Site-specific Nitrogen Fertilization Demand in Relation to Plant Available Soil Nitrogen and Water

Potential for prediction based on soil characteristics

S. Delin

Faculty of Natural Resources and Agricultural Sciences
Department of Soil Sciences
Skara

Doctoral thesis
Swedish University of Agricultural Sciences
Skara 2005

Acta Universitatis Agriculturae Sueciae
2005:6

ISSN:1652-6880
ISBN:91-576-7005-6

Tryck: SLU Service/Repro, Uppsala 2005

Abstract

Delin, S. 2005. Site-specific Nitrogen Fertilization Demand in Relation to Plant Available Soil Nitrogen and Water. Potential for prediction based on soil characteristics. Doctoral thesis.
ISSN 1652-6880, ISBN 91-576-7005-6

In precision agriculture, inputs are adjusted to the varying demand across a field in order to optimize net returns and avoid losses to the environment. For site-specific N application, it is useful to know how fertilizer N demand, plant available soil N (Np, i.e. soil N taken up by plants) and potential yield relate to each other and to different soil characteristics within a field. A 3-year field investigation was carried out on a 15-ha arable field with large soil texture differences in south-west Sweden, on which winter wheat and spring barley were grown. Variation in Np was considerable both within the field and between years but could only partly be explained by variations in soil organic matter, clay and elevation. Maps of yield, grain protein content and Np differed between years, partly due to differences in seasonal variation in soil moisture. Together, protein and yield maps indicated where N supply was sufficient and where factors other than N were limiting, which allowed the accuracy of the N fertilization to be evaluated retrospectively. Differences in yield response to N between areas with different soil texture were small when soil moisture was sufficient. In a dry year, yields were smaller at sandy sites, while in a wet year Np, and thereby yield, was lower on clayey sites. Soil moisture is related to soil electrical conductivity (SEC) and elevation, which are easily measured densely within the field. Therefore, these parameters are useful for dividing the field into zones with different risks for drought and waterlogging and can be used for variable N application, assuming that the season can be defined as dry, normal or wet at the time of fertilization. Average values in zones created from a densely measured variable proved to be a better alternative for many variables in this field than interpolation of sparsely collected soil data without respect to distinct borders.

Keywords: cereal production, grain protein content, grain yield, nitrogen fertilization, nitrogen mineralization, plant available water, precision agriculture, site-specific crop management

Author's address: Sofia Delin, Department of Soil Sciences, Division of Precision Agriculture, SLU, P.O. Box 234, SE-532 23 Skara, Sweden.

Contents

Appendix

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

Papers I-V

I. Delin, S. & Söderström, M. 2003. Performance of soil electrical conductivity and different methods for mapping soil data from a small dataset. Acta Agriculturae Scandinavica, Section B. Soil and Plant Science 52, 127-135.

II. Delin, S. & Lindén, B. 2002. Relations between net nitrogen mineralization and soil characteristics within an arable field. Acta Agriculturae Scandinavica, Section B. Soil and Plant Science 52, 78-85.

III. Delin, S. 2004. Within-field variations in grain protein content – relationships to yield and soil nitrogen and consistency in maps between years. Precision Agriculture (in press).

IV. Delin, S., Lindén, B. & Berglund, K. 2004. Yield and protein response to fertilizer nitrogen in different parts of a cereal field: potential of site-specific fertilization. European Journal of Agronomy (published online).

V. Delin, S. & Berglund, K. 2005. Management zones classified with respect to drought and waterlogging. (Submitted to Precision Agriculture)

The papers are reproduced with kind permission of the journals concerned.

All papers in this thesis are based on data collected in one investigation. Lindén and Berglund were responsible for bringing about this investigation and for its general aim. Delin was responsible for carrying out the investigation, with support from Berglund, Lindén and Söderström.

In Paper I, Delin was responsible for the scope and aim and statistical analyzes. Söderström was responsible for the SEC measurements, while Delin was responsible for the rest of the data collection. Interpolations were performed by Delin and Söderström, maps were made by Söderström and the writing was performed by Delin assisted by Söderström.

In Paper II, Delin and Lindén were responsible for the scope and aim, Delin was responsible for data collection and analysis, while the writing was performed by Delin assisted by Lindén.

In Paper III, Delin was responsible for the scope and aim, data analysis and writing, with support from Lindén and Berglund.

