved, this method lends itself for detecting rather long-term supplies of those nutrients, whose availability temporally does not change fast such as *e.g.* phosphorus.

Contrary to this, basing the fertilizing on **current crop properties** is a method that can provide signals for rather immediate, short-term control and hence with a high temporal precision. The ideal application for this method is associated with online and on-the-go proximal sensing and control in real-time. This in turn means that this method fits well to nutrients, for which the supply of crops changes rather fast. The classical macronutrient for this method hence is **nitrogen**, and so this section is devoted to the application of this nutrient. This limitation, however, does not imply that sensing on the basis of current crop properties might not be useful for other applications as well.

It is obvious that any use of **crop properties** for the control of farming operations is also a control that is oriented on soil properties – at least partly. This is simply because the properties that the plants have are not independent of the soil on which they grow. Therefore a very important advantage of basing the control on properties of the crops is that the signals that are thus obtained depend on an **interaction** between the plants and its soil. This means that *e.g.* the influence of the respective root development on the nutrient uptake is automatically taken care of.

All nutrient extraction methods that are used in soil laboratories so far aim at a simulation of this influence of the soil to crop relation on the availability of nutrients. However, this simulation of the extraction of nutrients by crops in laboratories has to cope with changing situations, *e.g.* varying root lengths during the development of plants. The best solution to this problem of fertilizing control certainly simply is to use the respective **site-specific soil to crop relation** in the field as it exists by an intelligent sensing system.

Fertilizing based on current crop properties can provide this. It can be oriented at the actual nutrient uptake of crops, assuming that suitable surrogate properties for this are available and selected.


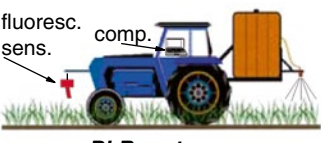

| system | physical criteria | crop criteria |
|--|---|--|
|  <p>reflect. sensor comp. Kiel system</p> | <p>special wavelengths from the visible and near-infrared range of the crop's reflectance</p> | <p>chlorophyll-concentr. in the leaves plus total area of leaves (leaf-area-index)</p> |
|  <p>fluoresc. sens. comp. DLR system</p> | <p>chlorophyll-fluorescence of plants, induced via laser-radiation</p> | <p>chlorophyll-concentr. in the leaves plus sometimes the canopy-surface</p> |
|  <p>pendul. sensor comp. Bornim system</p> | <p>diversion-angle of a pendulum that is dragged along the upper part of the crop</p> | <p>plant-mass, crop-resistance against bending</p> |

Fig. 9.16 Sensor based systems for site-specific nitrogen top dressing

Three presently used commercialized systems for on-the-go nitrogen top dressing that rely on sensing of crop properties are listed in Fig. 9.16. The names refer to locations of the research groups that originally developed the systems.

The **Kiel system** was initiated from research at the University of Kiel about two decades ago (Heege and Reusch 1996). It relies on sensing and processing the visible and near-infrared reflectance of crop canopies for signals to control the nitrogen application rate. Among the various alternatives (Fig. 9.16), this method is the most frequently used in farming.

The **DLR system** originated from research by Günther et al. (1999) in the Department of Optoelectronics of the DLR Research Center in Wessling near Munich. The signals for the control of nitrogen application are based on on-the-go sensing of the crop chlorophyll fluorescence. More details are outlined in Sect. 9.4.5.

Finally, a mechanical pendulum sensor has been developed in the **Bornim** Institute of Agricultural Engineering by Ehlert et al. (2004a). The deflection angle of a pendulum, which is dragged along the upper part of the crop canopy, is used to control the application rate. This sensing system is dealt with in more detail in Sect. 9.4.6.

Whatever sensing system is used, it will have to rely on quantitative effects of nitrogen supply on specific crop properties. Differences based on species, varieties, soil-conditions and prevailing weather must of course be expected.

In order to understand the functioning of optical nitrogen sensing systems, knowing about the effects of the nitrogen supply on the **chlorophyll content** in the leaves and on the **leaf-area-indices** of crops is fundamental. Because this knowledge helps to find the sources of reliable signals for nitrogen sensing. The leaf-area-index is the relation between the photo-chemically active, one-sided leaf area and the ground surface.

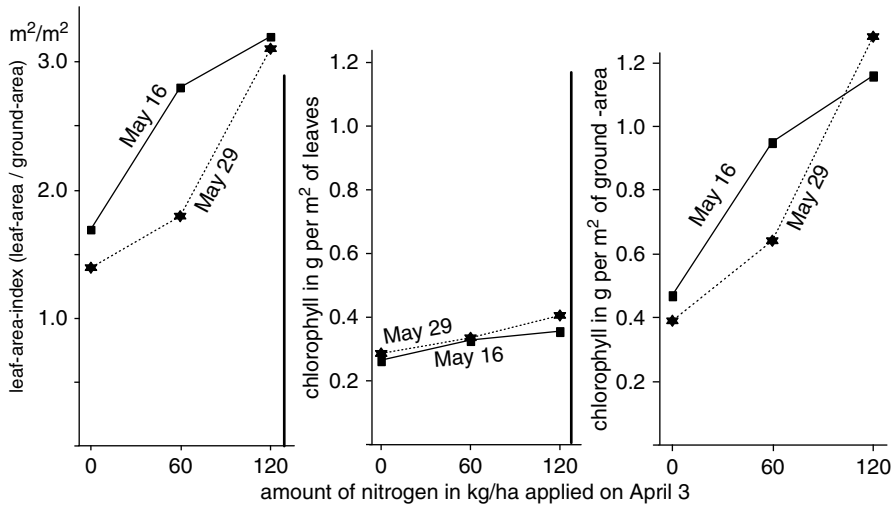


Fig. 9.17 Effect of nitrogen on the leaf-area-index (LAI) and on the chlorophyll content of winter-wheat in Indiana, USA. The chlorophyll mass per unit of field area in the *right graph* is the product of the leaf-area-index in the *left graph* and the chlorophyll mass per unit of leaf area in the *central graph* (Compiled from data by Hinzman et al. 1986)

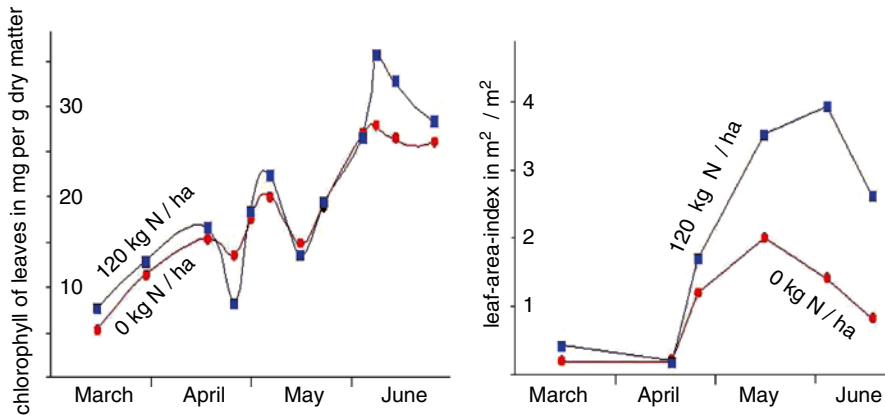


Fig. 9.18 Effect of nitrogen on leaf-area-index and on chlorophyll content of winter-rape (winter-colza) in Schleswig-Holstein, Germany. For the fertilized plots, the crop was dressed with 40 kg of N per ha respectively at the end of March, at the end of April and at the beginning of May. Hence for these plots, the total amount of N applied in the spring was 120 kg per ha (From Kappen et al. 1998, altered)

Research by Hinzman et al. (1986) with wheat and by Kappen et al. (1998) with rape (colza) revealed the effect of nitrogen on the chlorophyll concentration within the leaves as well as on the leaf-area-index. It can be seen from Figs. 9.17 and 9.18 that nitrogen changes the leaf-area-indices much more than the chlorophyll concentration within the leaves. The dominating effect of nitrogen on biomass production

or on leaf-area-indices probably holds for most crops. Belanger et al. (2005) as well as Jongschaap (2001) published similar results for potatoes.

A reasonable conclusion from these results is to use the product of both indicators of nitrogen application as the criterion for sensing. This product of the chlorophyll concentration within the leaves and the leaf-area-index can be defined as the **chlorophyll per unit of ground area**. The curves in Fig. 9.17, right, indicate that this product is sensitive to the nitrogen supply.

Using the chlorophyll concentration per unit of ground area as criterion is analogous to sensing methods that are oriented at defining the yield potential of crops as outlined in Sect. 6.3. However, it should be realized that sensing for **yield potentials** or for **nitrogen fertilizing** may not be quite the same. Because sensing for yield potentials is oriented at detecting the photosynthetic capacity of crops per unit of field area. And sensing for nitrogen fertilizing aims at recording the site-specific nitrogen uptake of the crop. Strong correlations between these sensing objectives can be expected, but differences should be looked forward too as well. Differences can result from the fact that not all the nitrogen in crops is within its chlorophyll. And the yield potential of crops depends on many growth factors, not only on nitrogen.

9.4.1 *Fundamentals of Nitrogen Sensing by Reflectance*

Nitrogen has two effects on the reflectance of a plant canopy (Fig. 9.19). Firstly, it increases the chlorophyll concentration per unit area in the leaves. Thus, more light is absorbed and consequently the reflectance decreases. However, this effect occurs only with the visible light, the photosynthetically active radiation (PAR).

Secondly, as mentioned above, nitrogen has a very pronounced effect on the growth of plant mass and, therefore, on the leaf-area-index of a crop. Theoretically, the higher the leaf-area-index, the more incident solar radiation should be scattered back by the canopy instead of by the bare soil. Yet in reality this is important only in the near-infrared region, since in these wavebands light is barely absorbed by plant pigments. As a result, the effect of nitrogen supply in the near-infrared range is opposite to that in the visible range.

The rather steep slope between the red and the near infrared reflectance is generally denoted as the red edge. It has a concave and a convex part, which meet at the **red edge inflection point**. This point moves to longer wavelengths when the supply with nitrogen is improved.

How can the information of the reflectance curves be processed for the control of the nitrogen supply of crops? Using full-spectrum methods is complicated as a result of the opposite effect of the nitrogen in the visible and the near-infrared wavelength range. Furthermore, these methods are associated with rather high costs for the sensing instruments. Using discrete narrow wavebands instead of these methods can simplify the sensing. The problem however is, finding the most suitable narrow wavebands including the best index that combines these mathematically.

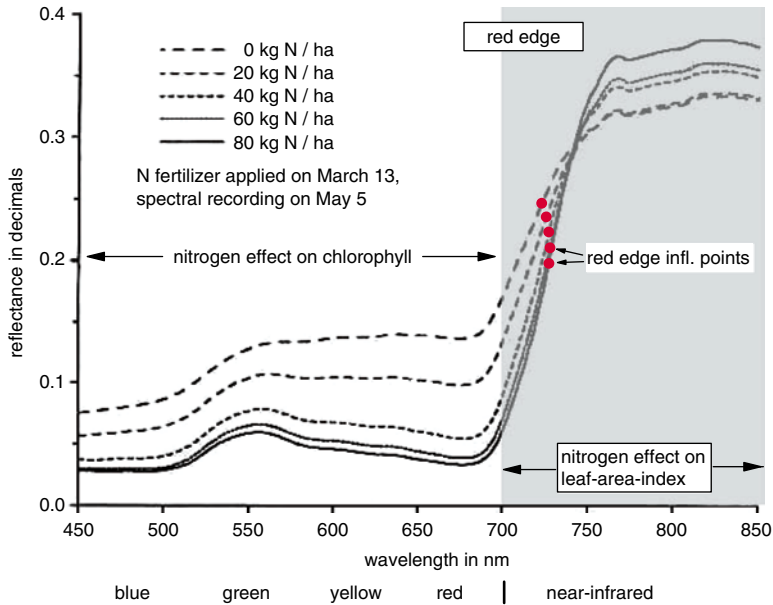


Fig. 9.19 Reflectance of winter-rye at time of second top-dressing depending on the amount of nitrogen spread 7 weeks earlier. The curves are based on natural illumination and vertical view directions. The red edge inflection points are not to scale (From Reusch 1997 and Heege et al. 2008, altered)

Two approaches have been used for detecting suitable narrow wavebands or optical indices. The first approach has been to rely on established, well known optical indices and to find out, which of these are the best indicators of the nitrogen supply. So the selection occurs among **standard indices** that originally just were used to detect and assess vegetation (see Sect. 6.2).

The second approach is based on the assumption that – regarding especially nitrogen – these standard indices may disregard or miss the information that can be obtained from very discrete parts of the spectral curves. Consequently, initially full spectra without any interruptions are processed with the objective of finding discrete narrow bands that are the most sensitive to the nitrogen supply. These wavelengths from suitable narrow sections may in a second step be combined to **new indices**, which then can be regarded as **special nitrogen indices** for agricultural crops.

Remote sensing from satellites mainly is done via standard indices, whereas for proximal sensing from farm machines increasingly new indices supply the signals. There are reasons for these differences.

The remote sensed signals from satellites hardly are used solely for sensing the nitrogen status of crops, especially until now not on a site-specific field basis. Predominantly, the remote sensed signals are employed on a whole field basis or for even wider areas for e.g. biomass sensing or crop classification. However, if the

objective in remote sensing is biomass sensing in combination with detecting the chlorophyll concentration in the leaves (see Figs. 9.17, 9.18, and 9.19), the optical indices that are useful for this may be similar to those that might be suitable for nitrogen sensing.

Any deficiencies that still exist for remote sensing regarding the spatial resolution that is needed for site-specific fertilizing are slowly being removed by technological progress. Hence for the future, site-specific nitrogen fertilizing based on field maps that were obtained by remote sensing of crop canopies from satellites may be feasible. However, this technology will probably be limited to areas where clouds seldom obstruct the transmission of radiation. In areas with maritime climate and hence frequent overcast situations, the concept of site-specific mapping of the nitrogen supply by crop-reflectance sensing from satellites will be difficult to apply. Because here a clear sky may not be available for days or even weeks. This means that the **temporal precision** that is needed for accurate nitrogen sensing often cannot be met when taking into consideration the transient supply by soils.

The situation is quite different with **proximal site-specific nitrogen sensing** from farm machines for on-the-go spreader control. Since in this case the control is done in real-time, the best temporal precision that is possible can be obtained and this irrespective of clouds. Standard reflectance indices as well as new indices – hence special nitrogen indices – can be used.

9.4.2 Sensing by Standard Reflectance Indices and Natural Light

Reflectance indices are defined by reflectance bands with special wavelengths and by mathematical combinations of these. Some standard reflectance indices and their formulas are listed in Table 9.3. Basic indices may consist just of **narrow bands**, e.g. from the green, red or near-infrared wavelength range. Instead of these, often also **simple ratios** of reflectances are used such as the ratio of the near-infrared to red or of near-infrared to green.

Other standard approaches are the “**Normalized Difference Vegetation Index**” (NDVI) or the “**Soil Adjusted Vegetation Index**” (SAVI). Both indices can easily be calculated from the reflectance in the red and near-infrared range. The NDVI is a very frequently used index for remote sensing of vegetation from satellites (see Sect. 6.2). The SAVI is also employed for this. It has the same wavelengths as the NDVI, however, there are additional correction constants in the formula (Table 9.3). The latter reduce the influence of varying soil colours (Huete 1988).