In Paper IV, the aim was set by Lindén, Berglund and Delin, data collected and analyzed by Delin and the writing was performed by Delin with assistance from Lindén and Berglund.

In Paper V, the aim was set by Berglund, data collected by Delin and Berglund, data analysis performed by Delin and writing by Delin and Berglund.

Introduction

Site-specific fertilization aims to match fertilizer dressings with crop requirements and soil nutrient contents as they vary across individual fields. Technology, such as global positioning systems (GPS), geographical information systems (GIS) and remote sensing, used for making rapid measurements of soil and crop properties, has made it possible to collect and analyze spatial data to make detailed yield and soil maps. Since fertilizer requirements are dependent on yield level and soil nutrient supply, such maps may constitute a basis for maps of fertilization requirements. This thesis deals with spatial variation in crop response to fertilizer nitrogen, its magnitude in different years and the causes of variation. One objective was to develop models for the prediction of fertilizer N demand based on within-field variations in plant available soil water and nitrogen. Numerous scientists have spent considerable time finding ways to predict the amounts of fertilizer nitrogen to be applied in crop production to achieve optimum yields and minimize losses to the environment. Why is this so important and why is it so difficult?

Grain yield and quality

In crop production in northern Europe, nitrogen and water are usually the major growth limiting factors. Of all nutrient amendments to Swedish agricultural soils, N fertilization has by far the greatest effects in terms of increasing crop production (Mengel & Kirkby, 1987). Nitrogen fertilization affects not only yield, but also the quality of cereals and other crops in several ways. The amount and timing of plant available N is crucial for the grain crude protein content (CP) in cereals (Gooding & Davies, 1997). The desired level depends on the final use of the product. For example, high CP is desired in bread wheat, but low CP in biscuit wheat and intermediate CP concentrations in malt barley. Too much N may lead to lodging, which in turn reduces grain quality due to over-moist conditions, with germination in the ear as a consequence. Therefore it is important for the economics of crop production to apply the economically optimum N rate.

Environment

Losses from the field

Nitrogen fertilization is also an environmental issue. If fertilizer N is applied in excessive amounts or before heavy precipitation, it may give rise to increased leaching and denitrification losses (Esala & Leppanen, 1998). Some fertilizers, *e.g.* farmyard manure, may lose large amounts of N through gaseous emissions of ammonia during and after application, depending on spreading technique and weather conditions (Misselbrook et al., 2002).

Fossil resources versus recycling

The production of mineral nitrogen fertilizers requires large amounts of energy, and therefore involves consumption of fossil fuels, which also adds to the greenhouse effect. However, the use of mineral fertilizers should not only be limited due to their energy requirements. They should be regarded as a complement to the N resources that already exist, *i.e*. plant available N from the soil, preceding crops and organic fertilizers, such as manure and other waste products. Organic fertilizers, including organic wastes from society, constitute a valuable source of nutrients for fertilization, but may cause eutrophication problems if these nutrients leach to the environment instead of being utilized in crop production. If all nitrogen that leaves the fields could be recycled and applied to the fields in such a way that it became available to the crop during growth, less mineral N fertilizer produced by industry would be necessary. However, some N will be lost thorough leaching in sewage treatment plants (Naturvårdsverket, 1997) or through gaseous emissions from manure and other organic wastes before they are applied to the soil and some N will be mineralized after the crop growing period and then be subject to leaching and denitrification. Human wastes are generally not applied to agricultural fields at all, due to problems with, or fear of, contamination by hazardous chemicals and pathogens. As long as these problems remain, we need mineral N fertilizer to complement organic fertilizers, but methods to economize on all N sources are essential.

Challenges

Nitrogen – a mobile element

Nitrogen circulates between the atmosphere, the soil and living organisms, and many factors and processes are involved in this N turnover. Only a very small proportion of the N in soil is directly available to plants, mainly in the form of NO_3^- and NH_4^+ ions. As nitrogen is a very mobile element, adequate amounts of fertilizer must be applied in each growing season, since excess amounts will not remain available to any large extent for the following growth period. Nitrogen must also be supplied at appropriate development stages of the crop to achieve the desired effects on yield and quality. Early N application primarily promotes vegetative growth and grain yield, whereas N available later in the growing season mainly favours grain filling and protein production.

Weather dependency

Yield response to fertilizer N varies depending on plant available soil N (Np) and potential yield, which in turn depend on a number of factors. Np is here defined as the amount of soil N that the crop takes up during the growing season. Both yield formation processes and Np are very weather dependent. As weather varies between years and is difficult to predict, the task of predicting N fertilizer demand in advance is very difficult.

Spatial variability

Since fertilizer N demand, as influenced by yield level and by quality requirements as described above, is dependent on many factors that can vary within a field, the N fertilization demand may vary spatially. When several influencing factors vary spatially, the variation in N demand can be difficult to predict.

Site-specific N fertilization

When the within-field variation in fertilizer N demand is large, uniform application may give rise to fertilization errors, caused by many influencing factors as described above, which are considerable in parts of the field, although the dose corresponds to the mean demand. To achieve the maximum net returns of added N, adequate quality and minimized losses to the environment, site-specific adjustment is necessary if the within-field variations are considerable. The development of such techniques, together with for instance better utilization of manures, efficient recycling of nutrients from society, the use of catch crops, *etc*., can be regarded as a measure for reducing nitrogen losses and thus protecting the environment. For this, models helping us to decide when and how to consider spatial variability are needed. In principle, traditional methods should still be valid when applied to smaller surface units. However, as these methods may involve laborious and time-consuming collection of data that is unrealistic to perform densely within the field, new approaches may be necessary. This thesis describes the magnitude of spatial variation in fertilizer N demand and factors influencing this within an arable field with large differences in soil texture. The sources of variation and potential for prediction were also investigated.

Objectives

The aims of the experiments in this thesis were to quantify spatial variation in crop response to fertilizer nitrogen and to identify relationships between soil characteristics, plant available soil N and potential grain yield. Since water is the most common factor limiting yield apart from nitrogen in most agricultural areas, relationships between yield and plant available water and related soil characteristics within the field were investigated. The objective was to find out whether such relationships could be used in models for the prediction of fertilizer N demand based on within-field variations in plant available soil water and nitrogen. As mentioned earlier, N fertilization demand is dependent on potential grain yield and plant available soil N. If these parameters are significantly related to soil characteristics within a field, the relationships could be used for estimating fertilization demand site-specifically.

To use soil parameters site-specifically, they must first be mapped. There are several methods for interpolating point data into continuous data and for dividing fields into smaller units. Some methods for interpolation from sparsely collected data were compared with classification into zones in Paper I. The objectives of Paper II were to investigate how much net N mineralization can vary within a field and whether this variation can be predicted from soil parameters such as elevation, clay content and soil organic matter content (SOM). In Paper III, the variation in and relationships between yield, protein (CP) and Np within the field were investigated. Differences in yield and protein response to fertilizer N and the causes of these are presented in Paper IV. In Paper V, the yield pattern within the field was compared between years with dry, intermediate and wet weather. The investigation sought to establish whether zones with a risk for yield depression due to drought could be defined from soil characteristics connected to plant water supply.

Background

Precision agriculture and site-specific nitrogen fertilization

Objectives of precision agriculture

Precision agriculture or site-specific crop management aims at matching inputs and agronomic practices with soil attributes and crop requirements as they vary across individual fields. Such differential treatments within fields are in contrast to the uniform treatments that characterize current management systems. The size of agricultural fields has increased during the past century through fusion of smaller plots and removal of open ditches and other obstacles. With the larger agricultural units of today, it is more difficult for farmers to maintain knowledge of specific details concerning their fields. At the same time, the development of information technology opens up new possibilities to handle large amounts of information. Precision agriculture is a way to again divide individual fields into smaller units and better adjust the management to the conditions of each unit. The aims are to optimize yield and quality of the crop, save inputs and improve profits. More economical use of inputs, such as fertilizers and pesticides, may not only be profitable for the farmer, but may also reduce undesired losses of substances to the environment.

Implementation

In the USA, precision agriculture was initiated in the mid-1980s, using newly available technology to improve the application of fertilizers by varying rates as needed within fields (Robert, 2002). Since then, the concept has been adapted to a variety of practices and crops in many countries. However, several challenges limit a broader adoption, including economic, agronomic and technological barriers (Robert, 2002). For instance, high costs are incurred in the collection of required data and in the acquisition of technical devices and there is some uncertainty regarding whether precision agriculture leads to increased returns. Moore & Tyndale-Biscoe (1999) demonstrated that the potential benefits of applying N fertilizer at the optimum rate for each soil type in a spatially variable field can be positive but small and with a great variability between seasons. Another reason for not adopting precision agriculture is the lack of qualified agronomic services for support. Advisors must possess tools and knowledge to interpret yield and soil maps and to produce maps for variable rate application. As the supply of qualified agronomic services increases and costs decrease, *e.g.* by better sampling schemes and cheaper technical devices, implementation may increase. However, agronomic services need tools and decision support models adapted for precision agriculture. Examples of agricultural practices in Sweden implementing precision agriculture are liming according to soil maps (Gustafsson,