Furthermore, signals for the nitrogen situation could be derived from the point of inflection of the S-shaped curve of the reflectance in the red and adjacent near-infrared range. This **red edge inflection point** (Fig. 6.6 or Fig. 9.19) can be obtained in different ways:

Table 9.3 Relationships between standard spectral reflectance indices and the nitrogen supply, expressed by coefficients of determination

| Definition | Formulas for wavelengths R (number added is wavel. in nm) | Coefficient of determination (r^2) |
|---|---|---|
| Green reflectance | R 550 | 0.910 |
| Red reflectance | R 670 | 0.888 |
| Near-infrared reflectance | R 800 | 0.569 |
| Ratio of near-infrared to red | $\frac{R\ 800}{R\ 670}$ | 0.911 |
| Ratio of near-infrared to green | $\frac{R\ 800}{R\ 550}$ | 0.943 |
| Normalized difference vegetation index (NDVI) | $\frac{R\ 800 - R\ 670}{R\ 800 + R\ 670}$ | 0.914 |
| Soil adjusted vegetation index (SAVI) | $\frac{1.5(R\ 800 - R\ 670)}{R\ 800 + R\ 670 + 0.5}$ | 0.907 |
| Red edge inflect. point, numerical differentiation | $\frac{d^2 R}{d\lambda^2} = 0$ | 0.932 |
| Red edge inflect. point, approx. formula (REIP) | $700 + 40 \frac{(R\ 670 + R\ 780) / 2 - R\ 700}{R\ 740 - R\ 700}$ | 0.970 |

The results are based on natural illumination and vertical view directions (From Heege and Reusch 1996)

- by numerically calculating the second derivative of the reflectance curve and determining the wavelength where it is zero,
- by using empirical approximating formulae.

The disadvantage of the first method is that the reflectance data must be available with a high spectral resolution. Therefore, many bands are needed and the method may become expensive. For the second method, several empirical approximating formulas have been proposed (Dash and Curran 2007; Guyot et al. 1988). The red edge inflection point in Table 9.3, bottom and those in the subsequent text (abbreviated as **REIP**) are based on Guyot et al. 1988.

The coefficients of determination in the last column of Table 9.3 refer to experiments with nitrogen fertilization of winter-rye and its spectral results as shown in Fig. 9.19. All spectral indices depend on the nitrogen fertilization. However, there are differences. The 800 nm near-infrared reflectance on its own – surprisingly – shows the weakest relationship. The red edge inflection point indices on the other hand are very closely related to the nitrogen application rate. The best coefficient of determination results from the **red edge inflection point** that is obtained by the approximating formula.

Another index that is closely related to the nitrogen supply is the simple ratio of near-infrared to green (Table 9.3). This agrees with results from Solari et al. (2008) with maize.

The outstanding ability of the red edge inflection point among the various standard spectral indices for indicating the nitrogen uptake of crops was also demonstrated in

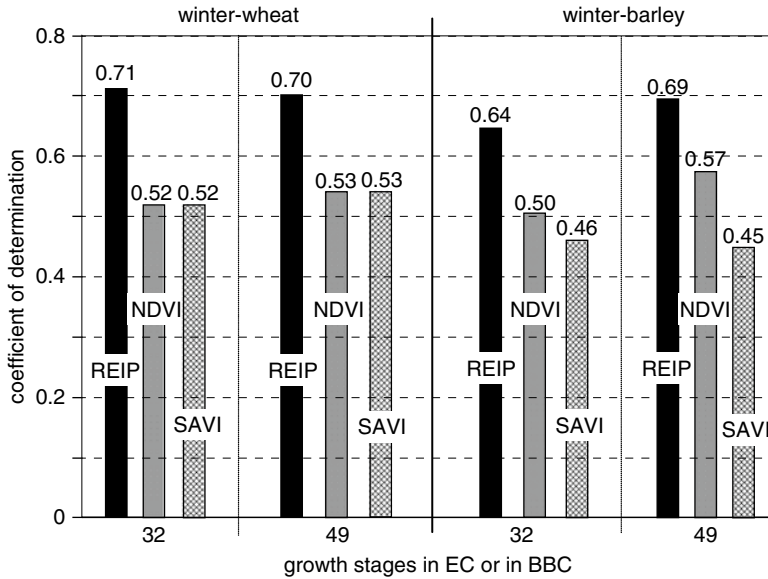


Fig. 9.20 Coefficients of determination (r^2) of standard indices for the nitrogen uptake of small grains. The results are based on reflectance measurements by handheld instruments, natural illumination and vertical view directions. *REIP* red edge inflection point, *SAVI* soil adjusted vegetation index, *NDVI* normalized difference vegetation index (Drawn from data by Schmid and Maidl 2005)

results that were obtained at Munich University in Southern Germany (Fig. 9.20). The red edge inflection point was based on the approximating formula as defined above. However, the coefficients of determinations of the same reflectance indices in Fig. 9.20 differ more than those listed in Table 9.3.

The ratio of near-infrared to green is not listed in Fig. 9.20, though this index too provided good results that were not much inferior to those of the red edge inflection point (Schmid and Maidl 2005).

9.4.2.1 Interfering Factors with Standard Indices and Natural Light

Main factors that can interfere with the reflectance are the soil-colour, the zenith-angle of the solar radiation (Fig. 9.21) and eventually cloud-covers. Which of these factors are important, depends on the illumination that is employed for creating the reflectance. If natural illumination is used – which is the rule for remote sensing and also sometimes the choice for proximal sensing – all three factors that are mentioned above are important. When artificial illumination induces the reflectance with proximal sensing and hence the zenith-angles of the sun as well as cloud covers become unimportant, it is only the soil-colour that might interfere.

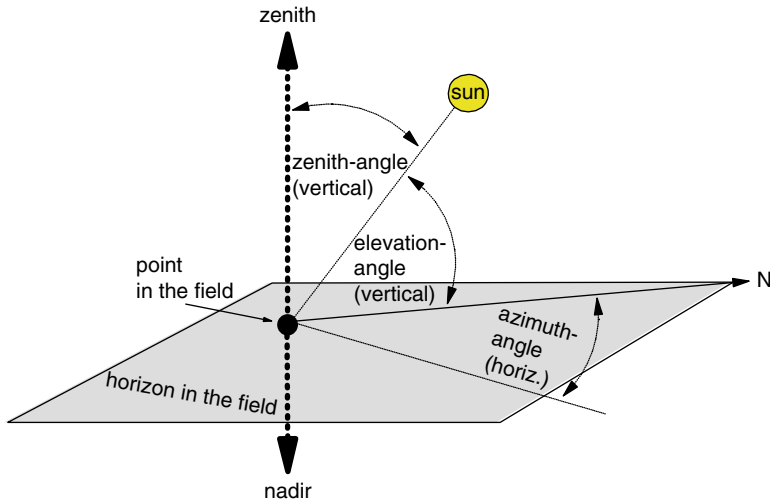


Fig. 9.21 Geometry of solar radiation

In order to evaluate the influence of the solar zenith-angle, records were taken in Northern Germany on a sunny day in mid-May with a field spectrometer vertically fixed on one spot in winter-barley. During the day, the zenith angle varied from 40° to 80°. Similarly, reflectances were recorded on a day with varying cumulus clouds. Finally, the soil-colour was altered by watering a dry, bright soil and thus creating a dark, wet soil. For further details see Heege et al. 2008 or Reusch 1997.

The effects of the interfering factors zenith angle, cloud cover and soil brightness were defined by coefficients as listed below:

Factor zenith-angle of the sun

$$\text{Coefficient } C_z = \frac{\text{index difference caused by altering the nitrogen dose}}{\text{index stand. deviation caused by change of zenith angle}}$$

Factor cloud-cover

$$\text{Coefficient } C_c = \frac{\text{index difference caused by altering the nitrogen dose}}{\text{index stand. deviation caused by change in cloud cover}}$$

Factor soil-brightness

$$\text{Coefficient } C_s = \frac{\text{index difference caused by altering the nitrogen dose}}{\text{index difference caused by wetting dry soil}}$$

The numerators of the coefficients or ratios are given by the index difference due to the change in nitrogen applied. The denominator is the index difference pertaining

Table 9.4 Evaluating the effect of interfering factors by coefficients and by their geometric means

| | Factors and coefficients | | | Geom. mean $\sqrt[3]{C_z C_c C_s}$ |
|---|--------------------------|--------------------------|------------------------|---------------------------------------|
| | Zenith C _z | Clouds C _c | Soil C _s | |
| Standard spectral indices | | | | |
| Reflectance at 550 nm (green) | 4.5 | 0.2 | 6.6 | 1.9 |
| Reflectance at 670 nm (red) | 7.2 | 0.8 | 8.4 | 3.6 |
| Reflectance at 800 nm (near-infrared) | 5.1 | 5.7 | 1.2 | 3.2 |
| Ratio of near-infrared to red reflectance | 7.4 | 4.9 | 7.9 | 6.6 |
| Ratio of near-infrared to green reflect. | 12.9 | 4.2 | 19.0 | 10.8 |
| Normal. differ. veget. index (NDVI) | 11.9 | 2.7 | 12.6 | 7.4 |
| Soil adjusted vegetation index (SAVI) | 11.5 | 7.4 | 32.4 | 14.4 |
| Red edge infl. point, num. differentiat. | 45.9 | 10.7 | 21.8 | 22.0 |
| Red edge inflect. point, appr. formula | 61.9 | 12.7 | 10.1 | 19.8 |

Large coefficients mean low interferences (From Heege and Reusch 1996)

to the change of the interfering factor such as the solar zenith-angle, the cloud-cover or the colour of the soil. Hence the coefficients represent the respective signal to noise ratio. Its suffixes z, c, and s stand for the zenith angle, the cloud cover or the soil colour respectively.

In Table 9.4, the coefficients of the interfering factors are listed. The larger the coefficients are, the lower the interference by the respective noise factor is and hence the more reliable the reflectance index is.

Since **natural illumination** provided the reflectance and consequently all three interference factors are important, it seems reasonable to use the mean of the coefficients as criterion. Instead of arithmetic means, **geometric means** are listed in the right column of Table 9.4. This is because generally geometric means are superior to arithmetic means when normalized results or ratios are averaged. And this is the case with the coefficients.

Regarding the geometric means, the best results – *i.e.* the lowest average noise – can be obtained with the **red edge inflection point** indices. These indices on the one hand depend very clearly on the nitrogen supply of the plants (Table 9.3) and on the other hand are not much influenced by the interfering factors. The widely used normalized difference vegetation index (NDVI) is on the average much more affected by these interfering factors. The soil adjusted vegetation index (SAVI) as well as the ratio of the near-infrared to green reflectance can be regarded as candidates in intermediate positions. However, when looking at the individual interference factors or its coefficients, it can be seen that the average “noise” ranking of the soil adjusted vegetation index results from the very low influence that in this case is exerted by the factor soil (red soil column in Table 9.4). On the other hand, the outstanding rankings of the red edge inflection point indices originate from the low influence (large coefficients) that the radiation factors zenith angle and clouds have.

If solely **artificial illumination** provides the reflectance, noise from changing solar zenith angles or from varying cloud covers practically is excluded. Hence from the coefficients listed, only the factor soil remains (Table 9.4). However, this

factor exerts its influence on the noise situation only if soil is in the field of view of the sensor. In case the sensor views only closed canopies, the factor soil too is excluded. So with artificial illumination and closed canopies, all these noise factors get irrelevant.

9.4.2.2 Viewing Directions with Natural Light

The reflectance sensor may have a vertical or an oblique **viewing direction** towards the crop canopy. The above results from Sects. 9.4.2 and 9.4.2.1 refer to vertical directions. Sensors that are operating on sprayer booms usually use this view (Fig. 6.5). And for sensing from aerial platforms or from satellites this vertical view too may be appropriate. However, for an on-the-go control of the widely used centrifugal fertilizer spreaders by proximal sensing, additional considerations deserve attention.

It is essential to have the field of view out of any shades of the field machinery and out of any tramlines, since this affects the reflectance. With vertical viewing, this can be achieved by means of a transverse boom. Sprayers and pneumatic spreaders have this boom anyway, but the dominating centrifugal spreaders do not. And because of this, sensing with oblique views from the top of the tractor's roof sideways into the canopy is widely practiced. This has an additional effect: the sensor is seeing less soil in case the canopy is not closed. Hence the noise that is caused by soil is reduced (Table 9.4).

However, an oblique viewing direction into the canopy means also that an additional solar radiation factor gets important. Whereas in case of vertical viewing only the **zenith angle** of the solar radiation needs to be considered, with an oblique viewing direction it is necessary to take into account the effect of its **azimuth angle** as well (Fig. 9.21). Because the oblique direction – as opposed to the vertical direction – inherently also has a horizontal component. And this horizontal component is affected in the course of a day by the varying azimuth angle as well as by changing directions of travel of the machinery in the field. An exception from this holds only when the sun is precisely in the zenith (zenith angle = 0°). But this happens only in the tropics and even there just at noon. So in most cases, the effects of solar azimuth angles cannot be neglected.

Reusch (2003) has shown that this adverse effect of the azimuth angle on the reflectance from natural light can be practically removed by increasing the number of viewing spots and distributing these evenly around the tractor (Fig. 9.22). He investigated the **correction of the azimuth-effect** that can be obtained by multiple viewing-directions and by averaging the results of these. As a criterion, the ratio of the near-infrared to red reflectance was used.

In case only one direction supplies the signals, the reflectance ratio goes from 18 to 30 % and back to 18 % while the azimuth angle goes from zero to 360° (Fig. 9.23). This wide range for the azimuth angle is encountered while the machinery is operating in different directions within a field. So this range can affect the signals within rather short time spans.