1999) and N fertilization with the Yara N-sensor (Link, Panitzki & Reusch, 2002; Söderström *et al*., 2004). The latter consists of a tractor-mounted multi-spectral scanner allowing real-time variable N application. These practices are performed by contractors and do not require large investments by the farmers. A number of farmers also have equipment for making yield maps, but few know how to use them.

Within-field variations in yield

Recording differences in grain yield within individual agricultural fields using yield monitors on the harvester (Figure 1) was facilitated when the global positioning system (GPS) became available. Commercial yield mapping systems have been available since 1992 (Blackmore & Moore, 1999). Since then, large within-field variations in grain yield have been recorded in Sweden (Mattsson & Thylén, 1994) as well as in other countries (Machado *et al*., 2000; Timlin *et al*., 2001; Blackmore, Godwin & Fountas, 2003). The size of the yield variation varies between fields from small, more or less random, variation to up to several thousands of kg grain ha^{-1}, which in many cases is related to the range of soil texture variation (Godwin & Miller, 2003). Yield is largely dependent on soil moisture conditions, which in turn are correlated to soil texture (Kritz, 1983). The magnitude of the variation in yield may also vary between years. In fields where yield variation is highly influenced by differences in the incidence of drought, yield variation is smaller in moister years and larger in dry years. Topography also affects yield by its effect on soil moisture and temperature, which for example influence crop development, *e.g*. germination, tiller production and grain filling. Yield losses may occur on north-facing land whereas south-facing slopes increase biomass production (Godwin & Miller, 2003). Yields are also influenced by weeds, pests and diseases. Yields of wheat in Europe are reduced by almost 30% due to pests, diseases and weeds (Gooding & Davies, 1997), which may vary considerably within the field (Dalsgård Bjerre, Nistrup Jørgensen & Secher, 1998).

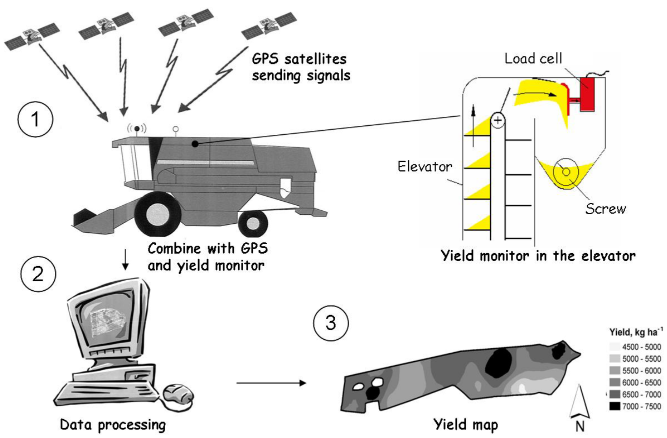

Figure 1. The different steps in producing a yield map: 1) On-the-go recording of yield and position during harvest, 2) data processing in geographical information system (GIS) software and 3) printing of a yield map.

In the early days of yield mapping, there was much hope that such maps could be used as a direct measure for *e.g.* fertilizer requirements within the field. However, yield maps vary between years and should be interpreted to identify causes of variation before they are used for adjusting management practices. By identifying low yielding areas and the reasons for limited yields, different types of measures can be taken. Inputs can be saved in low yielding areas by decreasing the fertilizer rates. On the other hand, measures such as drainage or liming may be needed in those areas to increase the yield.