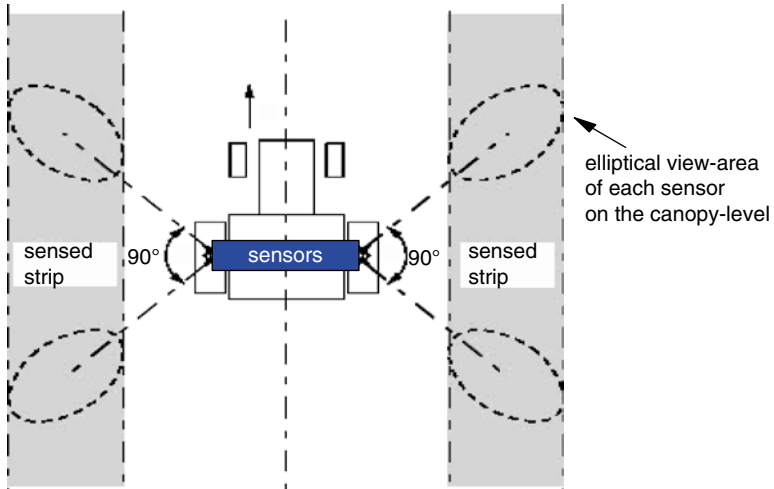


Fig. 9.22 Geometry for oblique viewing of the crop canopy by two sensors on each side of the tractor. The sensors are positioned on top of the roof of the tractor (From Reusch et al. 2004, altered)

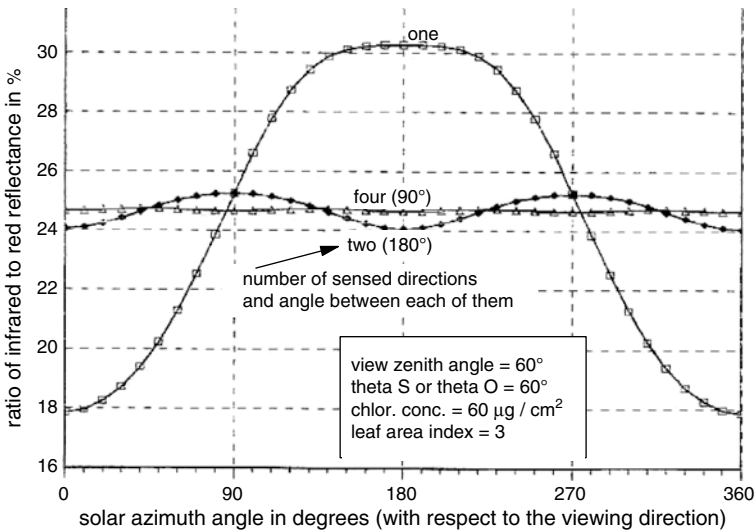


Fig. 9.23 Effect of solar azimuth angle on the ratio of near-infrared to red reflectance from natural light. The curves demonstrate the results that can be obtained by averaging the signals from multiple directions. The reflectance signals are based on the PROSPECT/ SAIL model. For details to this model see Sect. 6.1 and Fig. 6.3 (From Reusch 2003, altered)

The correcting effect of averaging the results from several directions is drastic. With two opposite directions, the reflectance varies only between 24 and 25 %, and when four equally spaced directions are used, it remains practically constant. It should be noted that the results are based on an optical model (see legend to Fig. 9.23) that does not take into account any other factors than the solar azimuth angle.

This averaging of the signals from four directions is state of the art in practical farming when the sensing is based on natural light.

9.4.3 Sensing Nitrogen by Reflectance Based on Artificial Light

A general experience with the Kiel system in Europe when operating on the basis of natural illumination is that the solar elevation angle – the complementary angle to the zenith angle (see Fig. 9.21) – should not be below 25°. This means that early and late hours in the day cannot be used. Yet in regions with maritime- or mountainous influence on the climate, this is just the time of the day when there is less wind. And high wind speeds can seriously reduce the accuracy of fertilizer-spreading, especially with the currently dominating centrifugal spreaders.

Artificial illumination can overcome this problem. It also eliminates the noise associated with any varying irradiance of natural light and with shade effects caused by the machinery or by trees. It allows operating not only during daytime, but at dawn and at night as well.

Technically, the spectral effects of the artificial light source need to be separated from those of any natural light. This **separation** can be achieved by subtracting the reflectance spectrum of solely natural light from the spectrum that results, when in addition the artificial illumination is switched on. The artificial light is applied as **regular flashes** and supplies “On” spectra. In the short intervals between the flashes, the “Off” spectra come from the natural light. The “Off” spectra are subtracted from the respective adjacent “On” spectra. The thus obtained spectral signals result only from the artificial illumination and any effect of varying natural light is eliminated.

In case continuous artificial illumination is applied, separating the effects of the different light sources would also be possible by **modulating the artificial light**. However, this separating technique is more complicated.

In the total cost calculation, the higher investment for artificial illumination might be offset by the capability of treating a larger area because of the longer operating time per day.

It should be mentioned that the **artificial light source** must adequately supply the respective wavelengths. Many commonly used light sources do not, as can be seen in Baille (1993) and Lawrence et al. (2005). If the wavelengths that are needed are provided, there is no reason why the nitrogen effect on the reflectance indices with artificial illumination should be different than with natural light. Commonly



Fig. 9.24 Control of nitrogen spreading via reflectance sensing based on artificial light with vertical viewing of the canopy from transverse booms in front of the tractor (Crop Circle concept, photo from Wilson J., SoilEssentials Ltd., England)

used light sources include xenon lamps, laser diodes and light emitting diodes (LEDs). As with natural light, the view on the canopy can be in a vertical or in an oblique direction.

For an oblique direction sideways down from the tractor-roof, there is no need anymore to take care of the effect of any solar azimuth angle. So, contrary to the concept dealt with above in Figs. 9.22 and 9.23, it suffices to use a single sensor on each side of the tractor.

Since shade effects on the signals that result from the machinery too are excluded with artificial illumination, the transverse booms needed for vertical viewing can be shorter (Fig. 9.24) than with natural light. Yet the most compact design still in possible with oblique viewing from the tractor roof (Fig. 9.25).

However, the mounting itself of the sensors probably is less important with artificial illumination. Crucial is that the sensors see what is needed for the control of the spreader. And this depends on the viewing direction too. With an oblique viewing direction, the sensor sees less soil than with a vertically oriented view. This is because the slanted view hides small bare patches by plants. In this respect, the oblique view is advantageous with early development stages and with widely spaced crops.

But because an oblique orientation sees more **biomass** than a vertical view, its reflectance indices also tend to saturate faster. The term “**saturation**” here is used for the relation between the respective reflectance index and the leaf- area-index of the crop. A saturated reflectance index cannot differentiate between leaf-area-indices at high levels. But the ability to indicate high levels of leaf-area-indices with precision is very important for nitrogen sensing. Because an increasing nitrogen supply affects the leaf-area-index of a crop even more than the chlorophyll concentration within its leaves (Fig. 9.17).



Fig. 9.25 Control of nitrogen spreading via reflectance sensing based on artificial light with oblique viewing of the canopy from the roof of the tractor (From Agri Con GmbH, Jahna, Germany)

In short, sensing by oblique viewing of the canopy particularly needs reliable reflectance indices that do not saturate. This is dealt with in the next section.

9.4.3.1 New Reflectance Indices Instead of Standard Indices

The standard spectral indices dealt with so far mostly have been developed for remote sensing of vegetation and landscapes from satellites and aerial platforms. The fact that some of these indices depend on the nitrogen supply of crops does not imply that they are best suited for the detection of this nutrient. The “Normalized Difference Vegetation Index” (NDVI) is widely used as the standard index for assessing the “greening” of the global surface. However, despite this, the potential of the NDVI to indicate the density or the leaf-area-index of the vegetation is rather limited. Therefore Schepers et al. (1998) proposed to use a **green NDVI** instead of the **standard NDVI**. In this green NDVI, the red reflectance in the standard NDVI equation (Table 9.3) is substituted by green reflectance.

It is well known that the standard NDVI saturates around a leaf area index of about 2.0–2.5 (Fig. 6.7). Yet a well developed cereal crop can have a leaf area index that is three to four times higher. A similar saturation effect applies to standard infrared to red ratios. The reason for this is the very high absorption of red light by photosynthesis. Because of this, the light does not penetrate deeply into dense crop canopies and hence is not able to sense higher leaf-area-indices. In the green and in

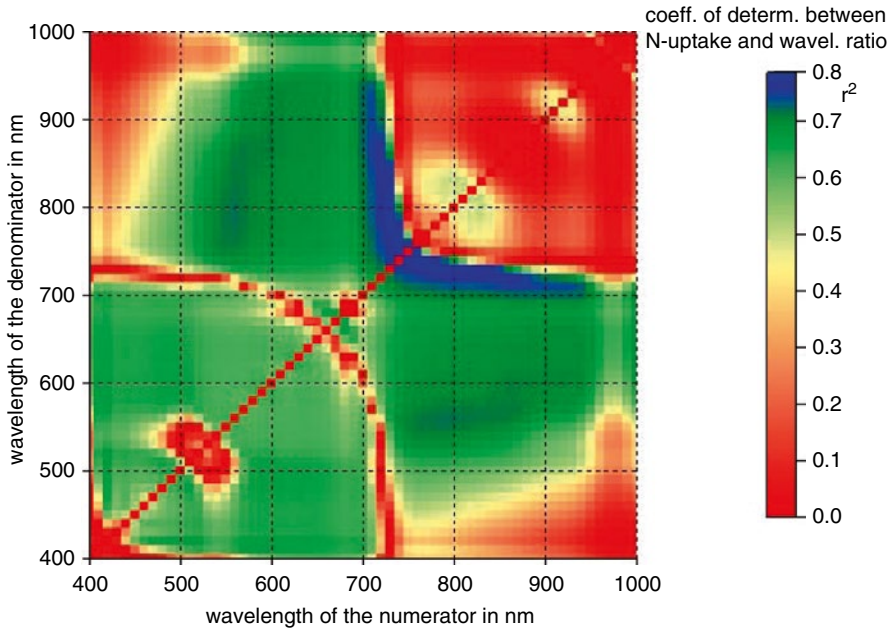


Fig. 9.26 Matrix showing coefficients of determinations (r^2) of simple reflectance ratios for sensing of N in wheat with a growth-stage in EC or BBCH of 31 (From Reusch 2005, altered)

the red edge range the absorption of light by photosynthesis is lower (Fig. 6.1), thus the light penetrates better into the canopy and thus can indicate its biomass. For sensing nitrogen, sensing the biomass of a crop or its surrogate – the leaf-area-index – is at least as important as sensing the chlorophyll concentration within the leaves well. This context explains why among the standard indices, the ratio of near-infrared to green and especially the red edge inflection points provided the best results for nitrogen sensing (Table 9.3).

However, none of the standard indices was developed especially for sensing of nitrogen. Even the best standard index for nitrogen sensing – the red edge inflection point – is essentially a chlorophyll index. Its potential for nitrogen sensing is derived from the fact that chlorophyll is an important carrier of plant nitrogen (Lamb et al. 2002), but it is not the only one.

These considerations lead to **systematic searching** in steps of 10 nm within the wavelength range from 400 to 1,000 nm (Reusch 2003, 2005). The searches were confined to simple ratio indices with one wavelength in the numerator and the other one in the denominator. Figures 9.26 and 9.27 show results that were obtained with oblique viewing of winter-wheat canopies and with artificial illumination. The colors stand for coefficients of determination between the nitrogen uptake and the respective wavelength ratios. The locations within the squares of the matrices represent the coordinates of the wavelength ratios.

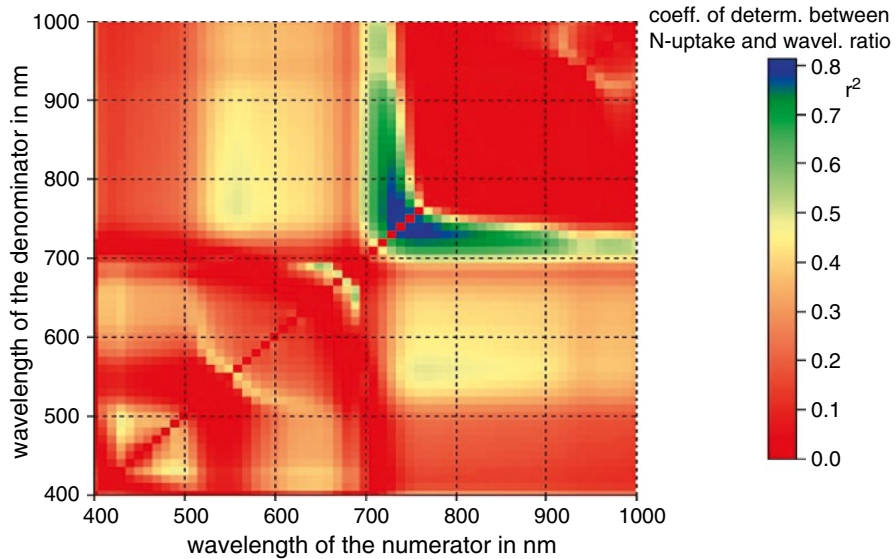


Fig. 9.27 Matrix showing coefficients of determinations (r^2) of simple reflectance ratios for sensing of N in wheat with a growth-stage in EC or BBCH of 38 (From Reusch 2005, altered)

The results are unambiguous: the highest coefficients of determination (r^2) and hence the most reliable predictions of the nitrogen uptake are obtained with wavelengths for both the numerator as well as for the denominator of the index ratio between about 720 and 800 nm. In the early development stage of EC or BBCH 31 (Meier 2001), wavelengths somewhat above 800 nm also provided still good results (Fig. 9.26). However, in the later stage of EC or BBCH 38 this is not so. At this stage, the colors in the matrix around 800 nm wavelength already indicate a slight decrease for the coefficients of determination. Müller et al. (2008) as well as Inoue et al. (2012) presented rather similar results of systematic spectral searching in steps of 10 nm in the form of matrices from experiments with vertical viewing and natural light respectively for oilseed rape (*Brassica napus*) in Germany or for rice (*Oriza sativa*) in Japan and China.

So the most reliable predictions of the nitrogen uptake come from wavelength ranges, in which also the red edge inflection point is located (Fig. 9.19). However, for reflectance sensing there is a fundamental difference between the red edge inflection point on the one hand and a simple wavelength ratio from the same spectral range on the other hand. The **red edge inflection point** indicates just a small dot on the spectral curve that is defined in nm of wavelength and its respective reflectance. The wavelength ratio instead depends on the slope of the spectral reflectance curve between the respective wavelengths and is dimensionless. Its precise definition in terms of wavelengths for the numerator and the denominator

might vary somewhat within the range indicated above. Wavelength pairs that have been proposed for this **red edge ratio index** are *e.g.*:

$$\frac{R\ 730}{R\ 780} \text{ (Reusch 2005) or also } \frac{R\ 760}{R\ 730} \text{ (Jasper et al. 2009) or identical to this}$$

$$\frac{R\ 760}{R\ 730} \text{ (Erdle et al. 2011) and } \frac{R\ 740}{R\ 780} \text{ (Müller et al. 2008).}$$

These proposals are based on experiments with winter-wheat (Reusch 2005; Jasper et al. 2009 as well as Erdle et al. 2011) and winter-oilseed rape (Müller et al. 2008). The small spectral differences between these indices probably hardly matter and inverse ratios of the wavelengths indicated can be used as well. Jasper et al. (2009) and Erdle et al. (2011) found that the red edge ratio index was largely unaffected by different varieties, varying seed densities and growth stages.

How do red edge ratio indices compare with the standard indices? And can nitrogen sensing still be improved by using more sophisticated indices, *e.g.* normalized difference indices with wavelengths that come exclusively from the red edge range? The criterion of a normalized difference spectral index is that it relates the difference of two wavelengths to the sum of the same wavelengths (Table 9.3). Would a normalized difference red edge index that relies solely on wavelengths from the red edge still improve the results?

The coefficients of determination (r^2) for the prediction of nitrogen uptake by reflectance indices in Table 9.5 refer to winter-oilseed rape. Among the standard indices, the best results again are obtained with the near-infrared to green ratio and especially with the red edge inflection point. Yet still better predictions were supplied by the new indices that rely exclusively on wavelengths from the **red edge range**. Whether **red edge ratio indices** or alternatively **normalized difference indices** from the **red edge range** are used seems to be unimportant (Table 9.5). These good results with various indices from the red edge range are in line with findings that support the significance of this spectral region for sensing of chlorophyll (Fig. 6.8), which is closely related to the nitrogen supply.

The relation between red edge ratio indices and the supply or uptake of nitrogen is nearly linear in most cases (Fig. 9.28). Similar regressions have been obtained with barley, oats, oilseed rape and maize and at different growth stages (Reusch et al. 2010). The sensor readings depend on the growth stages of crops, as does the nitrogen uptake of crops.

There is some influence of various **fungal infections** on the reflectance, as might be expected. Reusch 1997 made trials with barley that was infected by leaf blotch (*Rhynchosporium secalis*), by leaf rust (*Puccinia hordei*) and by powdery mildew (*Erysiphe graminis*) and that was either sprayed to remove the diseases or not. The result of the infections on the red edge inflection point index were rather small when compared to nitrogen effects. Yet it must be realized that the severities of fungal infections will affect such results.

Table 9.5 Standard indices or new indices for nitrogen sensing and results by coefficients of determination (r^2)

| Definition | Formulas for wavelengths R (number added is wavel. λ in nm) | Coeffic. of determination (r^2) |
|---|--|--|
| Standard indices (commonly used) | | |
| Near-infrared reflect. | R 850 | 0.16 |
| Ratio of near-infrared to red | $\frac{R\ 780}{R\ 670}$ | 0.63 |
| Ratio of near-infrared to green | $\frac{R\ 780}{R\ 550}$ | 0.72 |
| Normalized difference vegetat. index (NDVI) | $\frac{R\ 780 - R\ 670}{R\ 780 + R\ 670}$ | 0.55 |
| Soil adjusted vegetation index (SAVI) | $\frac{1.5(R\ 780 - R\ 670)}{R\ 780 + R\ 670 + 0.5}$ | 0.51 |
| Red edge infect. point, approx. formula (REIP) | $700 + 40 \frac{(R\ 670 + R\ 780) / 2 - R\ 700}{R\ 740 - R\ 700}$ | 0.73 |
| New indices with wavelengths exclusively from the red edge range | | |
| Red edge ratio index | $\frac{R\ 780}{R\ 740}$ | 0.82 |
| Inverse red edge ratio index | $\frac{R\ 740}{R\ 780}$ | 0.81 |
| Normalized difference red edge indices | $\frac{R\ 780 - R\ 740}{R\ 780 + R\ 740}$ | 0.82 |
| | $\frac{R\ 750 - R\ 740}{R\ 750 + R\ 740}$ | 0.82 |

The results are based on winter-oilseed rape, vertical viewing and natural illumination (Arranged from data by Müller et al. 2008)

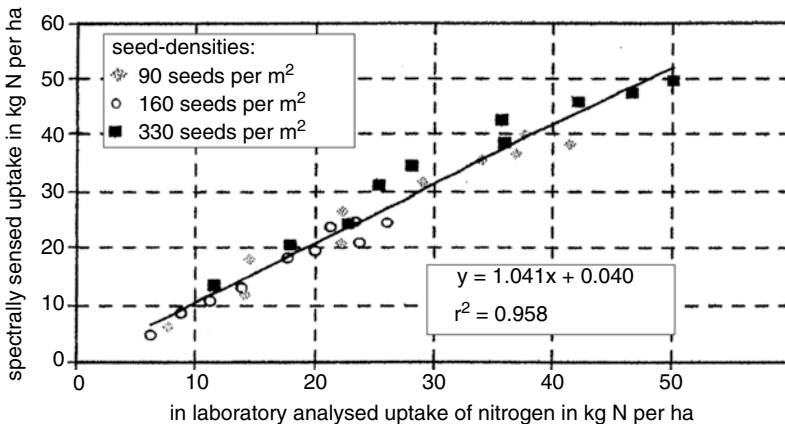


Fig. 9.28 Accuracy of nitrogen sensing by a red edge ratio index (R760/R730) versus analysing of samples chemically in a laboratory with winter-wheat in Northwest Germany. The sensing was done from the roof of a tractor in an oblique direction with artificial light and at a growth stage of EC or BBCH 31. The field was fertilized with different rates of nitrogen at a growth stage of EC or BBCH 20 (From Jasper et al. 2009)

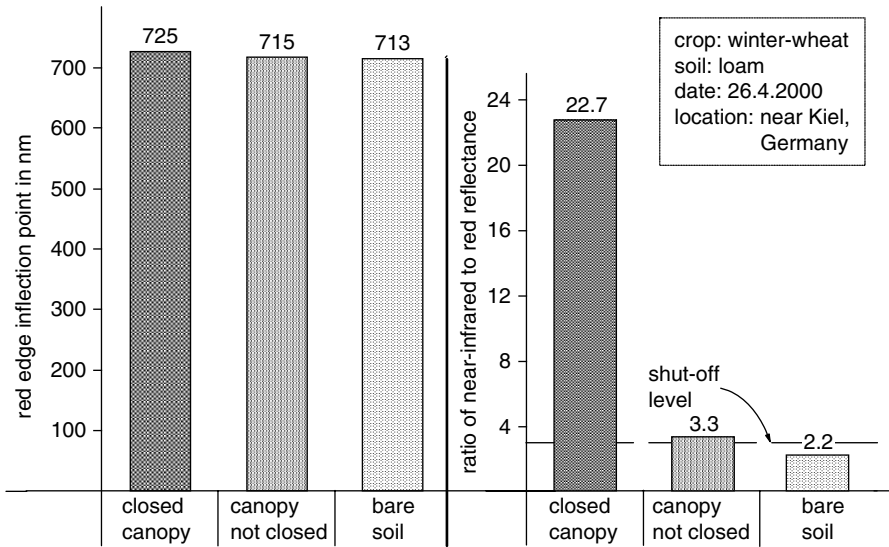


Fig. 9.29 Soil- and crop canopy effects on spectral indices (From Heege and Thiessen 2002)

9.4.4 Soil or Plants in the Field of View

Fertilizer control using reflection from the leaves requires **green plants** in the field of view of the sensor. In the case of patches with little or no plants, the resulting application rate may be inappropriate. The reason for this is that a lack of nitrogen within a canopy as well as bare soil instead of plants turns the signal in the same direction.

A lack of nitrogen within a normally developed canopy should be compensated for by increased fertilization, whereas it certainly is not reasonable to apply high amounts of nitrogen to larger patches of **bare soil**. In rolling landscapes with undulating fields, these patches of bare soil can be the result of uneven winter killing of plants. Therefore, an additional control for completely shutting off the flow of fertilizer is needed.

A reliable indicator for this control is the ratio of near infrared- to visible reflectance (Felton and McCloy 1992). The relation of near-infrared to red already is used for weed control by **spot spraying** in fallow fields or by strip spraying in crops with tramlines (Sect. 6.2). In the case of bare soil instead of a closed canopy, this relation decreases drastically from 20 or more to 3 or less (Heege and Thiessen 2002). For winter cereals in Germany, it seems to be reasonable to stop fertiliser spreading when the near infrared to red relationship drops below 3 (Fig. 9.29). This automatic shut-off does not necessitate additional sensing equipment if infrared and red reflectance signals are recorded anyway. This depends on the spectral indices that are used for the prediction of the nitrogen supply.

With small grains, the Kiel system is rarely used for the first dressing of small cereals. Its application is mostly limited to the second and later dressings. This is

mainly because at the time of the first dressing, the crop canopy is not yet closed. Even if an indication of biomass and chlorophyll content could be obtained at the time of the first dressing, the very small plants often do not provide a reliable estimation of the nutrient supply from the soil. Because initially the germinating and emerging plants obtain their nitrogen from the seeds and not from the soil. Therefore, differences in the supply from the soil might not well show up with small grains at a developmental stage below EC or BBCH 25 (less than 4 tillers).

Apart from this, for **not closed crop canopies** it is important to exclude the influence of soil on the reflectance as much as possible in order to avoid mixed signals. Two methods can be used for this, either **narrowing the view** of the vertically oriented sensor to a closed canopy strip exactly above and along a row, or using an **oblique view** that is oriented perpendicular to the row-directions. The first method – narrowing the view – can only be successful if the canopy strip above the row is really closed. The second method – oblique viewing – relies on getting the signals mainly from the upper part of the crop. The more oblique this field of view is, the more the reflectance received comes from the crop instead of the soil.

For most crops, the **minimum growth stage** for avoiding mixed signals is lower with oblique viewing than with vertical viewing. So for small grains, the minimum growth stage with oblique viewing is about EC or BBCH 30, which is the beginning of stem elongation (Meier 2001). With vertical viewing it is about EC or BBCH 32, which is stage node 2 (Schmid and Mairl 2005). A similar effect of the viewing direction on the minimum growth stage that is needed has been observed for maize (Bausch and Diker 2001).

However, oblique- instead of vertical viewing also means that the spectrum might saturate faster with increasing leaf-area-indices of the crops (see Sects. 6.2 and 9.4.3.1). Since this **saturation effect** reduces the sensitivity in measuring, reliable oblique viewing depends particularly on reflectance indices that do not tend to saturate fast. Consequently, accurate nitrogen sensing in lush crops with oblique viewing requires avoiding wavelengths from the main absorption regions, hence from the blue and especially from the red range. With proximal sensing, this practice presently is state of the art. The poor results of the red Normalized Difference Vegetation Index (NDVI) as defined in Tables 9.3 and 9.5 for nitrogen sensing might be even worse when the viewing occurs from an oblique- and not from a vertical direction.

With natural illumination, oblique viewing also increases the noise due to the varying solar azimuth angle. Yet an effective method of eliminating this noise – apart from using artificial light – is averaging signals coming from several and opposite directions (Fig. 9.23). The original Kiel system (Figs. 9.1 and 9.25) now is operating in practice with oblique viewing by sensors positioned on the roof of the tractor relying either on solar or artificial illumination.

9.4.5 Sensing Nitrogen by Fluorescence

In addition to the reflected radiance, crop leaves usually emit fluorescent light (see Sect. 6.4). The difference is that reflectance simply results from irradiance that is

thrown back, whereas the fluorescence comes from the photosynthetic apparatus of plants as surplus light energy or as a by-product. Artificial induction of fluorescence often is done by pulsed red laser beams.

In the red wavelength range, fluorescent light is emitted from the leaves with two peaks at 680 and 735 nm. It has been shown (Lichtenthaler 1996) that the relationship of the fluorescent intensities at these two peaks is an indicator of the **chlorophyll concentration** in leaves. This indication of chlorophyll concentration is explained by differences in the re-absorption of fluorescent light at these two emission peaks in the red and near-infrared range. The red fluorescent light at 680 nm wavelength is partly re-absorbed by chlorophyll for photosynthesis. This re-absorption depends on the chlorophyll concentration within the leaves. On the other hand, the fluorescent light at 735 nm wavelength is above the range of absorbed light. It therefore is barely reduced by absorption. For that reason, the **ratio of the two red fluorescence peaks** can be used to sense the chlorophyll concentration and thus also the nitrogen concentration in the leaves. So the background is chlorophyll estimation from **fluorescence absorption**. But what is the correlation between this fluorescence ratio and the nitrogen supply?

The fluorescence ratio was recorded by means of a handheld instrument (Thiessen 2002). Nitrogen top dressings for winter-cereals and winter-rapeseed were applied three times in the growing season, beginning in early March. Readings were taken at the time of the third dressing and 3–4 weeks after this date. The actual dates for the dressings depended on the crop species, but typical dates for Northern Germany were used (Fig. 9.30).

The basic assumption is that with increasing nitrogen supply by the preceding dressing, the chlorophyll concentration in the leaves should go up and thus the fluorescence ratio should drop. At the time of the third dressing – which is in mid-May for winter-barley or in early June for winter-wheat – this assumption is supported up to a preceding nitrogen supply of 120 kg/ha. Beyond this level of the nitrogen supply, the fluorescence ratio does not drop any more. On the contrary, it rises (Fig. 9.30, top).

A similar trend showed up 3–4 weeks after the third dressing with winter-barley, with winter-wheat and with winter-rapeseed. However, at this time, the fluorescence ratio decreased up to a preceding nitrogen supply of 160 kg/ha (Fig. 9.30, bottom), but above this rate, it also rose. In conclusion, at both dates and with all crops, there was no unidirectional relationship, which is a prerequisite for a simple control system. One might argue, that a unidirectional relationship up to a range of 120–160 kg/ha suffices, since higher pre-applications at earlier dressings seldom occur. So sensing of nitrogen by fluorescence absorption might be a feasible option except perhaps for very high dressing rates. For further results about nitrogen sensing by fluorescence see Thiessen (2002), Schächtl et al. (2005), Thoren (2007), Thoren and Schmidhalter (2009), Thoren et al. (2010).

Contrary to signals from reflectance, fluorescence sensing is never associated with erroneous information from **non-vegetated soil**. Because bare soil does not emit fluorescence. Neither any soil nor its plant residues or its stones influence the signals. The fluorescence ratio is solely based on the chlorophyll concentration in the leaves. This can be a distinct advantage when the crop canopy is not closed.

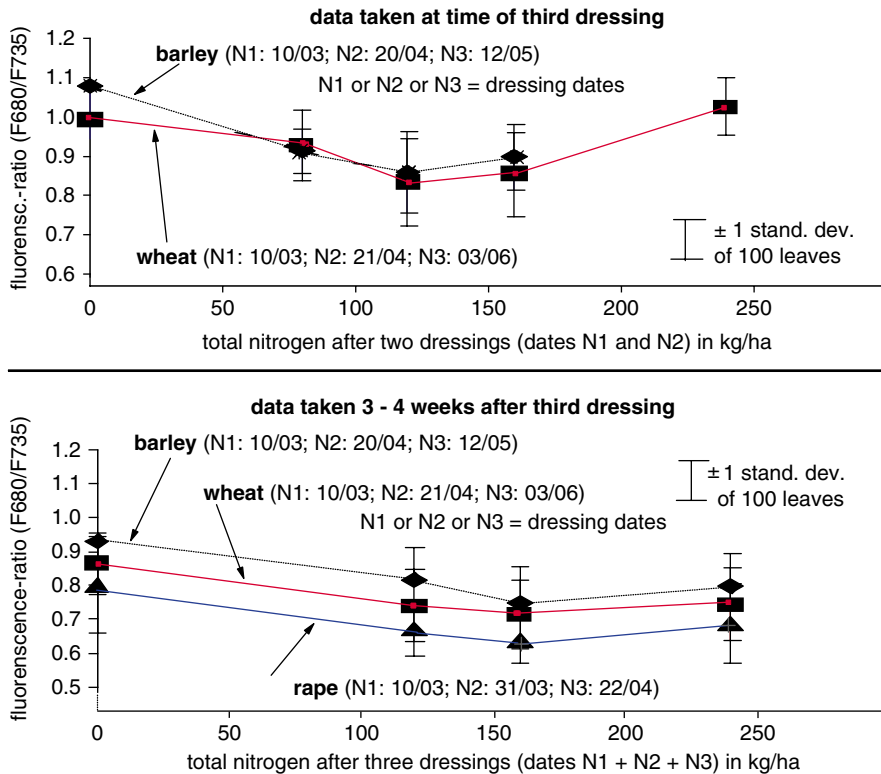


Fig. 9.30 Chlorophyll-fluorescence and nitrogen supply (From Thiessen 2002, altered)

Therefore, fluorescence signals might be better at early growth stages. Restrictions to this are outlined below. Another consideration is whether for the same reason, fluorescence signals should be preferred for widely spaced crops such as maize, potatoes and sugar-beets, since with these crops the canopy closes fairly late.