Site-specific fertilization

Since yields vary and plant nutrient requirements depend upon yield levels (Mengel & Kirkby, 1987), fertilization demand should also vary. In addition, soil nutrient conditions can also vary within the field (Earl *et al*., 2003). Yield maps together with soil nutrient maps indicate where more or less fertilizer is needed. A high yield potential and low soil nutrient content indicate the need for larger amounts of fertilizer. Several models have been proposed based on either yield maps, soil maps or both, or on multivariate methods including several yield limiting factors instead of yield itself (Ortega *et al*., 1999). Another approach includes models based on the current nutrient status of the crop (Link, Panitzki & Reusch, 2002), to be used when fertilization is performed in a growing crop. The latter is especially interesting for N application, since the seasonal variation in N demand can be considerable. For P and K, fertilizer requirements are not as sensitive to seasonal variations. They can therefore be based on soil maps and/or yield maps from previous years. Variable P application that considers yield responses and soil P will even out differences in soil P slowly, unless much larger P additions than required by the crop are applied on areas with low P contents. Goedeken *et al*. (1998) simulated a 50% decrease in variability over 20 years. Swinton *et al*. (2000) could not detect any significant grain yield increase within the first years when they compared variable and uniform application rates of lime, phosphorus and potassium. Several experiments have tested P and K fertilization based on topography, which seems to be profitable in areas where yield potential is dependent on elevation (Pennock *et al*., 1999). Variable rate application of lime can be based on pH maps complemented by clay and soil organic matter (SOM) maps. The contents of clay and SOM, which can be considered to influence the cation exchange capacity of a soil, thus affect the amount of lime required to reach a certain target pH (Gustafsson, 1999; Viscarra Rossel & McBratney, 2000).

Methods for the estimation of site-specific nitrogen fertilization demand

Soil N analyzes – principles and applications

Plant available soil N during the growing season can be divided into two components: soil mineral N ($NH_4^+ + NO_3^-$) in the root zone in early spring and N mineralized during the following growing season. In several countries the overwintering store of mineral N may be considerable and constitute a basis for N fertilization recommendations (Scharpf, 1977; Müller & Görlitz, 1984). However, this involves soil sampling, which is costly and time-consuming and is therefore not feasible for site-specific farming where information at many locations within the field is required. Several rapid techniques for the determination of soil mineral N exist and are reviewed by Ehsani *et al.* (1999). One of them, a nitrate selective electrode, has a fast and accurate on-the-go field unit, but requires tedious calibration. Another method is based on near infrared reflectance (NIR) of the soil, which could predict nitrate levels after field calibration. However, nitrate levels in spring in northern Europe are often very small in relation to the amounts of N mineralized later during the growing season. In addition, NIR is not directly affected by nitrate, but only by other related constituents. More interesting is perhaps that NIR in a similar way can be used to estimate plant available soil N during the growing season (Np) in fields with large variation in SOM content (Stenberg, Jonsson & Börjesson, 2002; Russell *et al.*, 2002; Stenberg, Jonsson & Börjesson, 2004). NIR can be a better predictor of Np than SOM content (Figure 2) (Stenberg, Jonsson & Börjesson, 2002), probably because NIR may be affected not only by SOM content, but also by the quality of SOM, as well as by other soil properties that affect N mineralization.

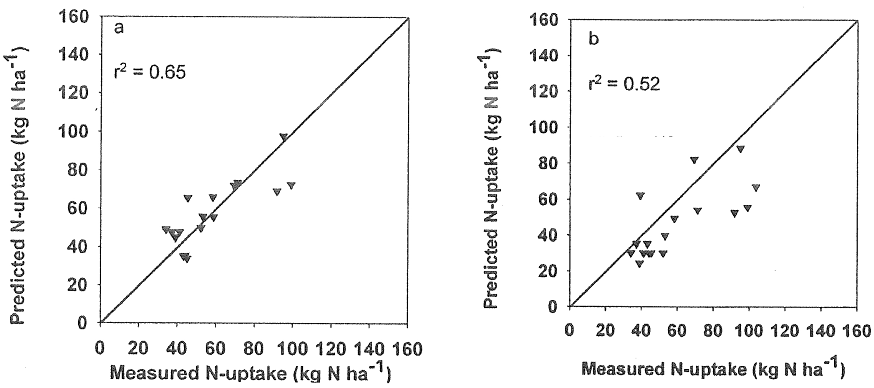

Figure 2. Predicted versus measured plant available soil N in a field. For the prediction, models calibrated on data from another field were used. The models were based on a) NIR spectra and b) SOM data (from Stenberg, Jonsson & Börjesson, 2002).