However, the fluorescence ratio is not *per se* influenced by the leaf-area-index, in contrast to reflectance indices derived from the red edge and near-infrared range (Fig. 9.19). Since the chlorophyll concentration in the leaves often is inferior to the leaf-area-index as an indicator of nitrogen supply (Fig. 9.17), fluorescence sensing has been combined with means of recording the plant density. A concept for this approach is the combination of fluorescence sensing with a **scanning technique**. Bredemeier and Schmidhalter (2005) as well as Thoren (2007) used such a laser-induced fluorescence sensing combined with the recording of a “biomass index” by scanning the field surface. The surface scanning was obtained via the **number of fluorescence signals** per unit area that was sensed when the plants were irradiated by pulsed red laser beams and thus were induced to emit fluorescence. Hence a relative indication of the site-specific **plant density** per unit area was obtained. The sensors were located on the roof of the tractor and had an oblique field of view



Fig. 9.31 Simultaneous sensing of the fluorescence ratio (F680/F735) and of estimates of the plant density per unit area. The plant density is sensed by the number of signals per unit of area above a noise level. The inclination of both sensors perpendicular to the direction of travel oscillates with a frequency of 1–2 Hz while driving through the field. Hence the field surface is scanned for signals (From Thoren 2007, supplemented)

(Fig. 9.31). By varying the inclination of this oblique view continuously while driving through the field, the canopy surface was scanned. In this way, signals related to the chlorophyll concentration in the leaf area as well about the vegetated area in the field were recorded.

Yet despite this there are still limits with the present technology of nitrogen sensing by fluorescence. These limits have to do with the irradiation that induces the fluorescence in the photosynthetic apparatus. The irradiance that causes the emission of fluorescence has wavelengths below the near-infrared. In most cases, red radiation is used for the induction. Contrary to this, the indices for nitrogen sensing by reflectance sensing include near-infrared radiation. And there are fundamental differences in the ability of near-infrared or red irradiance to record the development of a canopy.

The near-infrared irradiation is not absorbed, but highly transmitted. The red irradiation is mainly absorbed and barely transmitted. Consequently, the near-infrared irradiance induces mainly **volume-reflectance**. Red radiation causes, for the most part, **surface-reflectance** (Fig. 9.32) or **surface-fluorescence**.

This explains, why near-infrared reflectance responds much better to an increasing **leaf-area-index** of a canopy than red reflectance does (Fig. 9.32, right). Above a leaf area index of 2, the red radiation does not deliver reliable signals. In principle, the same applies to fluorescence that is induced by the red radiation.

In short, nitrogen sensing by fluorescence instead of reflectance is better at early growth stages. But at later development stages, the situation is *vice versa*. Intermediate growth phases can be sensed by either method. So the problem boils down to the question, at which developmental stage of crops, site-specific nitrogen sensing is reasonable or needed.

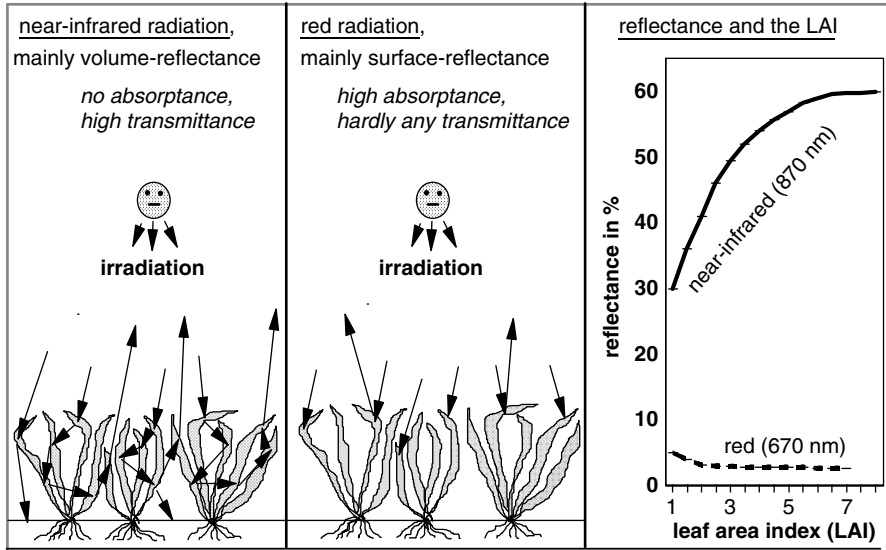


Fig. 9.32 The optical background of volume and surface reflection (The curves in the right part are from Guyot 1998)

At very early growth stages – *i.e.* below EC or BBCH 29 with small grains – the nitrogen content of the leaves often is not yet a reliable indicator of the supply by the soil. This is, because the seedlings get their initial supply from the seed and not from the soil.

There may be exceptional cases that call for an early nitrogen dressing on a site-specific basis. These cases might arise when local differences in field emergence develop because of uneven fields or irregular sowing and an early site-specific nitrogen dressing is targeted at compensating for this. The compensation might not be based on the nitrogen content in the leaves, but instead rely on using a fluorescence technique for sensing the **plant density** per unit area (Thoren 2007). An alternative to this method could be a site-specific first dressing that is oriented at the height of the plants (see next section).

Up to now, fluorescence sensing for controlling the nitrogen application is rarely used in practical farming. Interesting applications for fluorescence sensing might develop in combination with the detection of fungal diseases.

9.4.6 Sensing Nitrogen Based on Bending Resistance or Height

These methods inherently omit the chlorophyll as a control factor for the nitrogen fertilization. Instead, these methods rely on physical properties of crops for the control, either the resistance of the canopy against bending or alternatively the height of the plants.

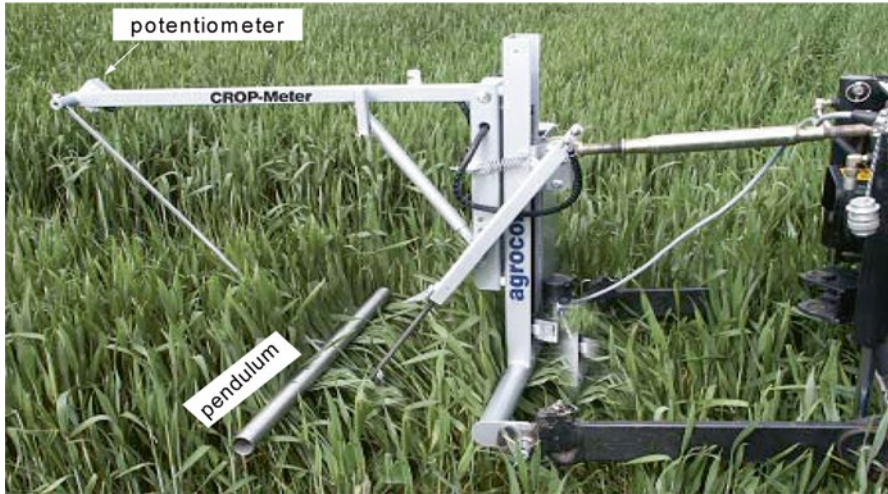


Fig. 9.33 Sensing the canopy resistance against bending in a small cereal crop by a pendulum that operates in front of a tractor (From Thoele and Ehlert 2010, altered)

The **resistance of the canopy against bending** is sensed via the deflection of a pendulum that operates in front of a tractor (Fig. 9.33). The deflection of this pendulum is indicated by its angle to the vertical via a potentiometer. And the use for site-specific farming is based on the correlation between this angle and the biomass or the **leaf-area-index** of crops. Actually, the coefficients of determination (r^2) between the pendulum deflection angles and the biomasses were 0.89 or higher (Ehlert et al. 2003) and those for leaf-area-indices were between 0.64 and 0.91 (Dammer et al. 2008). However, there are limits of precise sensing in rough fields because of vibrations or in areas with varying slope.

This rather simple method of sensing crop properties is state of the art in farming and aims at applications in the site-specific control of both **nitrogen fertilizing** and **fungicide spraying**. The results that have been obtained are encouraging (Dammer et al. 2008; Thoele and Ehlert 2010) despite the fact that this method inherently leaves out any influence of chlorophyll on applications of agrochemicals.

A serious limitation is that it needs advanced growth stages. With small cereals, a growth stage of at least EC or BBCH 35 is essential (Ehlert et al. 2004b), whereas with reflectance sensing the minimum growth stage is about EC or BBCH 30. This means, the earliest time for sensing by the pendulum is when the first flag leaf – still rolled – has appeared, while reflectance sensing can already start when the tillering has ended.

Another concept that also leaves out any direct influence of plant ingredients is based on sensing the apparent **crop height** by an ultrasonic transducer. This method relies on distance recording as shown in Fig. 8.7 and operates similar to well known applications in automobiles as driver aids for parking. Reusch (2009) has shown that an ultrasonic transducer, which is pointing vertically downwards from a front mounting of a vehicle towards the crop canopy, simultaneously can

indicate the distance to the soil surface as well as to the top of the canopy. Hence from the difference of these distances, it can sense the apparent crop height, which in turn is well correlated to the biomass dry matter. In experiments with winter-wheat and growth stages between EC or BBCH 21 and stepwise up to EC or BBCH 69, the biomass was indicated with coefficients of determination (r^2) between 0.79 and 0.94. Contrary to sensing via canopy resistance against bending, the biomass was also precisely recorded in early developmental stages between BBCH 21 and 32. Hence this rather simple physical method could be used even for the first top dressing of small cereals. However, practical experiences in this direction do not yet exist.

9.4.7 Cell Sizes or Resolution

An important question is the spatial resolution in site-specific nitrogen application. In case the resolution that is obtained is too low, and consequently the cell sizes are too large, any site-specific application might be useless (see Chap. 2). However, it is essential to differentiate between

- the cell sizes for site-specific **distributing** (spreading or spraying)
- the cell sizes for site-specific **sensing** of the crop status during fertilizing
- the cell sizes when **recording the heterogeneity** of crops is done.

An adequate cell size in site-specific distributing is the final aim. But having a distributing cell size that is below that of sensing is useless. To be effective, the cell sizes that hold for site-specific distributing must be as large or larger than those that are sensed. Usually the cell sizes in proximal sensing are much smaller and averaged during processing because of the speed and frequency with most optical methods. Yet a prerequisite of having adequate cell sizes both for distributing and for sensing during fertilizing is knowledge about the heterogeneity of crops.

Recording the **heterogeneity** of crops in respect to the nitrogen supply can easily be done by proximal reflectance sensing of crop canopies with a high frequency. This method can provide more than 100 basic signals per second for small sampling areas and the field-transects thus recorded or mapped are very accurate if a precise georeferencing method is used (Thiessen 2002). The semivariograms that are obtained from the transects can supply the upper limits of cell sizes or of cell side lengths as outlined in Fig. 2.5. Exceeding this **upper limit of cell side length** deteriorates the precision in site-specific management. The upper limit of cell side length sometimes is called the mean correlated distance.

Results from this method of recording the heterogeneity by sensing of red edge inflection indices and hence of the nitrogen supply of small cereal crops in Schleswig-Holstein, Germany are listed in Table 9.6.

The upper limits of cell side lengths vary between 5.9 and 139.0 m. The reasons for this wide span are difficult to find out. The geographic areas in Schleswig-Holstein that are involved are

Table 9.6 Heterogeneity of small cereal crops in three regions of Schleswig-Holstein, Germany

| Field and crop | Date | Upper limit of cell side length |
|---|---------------|------------------------------------|
| Eastern hilly, loamy region of Schleswig-Holstein | | |
| Achterkoppel, winter-wheat | 23rd of March | 33.5 m |
| | 27th of April | 28.4 m |
| | 31st of May | 13.2 m |
| Achterkoppel, winter-barley | 4th of April | 5.9 m |
| | 23rd of April | 32.8 m |
| | 30th of May | 34.1 m |
| Achterkoppel, winter-rye | 16th of April | 75.0 m |
| Kronskoppel, winter-barley | 26th of April | 11.8 m |
| | 11th of May | 14.7 m |
| Viehkoppel, winter-wheat | 27th of April | 8.6 m |
| | 26th of May | 12.0 m |
| Niedeel, winter-wheat | 4th of April | 13.4 m |
| | 17th of April | 7.2 m |
| | 7th of May | 7.5 m |
| | 30th of May | 7.4 m |
| Niedeel, winter-barley | 13th of June | 32.9 m |
| | 16th of April | 17.0 m |
| | 26th of May | 99.1 m |
| <i>Average for Eastern hilly, loamy region</i> | | 25.3 m |
| Central flat, sandy region of Schleswig-Holstein | | |
| Olenhoebek, winter-wheat | 8th of May | 46.9 m |
| | 7th of June | 27.3 m |
| Olenhoebek, winter-barley | 23rd of April | 29.4 m |
| | 19th of May | 33.7 m |
| Olenhoebek, winter-rye | 11th of April | 18.0 m |
| <i>Average for central, flat, sandy region</i> | | 31.1 m |
| Flat, loamy region of Fehmarn Island, Schleswig-Holstein | | |
| Ostenfeld, winter-wheat | 6th of May | 116.1 m |
| | 4th of June | 139.0 m |
| Hohlblöcken, winter-barley | 6th of May | 28.6 m |
| | 4th of June | 32.0 m |
| <i>Average for flat, loamy region of Fehmarn</i> | | 78.9 m |

The criterion of the heterogeneity is the upper limit of cell side length as defined in Fig. 2.5. The results are from vehicle based, site-specific sensing for N with red edge inflection indices and a vertically viewed sampling area of 1.5 m² (From Thiessen 2002, altered)

- the eastern, hilly, loamy region with mounds and depressions in the fields
- the flat, sandy, central region
- the very flat, loamy region of Fehmarn island.

From the topography of the fields, the highest heterogeneity should be expected from the rolling, hilly fields in the eastern region and the opposite from the very flat agricultural areas in Fehmarn. The average upper limits of cell side lengths confirm these expectations, however, there is much overlapping of individual data.

The results from different times within the growing season differ widely for the same crops, and there is no uniform trend discernible. The same holds for differences in the results between the crop species. In short, there seem to be some factors involved that are not listed.

From the **averages** of the upper limits of cell side length (Table 9.6), it can be concluded that the working widths of most present day fertilizer spreaders probably comply with the site-specific application needs for nitrogen. The lowest average limit of cell side length is about 25 m. Although the spreading widths of modern **centrifugal spreaders** exceed this range, the overlapping that occurs with this method of distributing must be considered. The actual working widths of centrifugal spreaders that are obtained after taking into account the overlapping are usually not above this range.

For modern **pneumatic spreaders**, the working width can be above 25 m. However, with many of these spreaders, it is technically feasible to practice sectional control and thus to supply the right and left section with separate rates of fertilizer. Hence with this method too it would be possible to stick to the needed limits of cell side length.

Very high resolutions and thus small limits of cell side lengths can be realized with **sectional rate control** for the outlets or nozzles of either pneumatic spreaders or of sprayers. This method is state of the art for spot spraying of herbicides in fallow fields with dryland farming (Fig. 6.5). With proper reflectance indices and variable control devices, it could be used for site-specific nitrogen application as well and would allow for an upper limit of cell side length that is as low as 0.5 m.

Hence it can be concluded that principal technical limits for nitrogen application with resolutions that correspond to the needs of crops probably do not exist. The overriding question is: what resolution is needed in order to correspond to the heterogeneity of the crop? Most present day machinery for site-specific nitrogen application is designed for lateral cell side lengths that comply with the working widths of conventional centrifugal spreaders (Figs. 9.24 and 9.25).

The really sensed widths or areas usually account only for a small fraction of the fertilized width or area (*e.g.* Fig. 9.22). The inaccuracy that might result from this is partly offset by averaging of optical signals that are received in the direction of travel. The finally obtained **cell side lengths** in the direction of travel are much smaller than the working width in fertilizing.

So the presently realized resolution in distributing results in **cell-shapes** that correspond to rectangles whose long side is oriented perpendicular to the direction of travel. Theoretically it might be better to have squared cells. However, the present rectangular cells with long sides perpendicular to the direction of travel result from technical possibilities with conventional spreading machinery.

It must be mentioned that any results of heterogeneity sensing (Table 9.6) depend on the **sample areas** that are recorded. This is because of the averaging effect that automatically takes place when the sample area is increased. Thus the resolution that is used for recording the heterogeneity of crops greatly influences the obtained upper limit of cell side length (Solie et al. 1996). An interesting question to the

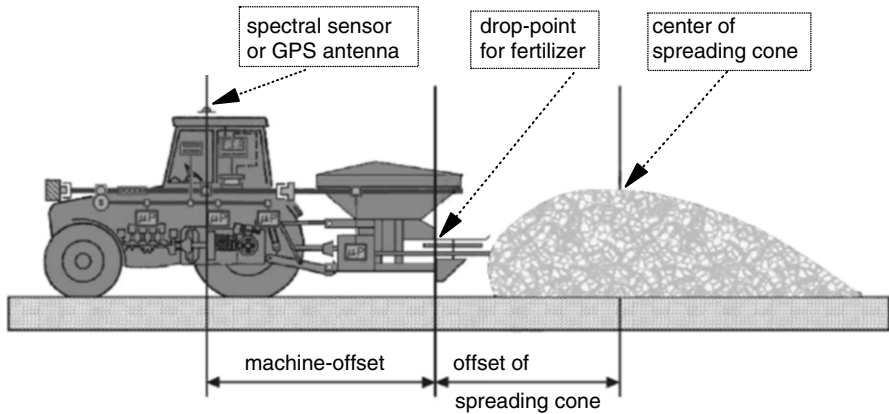


Fig. 9.34 Offset distance between locations of signal reception and distribution of fertilizer, consisting of a machine-offset plus a spreading cone-offset (From Griepentrog and Persson 2001, altered)

method of determining the heterogeneity of small cereal crops is this: is the sample area of 1.5 m² that was used (Table 9.6, legend) adequate? This thinking reduces the question about the resolution in site-specific distributing to a problem of selecting the suitable sample area. And the latter will certainly depend on the crop species and on the nitrogen flux within a soil.

9.4.8 Distance- and Time Lag in Site-Specific Application

The signals for site-specific fertilizing normally are received by a process-controller that is located within the tractor-cabin. These signals are supplied either by the spectral sensor or – in case of mapping – by the GPS system that correlates the mapped data to the geographic location within the field. The fertilizer, however, is distributed some distance away from the tractor. This **offset distance** is composed of a machine offset plus an offset of the fertilizer position in the field that is due to the spreading (Fig. 9.34). Accurate site-specific fertilizer placement is not possible without compensating for this offset distance.

In addition to this offset distance, a **time-lag** in the control of site-specific spreading or spraying must be considered. This time-lag is the result of response-delays in the control adjustments for the spreading or spraying. With mounted centrifugal spreaders that feed the spinning discs by gravity, this time-lag is approximately 2 s. When the feeding of the spinning discs is done by conveyor belts, the time lag increases to about 3.8 s.

And finally with mounted pneumatic spreaders, the time-lag is between 4 and 5 s (Griepentrog and Persson 2001). In most cases, sprayers for liquid applications have rather low time-lags that are between 1 and 2 s (Bennur and Taylor 2010).

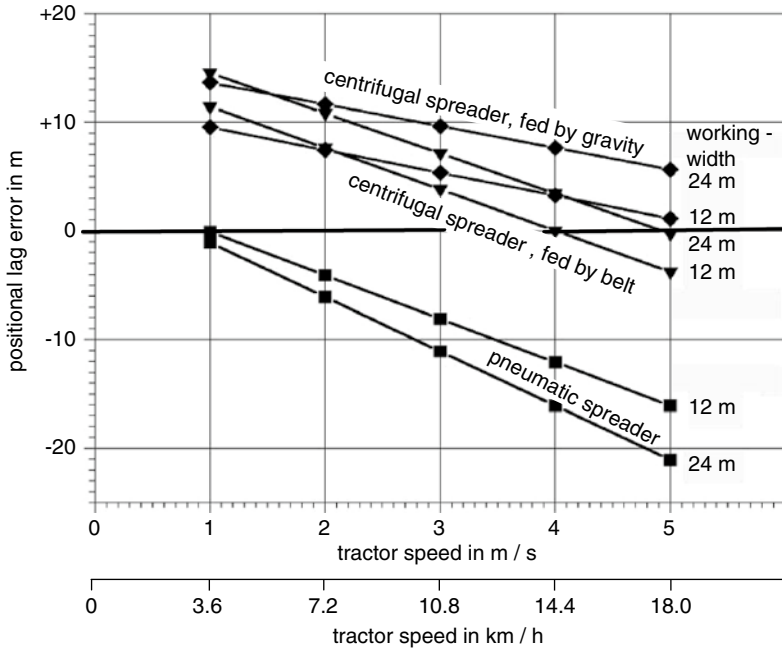


Fig. 9.35 Positional lag error versus tractor speed for three fertilizer spreading techniques. The positional lag error is the difference between the offset distance and the time-lag distance (From Griepentrog and Persson 2001, altered)

For precise site-specific application, the distance that the machinery moves in the field within the time-lag is important. If this **time-lag distance** does not match the total offset-distance, an error in the site-specific placement of the fertilizer results. Any difference between the offset-distance and the time-lag distance here is called **positional lag error**, which can be positive or negative.

The aim is to have a positional lag error close to zero. In case the positional lag error is positive – *i.e.* the total offset-distance is larger than the time-lag distance – a correction can rather easily be obtained by purposely increasing the response time of the controller.

If the positional lag error is negative, the travel speed can be reduced in order to decrease the time-lag distance. However, this deteriorates the labor efficiency of field operations. So the question is, which positional lag errors occur with the presently dominating distributing techniques and their typical time lags.

As can be seen from Fig. 9.35, the mounted **centrifugal spreaders** have positional lag errors that are positive except for very high tractor speeds. Yet these positive lag errors can rather easily be removed by adjusting the control devices for longer response- or default times. Contrary to this, the mounted **pneumatic spreaders** have negative positional lag errors with the exception of very low tractor speeds. These errors can only be avoided by driving more slowly.

The positional lag error for **spraying** of liquid fertilizers (not shown in Fig. 9.35) corresponds approximately to the situation for centrifugal spreaders. This is because for sprayers the time-lags or response-times are on a low level as well and hence any positive positional lag errors that exist can be removed by adjusting the control devices for longer response times.

9.4.9 Sensed Signals and the Control of Nitrogen Application

9.4.9.1 Agronomic Background

The site-specific signals that indicate the crop properties cannot be used directly for the control of the nitrogen application. These signals just provide information about the chlorophyll content of the leaves, the biomass or the leaf-area-index. The property-substitutes must be converted into fertilizer application rates.

In early **growing stages** of crops, the general consensus is that when crop properties indicate a low nitrogen supply, the application rate should be increased and *vice-versa*. With sensing by reflectance indices this means that when *e.g.* the red edge inflection point or the red edge ratio (Table 9.5) go up, the application rate should go down. This basic relation is rather easily implemented into the control-algorithm, however, there is much more needed. The site-specific indications that modern crop sensors supply do not at all spare the need for a detailed agronomic knowledge about the reasonable use of nitrogen fertilizer by taking into account

- the crop species and varieties
- the soil properties
- the growth stages
- the water supply
- the effects of rotations, crop-residues, manure and nitrogen-mineralization
- the use of the product (food, feed, fiber *etc.*)
- the costs of fertilizers and product prices.

The list is not complete and just should demonstrate that about every situation in a field is a unique one. In order to simplify the search for the best application rate, it has been proposed to use integrating factors. One such **integrating factor** is the final crop yield. Several of the items listed above affect the crop yield. And if this yield were known precisely at the time of fertilizing, taking this into account would simplify the control needs definitely.

The problem is that the final crop yield cannot be predicted precisely enough at the time of fertilizing. This is because the final crop yield is affected by the weather in the growth stages that still lie ahead. The uncertainties in the weather-forecasting beyond a few days do not allow a precise prediction of the expected final yield.

So in view of the abundance of factors that have to be considered, it might be asked how generally the rates for in-season nitrogen application are defined. The usual procedure in practical farming is that the farmer or his consultant inspects and

Fig. 9.36 Measuring the transmittance of the youngest wheat leaf for precise calibrating of site-specific nitrogen application (From Agri Con GmbH, Jahna, Germany)



considers the local situation of the crop and makes a decision. Small handheld meters that can indicate the chlorophyll content of plant leaves at a few spots in the field (Fig. 9.36) and specific schemes of advisory services are often used to assist in defining the proper rate. Yet the decision still relies largely on the knowledge and experience of the farmer or consultant. And this decision is indispensable for a uniform application in the whole field as well as for a site-specific application. The difference is just that for a uniform application the decision is about the constant rate in the whole field, whereas for a site-specific application a minimum rate, a maximum rate – hence the limiting rates – and the control line between these must be defined.

9.4.9.2 Limiting Rates and Slope of the Control-Line

Entering the minimum- and maximum rate into the algorithm is easily done with modern process-controllers. For the control-line that extends between these **limiting rates**, its relation to the reflectance index must be defined. Presently, the dominating practice is to assume a simple linear relation between the points along the control-line and the reflectance index, *e.g.* the red edge inflection point or the red edge ratio. This simplifying assumption may not be far off, though there are indications that a still more precise definition of the relation between the nitrogen needed and the reflectance indices is possible (Holland and Schepers 2010).

The **control-line** stands for the relation between the reflectance index and the nitrogen rate (Fig. 9.37). As a linear line, its course is defined by the slope and an intercept. Its course can also be determined by the position of the minimum- and of the maximum rate in the graph that has the reflectance index and the nitrogen rate as ordinates.

Hence a logical method of defining the control line is to direct the field of view of the reflectance sensor on one spot in the field that needs only the minimum rate

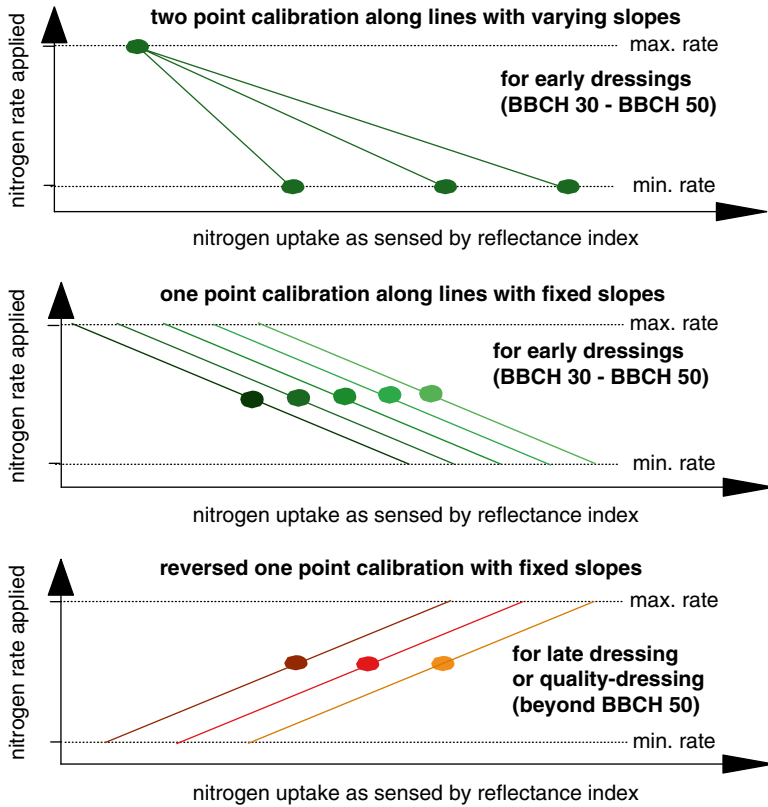


Fig. 9.37 Principal control-algorithms for site-specific nitrogen application based on reflectance sensing and limiting rates. The course of the linear control lines is defined by the minimum rate, the maximum rate and by the slope of the lines. The developmental stages for small cereals are indicated in BBCH units. These are identical to EC units or Zadoks units (From Thiessen 2001, 2002, altered)

and then on another place for that the maximum rate seems adequate. At these two points, the respective reflectance indices of both limiting rates are obtained for the algorithm. The site-specific control should then logically take place along the line that connects these two extreme points (Fig. 9.37, top). A prerequisite for accuracy with this **two point calibration concept** is that the farmer carefully selects the best spots for the minimum- and maximum rate in the field.

In order to ease the calibration work for the farmer, a **one point calibration concept** has been introduced and now has become a standard method for main crops (Fig. 9.37, center). With this concept, a **default slope** of the linear control line is in the program of the algorithm. The default slope has been obtained from numerous field experiments with the respective main crop. This allows to calibrate the sensor by just recording the reflectance on one spot or on one short strip within the field and assigning an estimated nitrogen rate to it. Within this spot or short strip, the farmer

can enhance his estimate about the nitrogen supply and hence the needed rate by transmittance measurements from the youngest leaf of some plants (Fig. 9.36). This too supplies information about the chlorophyll content.

With all these site-specific calibration methods, the farmer does not know well at the outset of the fertilizing operation how much nitrogen finally the whole field will get. Because this depends on a sum of many small applications that are not known in advance. Yet increasing the sample area that correlates reflectance and estimated nitrogen rate allows to correct this at least partially. So instead of a spot or short strip within the field, some farmers take a **full transect** in a typical region and relate its mean reflectance index to an estimated nitrogen rate. But also in this case, the control line is based on a one point calibration concept.

Whenever default slopes from past experiences are not available, the two point calibration method is indispensable. This method also is essential if more flexibility in the site-specific application is desired. In case knowledge about a locally different reaction of a crop on nitrogen fertilizer is available, this flexibility can be necessary. But how to get information about this local reaction to nitrogen?

The use of **nitrogen-rich strips** within fields aims at getting information about this. These strips are applied at the start of the growing season in one or several small areas of the field with the objective to test the effect of the nitrogen. The term “N-rich” indicates that the crop within this strip really has sufficient nitrogen. Since it is known how much nitrogen was applied, the comparison of the strips with the adjacent non-rich plants can inform about the slope that the control line should have. If the reaction to more nitrogen is small, the slope to the horizontal should also be small and *vice versa*.

But on what scale or resolution should this information from N-rich strips be applied? The use can be oriented at **field scales** and hence assist in getting the right slope of the control line for an individual field. Yet nitrogen-rich strips can also be applied in such a way that the slope of the control line is continuously adjusted while the tractor with the spreader or sprayer is moving through the field. The implementation of such a continuously adjusting system for the slope of the control line needs a thin enriched strip or **transect within each pass** of the fertilizing machine. By sensing the reflectance precisely along this narrow strip and referencing it to a standard, the signals for adjusting the slope of the control line in an on-the-go mode are obtained. Thus the N-rich concept is based on **site-specific cell scales**. The result is that the site-specific control of nitrogen application occurs in a combined **dual mode**. The control is based firstly on the nitrogen supply that the plants have, but secondly also on the site-specific reaction to more nitrogen. Both the nitrogen supply as well as the reaction to more nitrogen are sensed by reflectance. For details to this concept of dual mode site-specific sensing of the nitrogen supply as well as the response to nitrogen see Thiessen (2001, 2002).

However, any calibration method – whether used on a field scale or on a site-specific scale – represents a reaction that is based on the weather conditions of the past. But the application control aims at reactions in the future. This temporal difference implies errors that can result from varying weather and its effect on changing soil or crop conditions (Roberts et al. 2011).

Another concept of a site-specific adjustment for the slope of the control line would be to take into account the effect of different soils. It is well known that – *ceteris paribus* – the efficiency of nitrogen use also depends on the **texture of soils** (Tremblay et al. 2012). On sandy soils, the nitrogen use efficiency often is not as good as on soils with more clay or silt. And since a surrogate of texture – the soil conductivity – can rather easily be mapped, a feasible approach would be to orient the slope of the control line on site-specific field maps of this soil property. The result would be a site-specific **soil conductivity based slope** of the control line. This approach is not state of the art, but it would be rather easy to implement such an additional control mode.

9.4.9.3 Controls for Improving the Quality of Products

A completely different situation arises for small cereals when it comes to a **late dressings** that might be applied after heading, *i.e.* after BBCH stage 50. The objective of such late applications is not to increase the yield mass, which hardly is possible at this stage any more. Instead, the application of small amounts of nitrogen in this developmental period aims at raising the protein content of the kernels. Accordingly, this rather late application is denoted as “quality-dressing”. However, this “quality-dressing” needs biologically active plants. Therefore, the more dark and green the canopy is, the more effective this late application can be, and the higher the nitrogen rate beyond BBCH 50 should be. This explains why, for quality-dressing, the basic controlling mode goes in the opposite direction: with rising red edge inflection point or red edge ratio index, the application rate is increased (Thiessen 2001, 2002; Reckleben and Isensee 2004). Hence, compared to earlier dressings, the slope of the control line is inverted (Fig. 9.37, bottom).

Proper quality-dressings of nitrogen for small cereals result in a higher protein contents, which can improve the value of the grain if it is used for bread or for feed. The advantage of applying this quality-dressing in a site-specific mode instead of a uniform way for the whole field is that this can provide for less **variation in the protein content** of the harvested grain. This holds especially for small cereals from fields with varying soil texture (Reckleben 2003).

Still another situation exists if the objective is to produce **malting barley** for beer breweries. For this product, the ideal crude protein concentration is not high, but rather low, namely about 10.7 % of the dry matter. Site-specific nitrogen application too can assist in getting close to this protein content. Any late dressings after heading can be left out completely, since high levels of protein content deteriorate the quality in this special case. The approach for keeping the protein content at this rather low level is reflectance sensing for the control of nitrogen application at the earliest possible growth stage, *i.e.* at about BBCH 30 – BBCH32 (Hopkins et al. 2007; Pettersson and Eckersten 2007; Söderström et al. 2010). The site-specific control provides the means for limiting the application and for evening out variations in the protein content within a field that – without using this technique – might develop as a result of differences in soil texture.

Similar concepts of improving the quality of plant products by correcting an uneven supply that is due to varying soil conditions via site-specific control of the nitrogen supply are conceivable for many crops, *e.g.* potatoes, sugar-beets and vegetables.

9.4.9.4 Control by a Sufficiency Index

This method for the control of site-specific nitrogen application via reflectance sensing was – starting with maize – developed by Holland and Schepers (2010). It is based on defining normalized reflectance indices by using a generalized plant growth function. The premise is that the plant growth function depends on the nitrogen supply. The **normalized reflectance indices** are given by a **sufficiency index** that represents the ratio of the locally sensed reflectance index to the same index that stands for plants of the same crop that have no nitrogen limitation. Hence:

$$\text{sufficiency index} = \frac{\text{locally sensed reflectance index of crop}}{\text{reflectance index of non-N limited crop}}$$

For suitable reflectance indices that can define the sufficiency index see Table 9.5.

The corresponding **generalized plant growth function** is assumed to be a second order polynomial with downward cavity, thus a quadratic function of the nitrogen that was applied (Fig. 9.38). The basic concept is that the sufficiency index is a surrogate for the ability of the crop to grow, thus for its vigor, and that the nitrogen rate given should be related to it.

It is essential to differentiate between on the one hand the nitrogen supply of a crop in the past that provides the sufficiency index (Fig. 9.38) and on the other hand the nitrogen rate that should be applied. Both nitrogen parameters need to be detected on a site-specific basis. The first parameter, the nitrogen supply of the past, is directly represented by the sufficiency index. The second parameter, the nitrogen to be applied, must be derived from the sufficiency index.

Holland and Schepers (2010) provide a mathematical deduction of the nitrogen rate that should be applied. The result of this mathematical deduction is that the site-specific nitrogen rate to be applied can be described by a rather simple equation:

$$\text{Nitrogen rate in kg per ha to be applied, } N_{\text{appl}} = C \sqrt{\frac{1 - \text{sufficiency index}}{\text{delta sufficiency index}}}$$

The term in the numerator, $(1 - \text{sufficiency index})$, is represented by the respective vertical distance in the green area of Fig. 9.38 for a given *ex ante* nitrogen supply. And the delta of the sufficiency index is the vertical difference between the intercept of the plant growth function and maximum of the latter. The term C stands for factors such as *e.g.* nitrogen from mineralization of soil organic matter and organic fertilizers or from previous legumes. This term can also take into account the fact that the agronomic optimal nitrogen rate in practice should be replaced by

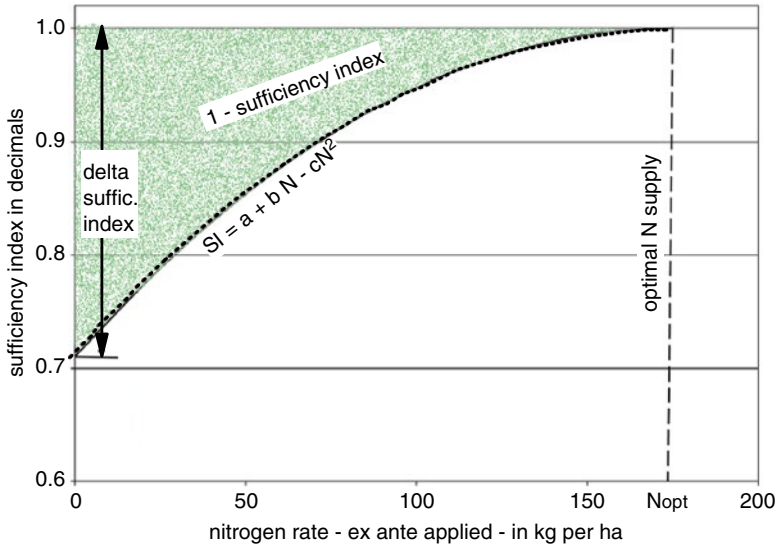


Fig. 9.38 The sufficiency index SI as defined by the *ex ante* applied nitrogen rate via a generalized plant growth function (From Holland and Schepers 2010, altered)

an **economically optimal nitrogen rate**, which is a little lower because of the costs of the fertilizer. So an interaction by the farmer with his local situations and experiences is possible via the term C.

Compared to the use of a limiting rate method from the previous sections, the control by the sufficiency index does not simply follow a straight line but depends on the respective plant growth function. This can be regarded as an improvement, since the plant growth function defines the response of the crop to nitrogen probably better. The control via the sufficiency index does not exempt the farmer from deciding about minimum- and maximum rates. The difference is that with the control by the sufficiency index these rates just limit the application. The maximum- and minimum rate do not any more define the course of the control line in between as they do with the limiting rate method (Fig. 9.37).

There remains one problem for all algorithms and all present fertilizing strategies for site-specific control as well as for whole fields: they are based on informations that are related to the past of the crop. But what is needed is an adequate supply for some weeks in the future. This fact presents uncertainties since the weather and especially the water supply of the crop are not known *a priori*.

9.4.10 Interactions Between Nitrogen and Water

Water stress is one of the most common limitations in plant production. When the water supply is inadequate, nitrogen transport from the soil to the leaves is hindered.

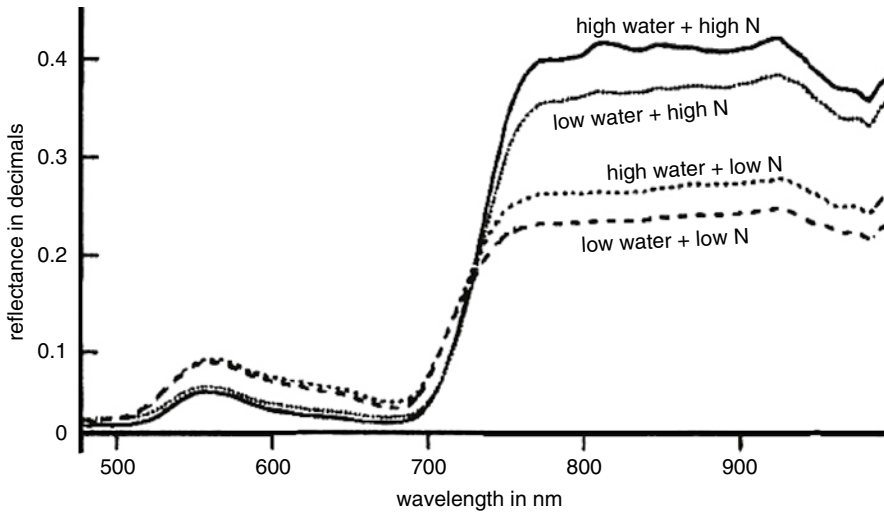


Fig. 9.39 Spectral reflectance of pepper (*Capsicum annuum*) with four treatments concerning the nitrogen- and water supply (From Filella and Penuelas 1994, altered)

If the whole field is too dry, any application of nitrogen might be useless, except in cases, when a remedy by artificial irrigation or by natural rain soon can be anticipated. But this is reasoning about the water supply in the **future**.

Reasoning about the water supply of the crop in the **past** leads to other considerations. Since the signals of the past nitrogen supply of the crop have been derived from the plants appearance, it could be possible, that these signals were influenced by the previous water supply. This is indeed an important point.

Penuelas et al. (1996) have shown that a lack of water as well as an insufficient nitrogen supply have similar effects on the visual appearances of wheat. In both cases, the plants tend to have **xeromorphic characteristics**: the cell elasticity is reduced, the cell walls are thicker as well as more rigid and the cellulose content of the leaves is higher. But how are the effects on the reflectance?

Starting with the not **decomposed reflectance curves** of the visible and near-infrared region, the prospects of separating the effects of nitrogen from those resulting from the water supply do not look good. The reason for this is that the influences of nitrogen deficiency and lack of water have similar effects on the general course of the reflectance curves in the visible and near-infrared range. A rising water stress results in an increase of the visible- and in a decrease of the near-infrared reflectance. The same effect is caused by a lack of nitrogen (Fig. 9.39).

Fortunately, modern reflectance sensing generally has moved away from signals derived from the course of not decomposed curves, which extend over long ranges of wavelengths. Reflectance sensing for site-specific plant production has gone from red-green-blue (RGB) digital imaging to broad band recording and presently to hyperspectral narrow band signals. And further decomposing of the reflectance

Table 9.7 Correction of nitrogen rate depending on the water situation

| | | | | |
|-------------------|------|------|------|------------|
| Nitrogen supply | High | High | Low | Low |
| Water supply | High | Low | High | Low |
| Correction needed | No | No | No | Yes |

curves by using first or second derivatives, Fourier- or wavelet analyses should not be excluded (see Sect. 9.3.1).

The use of the red edge inflection point or of red edge ratios near this point for nitrogen sensing (Table 9.5) is an example for this trend of **targeted decomposing** of the reflectance curve. Several authors as *e.g.* Filella and Penuelas (1994), Yang and Su (2000) as well as Shiratsuchi et al. (2011) found that the red edge inflection points or red edge ratios were not much influenced by the water supply. Among the various spectral indices that were used for nitrogen sensing, the red edge inflection points and especially the red edge ratios were the least affected by crop water stress.

However, even if the red edge inflection points and particularly the red edge ratios are less influenced by water stress, this does not completely remove the problem. These indices allow only for a look at the supply of the crop in the past days or weeks. The actual sensing is directed at providing the nitrogen for coming weeks. And it can be taken for granted that when the crop cannot transpire because of a starting or ongoing drought, it will not be supplied with nitrogen. Hence the current supply of nitrogen as well as of water should be sensed separately and simultaneously by a **dual sensing strategy**. The prerequisites for doing this are good. Fortunately, the best wavelengths for sensing nitrogen on the one hand and water on the other hand are well separated within the spectrum (see Sects. 6.5 and 9.4.3.1).

How should the site-specific nitrogen rate be adapted to the water situation? Only the extreme cases can be outlined here. These extreme cases are described by respectively high or low supply of either nitrogen or water (Table 9.7).

In places of high nitrogen supply, the crop needs no fertilizer; therefore the water situation is of no avail for the fertilizing strategy. This also applies, when the sensing signals indicate a low nitrogen supply, while the water situation is good. The alert situation is, when both the nitrogen as well as the water supply are signaled as low. Without any information about the water situation, a high site-specific nitrogen dose would be applied. The dual sensing of nitrogen and water would prevent wasteful and perhaps environmentally harmful nitrogen application in this case. However, this concept of dual sensing is not yet state of the art.

Since it probably can be assumed that the water supply of crops varies temporarily as much as the nitrogen supply does and hence calls for short-termed control reactions, the best concept would be tractor based **on-the-go dual sensing**. An alternative would be a dual control via a combination of mapping the water supply of the crop by signals from satellites and tractor based on-the-go nitrogen sensing. This could be a reasonable solution provided the transmission of the radiation is neither impeded by the atmosphere nor by clouds and the frequency of remote recording suffices. Unfortunately, the prime candidate for water sensing, namely infrared

radiation, does not get through clouds. Hence the concept of remote sensing based on infrared reflectance would be risky for regions with maritime climate.

The restrictions that result from clouds do not exist for remote sensing via **radar**. However, remote water sensing of soils or crops via radar still is in an experimental state. This applies especially to water sensing in crops, which would be preferable, because it automatically takes into account any interaction between soils and roots on the supply of plants.

9.4.11 *Benefits, Costs and Economics*

9.4.11.1 **Benefits**

The potential benefits from site-specific nitrogen application can vary between

- higher yields in masses of product per ha
- savings for nitrogen fertilizer
- better conditions for harvesting the crop
- better qualities of the harvested product
- less leaching of nitrogen into ground-waters.

Which of these possible benefits dominates, might depend on the crop, the variations in soil properties and weather, the control algorithm as well as on the time within the growing season when the site-specific technique is used. Hence for comparisons of uniform- versus site-specific nitrogen applications, a variety of results might evolve.

Higher **yields** in masses of product per ha can be expected if the average nitrogen rate for site-specific application is about the same – and hence not lower – than with uniform fertilizing. In field experiments with site-specific and uniform application, this is not easy to obtain, since the average rate with site-specific fertilizing is not known precisely beforehand. Another prerequisite for higher yields is site-specific application within a rather early vegetation stage, *e.g.* EC or BBCH 30–40 with small grains.

The comparisons of site-specific and uniform applications in Fig. 9.40 are based on approximately the same average nitrogen rate and early dressings of winter-wheat. The site-specific applications were controlled by reflectance sensing. It can be seen that for the location Raguhn the yields hardly were influenced. The reasons for this probably are uniform soil properties or low rainfall in the growing season. The other 16 locations resulted in a **mean yield increase of 4.1 %**. However, the spread around this average result is remarkable and presumably due to the many factors that affect the yields of crops.

Savings for nitrogen fertilizers can be based on the area that is treated or on the product that is harvested. The latter approach is probably preferable, because the product is the objective. This leads to defining the efficiency of mineral N use, *e.g.* in kg of grain per kg of N applied.

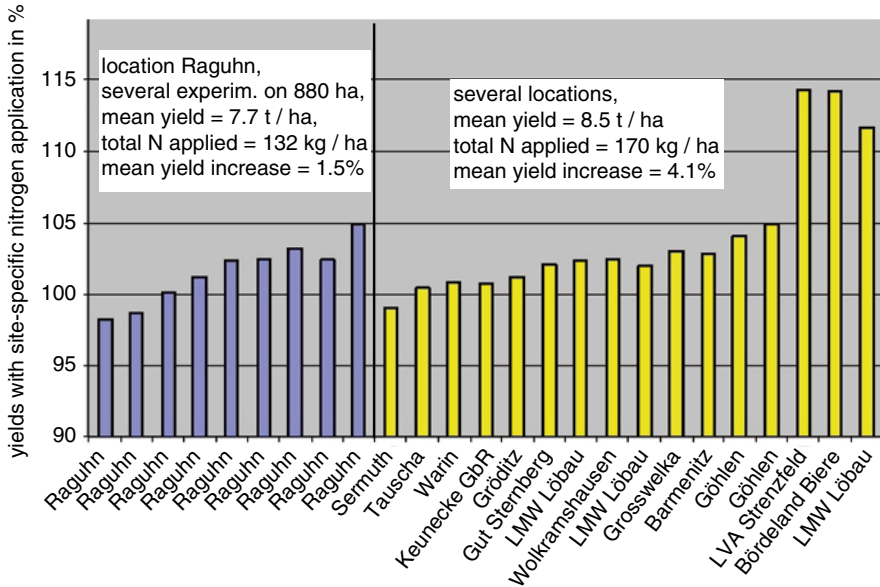


Fig. 9.40 Yields of winter-wheat in field experiments with site-specific nitrogen application via the Kiel system of reflectance sensing versus uniform nitrogen fertilization. The results of uniform nitrogen application are set to 100 %. The average nitrogen rates within each field with site-specific and with uniform application are about the same. The names below the columns represent the locations of the fields in Germany (From Werner et al. 2004, altered)

Higher yields that are obtained with the same level of total nitrogen application (Fig. 9.40) indicate an improvement of mineral N use. However, it should be realized that the **efficiency of N use** depends on the yield level. This is because of the law of the diminishing returns (Mitscherlich 1922; Holland and Schepers 2010). Hence a precise indication of the efficiency of N use can only be provided from experiments in which the yields from uniform N fertilizing on the one hand and from site-specific application on the other hand do not differ significantly. Such results can be expected from experiments in which the N rate with site-specific application is lower than with uniform fertilizing. The experiments that are listed in Table 9.8 comply with this.

The site-specific control is either based on topography (Griepentrog and Kyhn 2000), on reflectance sensing (Havrankova et al. 2008) or on the resistance of the canopy against bending (Thoelle and Ehlert 2010). It can be seen that all site-specific methods improve the efficiency of nitrogen use (Table 9.8). Especially the control based on topography clearly enhances the nitrogen use. This suggests that in hilly fields a combined control both by a surrogate for the nitrogen supply and in addition via mapped topography might make sense.

A key question in this respect is whether site-specific nitrogen control should aim at **higher yields** in masses of product per ha or at **lower expenditures** for

Table 9.8 Efficiency of mineral nitrogen use expressed in kg grain per kg N

| Crop | Mean yield in t/ha | Total mineral N used in kg per ha | | Efficiency of min. N use in kg grain per kg N | |
|--|-----------------------|--------------------------------------|-----------|--|-------------|
| | | Unif. rate | Var. rate | Unif. rate | Var. rate |
| <i>Griepentrog and Kyhn (2000), experiments in Schleswig-Holstein, Germany</i> | | | | | |
| W. wheat | 11.0 | 201 | 149 | 54 | 74 |
| W. barley | 9.5 | 191 | 147 | 50 | 64 |
| W. wheat | 10.8 | 206 | 131 | 53 | 81 |
| <i>Havrankova et al. (2008), experiments in Bedfordshire, United Kingdom</i> | | | | | |
| W. wheat | 7.5 | 221 | 205 | 34 | 37 |
| W. wheat | 7.3 | 221 | 205 | 33 | 36 |
| <i>Thoele and Ehlert (2010), mean of 13 experiments in Eastern Germany</i> | | | | | |
| W. cereals | 6.2 | 156 | 138 | 43 | 49 |
| Average efficiency of mineral N use | | | | 44.5 | 56.8 |

The results are based on experiments in which the yield level with both site-specific and uniform application of nitrogen is approximately the same. However, the site-specific variable rate application is limited to the second dressing and does not apply to any first dressing

nitrogen fertilizer. Thriwakala et al. (1998) dealt with this question on the basis of a simulation model for whole fields with varying fertility. The latter was defined on the basis of the *a priori* given nitrogen supply, *e.g.* from mineralization of organic matter. The result was that for whole fields with a high mean fertility the site-specific application control should be programmed for higher yield averages. And for fields with a low fertility it should be targeted for lower mean fertilizer expenditures. The problem is that the fertility as defined above does not only depend on soil properties but on weather as well.

The **efficiency of nitrogen use** is a very important criterion for the environmental impact of plant production. This is not only because inefficient nitrogen use causes higher fertilizer costs per unit of the product. In humid areas, inefficient nitrogen use by crops also results in more nitrate that seeps into groundwaters (Schepers et al. 1995; Schepers 2008). This side-effect of nitrogen fertilization has generated the most serious environmental problem that is caused by agrochemicals, namely too high nitrate contents in drinking waters. In the human digestive system, most nitrate is reduced to nitrite. This holds especially for babies. The nitrite in turn lowers the ability of the red blood cells to carry oxygen. So a serious disease due to the lack of oxygen may develop, called “blue baby syndrome” or methemoglobinemia. As a safeguard, government directives have set **limits for drinking water** in large parts of the world. For many countries, the limit is 50 mg of NO_3^- ions per one liter of water, which too meets the proposal by the World Health Organization of the United Nations (WHO 2006). The USA set the limit at 10 mg nitrate N per one liter of water (EPA 2011). This corresponds to 45 mg of NO_3^- ions per liter water. So there is rather good agreement in the objective.

However, the actual situation is that despite small recent improvements, these limits quite often are exceeded (Nolan and Stoner 2000; Sprague et al. 2009,

Umweltbundesamt 2011; Wolter 2004). In agricultural areas, the main cause for this is fertilization. Reducing this by generally accepting lower yields is no worldwide solution of the problem when taking into consideration that still about 800 million people are starving. Instead, technologies that provide a high efficiency of nitrogen use should be aimed at. Because nitrogen that is taken up by a crop is prevented from leaching into groundwaters. Hence more precision in application is needed. Important means for improving the efficiency of nitrogen use are site-specific applications (Table 9.8) as well as temporally split dressings. In other words, the application should be at the right place, in the right time and with the right rate. The thus obtained higher efficiency in nitrogen use results in two-sided advantages: both higher yields or lower nitrogen expenses and in addition better qualities of water resources.

For small grains, also the effect of site-specific nitrogen application on the **conditions for harvesting** the crop should be considered. Nitrogen application for high yielding small grains can result in crop canopies that at harvest time are **lodging** partly. This nuisance for harvesting is mainly caused by disregarding site-specific differences in soil qualities, hence by a local oversupply with nitrogen. Site-specific nitrogen application is oriented at local differences in the condition of the crop, therefore can remove this local oversupply and thus can homogenize the canopy. If the site-specific control is well adjusted, the lodging problem is gone.

However, there is a homogenizing effect via site-specific fertilizing also if no lodging occurs. This is due to the fact that this technique provides more **even shoots**. At harvest time of small grains, this means for shoots of a low order that the ears are located higher from the soil level. Hence harvesting by a combine is facilitated even if no grain lodges (Feiffer et al. 2005).

For combines there exists a relationship between throughput in tons of harvested product per time unit on the one hand and losses in % of the grain on the other hand. Generally it holds that when – *ceteris paribus* – the throughput or the travel speed is increased, the losses get higher and this in a more than proportional manner. Farmers try to keep the losses at a level of approximately 1 % of the small grain harvest and adjust the travel speed accordingly. Under this premise, the site-specifically fertilized and hence more uniform crop allows for a higher throughput. In extensive trials by Feiffer et al. (2005) in Eastern Germany, the field capacity of combines in ha/h for strips of small grains that had been homogenized by site-specific nitrogen application was on the average about 10 % higher than for strips that had been fertilized uniformly. With average costs for combine operations including the driver of 100 euros per ha, this means a saving of 10 euros per ha.

Another potential benefit from site-specific nitrogen application can result from better qualities of the harvested product, especially a more precise control of its **protein content** (see Sect. 9.4.9.3). Perspectives in this direction might exist for many crops, not only for small grains. However, much more knowledge about control algorithms for site-specific quality control is needed.

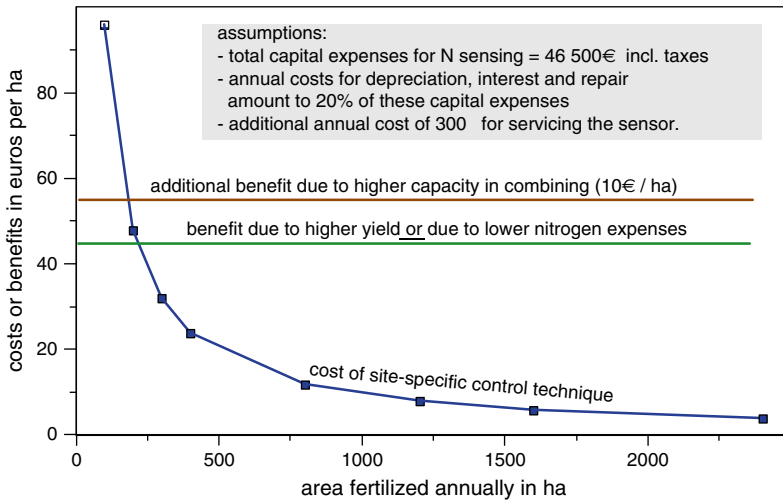


Fig. 9.41 Costs of the control technique *versus* benefits of site-specific nitrogen application for winter-wheat. It is assumed that the site-specific application – depending on the control setting – provides either for a yield increase *or* alternatively for a saving of nitrogen expenses. With present market prices for grain or for nitrogen fertilizer, both alternatives amount to approximately the same financial benefit, hence both are represented by the *green line*. The homogenizing effect of site-specific nitrogen application on the crop results in a higher capacity of the combine. This benefit amounts to 10 euros per ha (*brown line*). For details see Sect. 9.4.11.1

9.4.11.2 Comparing Benefits and Costs

The costs of site-specific in-season nitrogen application result primarily from the capital expenditures for the equipment that is needed for the control of the spreading machine. These expenditures amount to about 46,500 euros for an implement that is designed for reflectance sensing by means of artificial light (Fig. 9.25) including operational terminal, software, a handheld transmittance meter to assist the calibrating procedure and taxes. If natural- instead of artificial light is used, the total expenditure for the corresponding items is about 31,000 euros. However, the annual area that can be treated with the latter outfit might be smaller too because of limitations in operational time.

The control costs per ha that result from the equipment depend heavily on the annual area that is treated (Fig. 9.41).

As for benefits that may result from higher **yields**, an average increase of 4 % is assumed (Fig. 9.40, right). With a yield level of 8.5 t/ha, the corresponding absolute increase of 0.34 t/ha represents a benefit of approximately 45 euros per ha, assuming that the unprocessed small grains in the field are valued at 130 euros per t.

Alternatively, the site-specific control can be used in such a way that no yield increase, but instead a **saving of nitrogen** fertilizer results. From the average efficiencies in Table 9.8, bottom line, it can be calculated that for the same yield of

8.5 t/ha, the saving would amount to 44 kg of N per ha. Since the expenses per kg N for fertilizers – with the exception of anhydrous ammonium – are around 1 euro, the monetary savings would add up to 44 euros per ha. Hence the financial value of the eventual yield increase on the one hand or of the possible saving in nitrogen fertilizer instead of this on the other hand hardly differs and therefore is represented in Fig. 9.41 by a common green line.

The benefits via higher yields or via lower expenses for nitrogen plus those via the higher **capacity of the combine** cross the cost curve for the control technique for an annually fertilized area of about 175 ha. So this area should be exceeded for an economic investment. Since a fertilizer spreader or sprayer with a width of 20 m and a speed of 10 km/h theoretically covers 20 ha per hour, this area might even be handled per day. With large farms or by means of contract management, annual areas of 1,000 ha or more can easily be treated per machine set. Under these circumstances, the financial advantage of site-specific application as represented by the difference between the sum of the benefits and the cost of the control technique (Fig. 9.41) can go up to 40–50 euros per ha. This explains why in practice site-specific nitrogen application has become a leading technique in precision farming.

In addition, there may be benefits from better **qualities** of the harvested products and from less **leaching of nitrogen** into ground-waters. Future experience will show how these benefits should be evaluated. And more knowledge about the best control algorithms will help to fully exploit the possibilities with various crops.

9.5 Summary

The prospects for the realization of **site-specific fertilization** concepts differ substantially among nutrients:

- for phosphorus, the application according to a mapped removal by previous crops is promising. An alternative to this might be the control of fertilizing via flat surface-soil-sensing by visible and near-infrared reflectance.
- as for potassium, too fertilizing proportional to the mapped removal by previous crops has good prospects. However, contrary to phosphorus this holds not for sandy soils.
- concerning nitrogen, excellent prospects exist for sensing the supply and hence the need during distributing via the reflectance of the crop. This limits the application to the respective growing period. Yet this temporal limitation is inevitable as long as efficient nitrogen fertilizing necessitates “immediate feeding” of the crop.
- for the control of soil pH via calcium or magnesium, sensing and mapping the situation by means of ion-selective-electrodes is a promising technique.

With many applications, a site-specific control that takes into account several soil- or crop properties simultaneously might be worth to aim at in the future.

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