Remote sensing for estimations of plant N status – principles and applications

Remote sensing is the art of obtaining information about an object through the analysis of data acquired by a device that is not in contact with the object under investigation (Lillesand & Kiefer, 2000). Remote sensing, *e.g.* image and spectral analyzes, is used in precision agriculture to map differences within fields. Image analysis makes it possible to map weeds (Gerhards & Christensen, 2003) and spectral analysis can be used to map fungal infections (Hamid Muhammed & Larsolle, 2003), plant density (Flowers *et al.*, 2003), nutrient status of the crop (Osborne *et al.*, 2002) and, as mentioned earlier, for the description of soil properties (Stenberg, Jonsson & Börjesson, 2002). Plant density and nutrient status of crops are of significant importance for fertilizer demand (Siman, 1974; Wood *et al.*, 2003) and therefore spectral analysis can be used to estimate fertilizer N demand within the growing season. The proportions of radiation reflected, absorbed and transmitted at different wavelengths vary for different features, depending on material and condition (Lillesand & Kiefer, 2000). When a plant canopy grows, the bare soil reflectance spectrum is progressively replaced by the reflectance spectrum of the plants. Thus, the higher the leaf density during growth, the lower the visible reflectance and the higher the near-infrared reflectance (NIR) until a saturation level is reached when the soil is completely covered by the crop (Guyot, 1990). In addition, N deficiency changes the reflectance pattern (Figure 3). As a result of insufficient N supply, the visible reflectance is increased due to decreasing chlorophyll content and the NIR is decreased due to decreasing number of cell layers (Guyot, 1990).

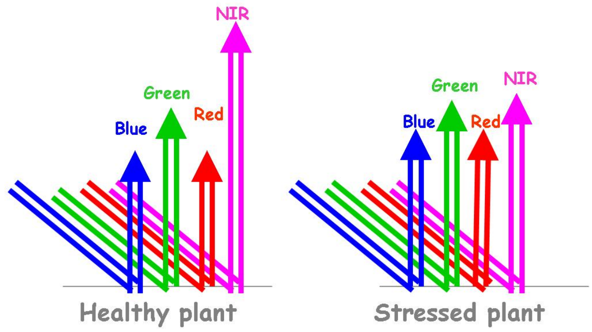

Figure 3. Schematic illustration of reflected light within different wavelengths for a healthy plant and a stressed plant, *e.g.* suffering from N deficiency (after Berry, 1999).

Reflectance of selected wavelength bands within the visible and the near infrared spectrum is used in different indices to estimate biomass and N concentration and thereby fertilization demands (Reusch, 1997; Flowers, Weisz & Heiniger, 2003; Wood *et al*., 2003). Variable rate applications of N based on real-time assessments of canopy size have been successful, resulting in more efficient use of N, and thereby better N economy and reduced N surplus (Wood *et al*., 2003). The principle of using biomass to estimate crop N demand can be used in several stages of plant development at which fertilization is performed. For fertilization at tillering, the smaller the plant density, the more N is needed to achieve optimal shoot density for larger yield (Flowers, Weisz & Heiniger, 2003). At a later stage, however, a small biomass indicates low potential yield, and fertilization should therefore in principle be decreased. However, decreased biomass is often associated with N deficiency and in that case fertilization should be increased, as it is in the concept of the Yara N-sensor (Link, Panitzki & Reusch, 2002). With very large biomass there is a risk for lodging if too much N is applied, which motivates decreased N fertilization. At very small biomass, N fertilization is not considered to be able to compensate for N deficiency and the N fertilization at biomass lower than a certain value is therefore not increased any further. Reflectance data can be collected either with aerial photographs or with sensors mounted on a tractor. Sensors on the tractor provide the opportunity for on-line application directly during measuring, and the technique is less dependent on suitable weather conditions than aerial photography.

Mapping soil characteristics

Soil characteristics, such as pH and contents of nutrients, clay and soil organic matter, may traditionally be mapped through soil sampling at various points in the field. To achieve data coverage of the whole field, the measured data must be interpolated. However, soil sampling is time-consuming and expensive and therefore available samples are often few and sparse, which in turn makes the interpolated data unreliable, especially in small fields where too few samples are taken to check if there is any spatial correlation between observations. There must be a spatial correlation between neighbouring observations to motivate an interpolation. Spatial correlation is described in variograms (Burrough & McDonnell, 1998) created from raw data prior to interpolation. The variogram is necessary for geostatistical interpolation methods such as kriging, whereas other purely mathematical methods such as inverse distance weighting are possible to carry out without any variogram, even though it gives good hints about what parameter settings to use. The variogram (Figure 4) is characterized by its *nugget* (uncertainty at short distances), *sill* (total semivariance) and *range* (distance within which spatial correlation exists).

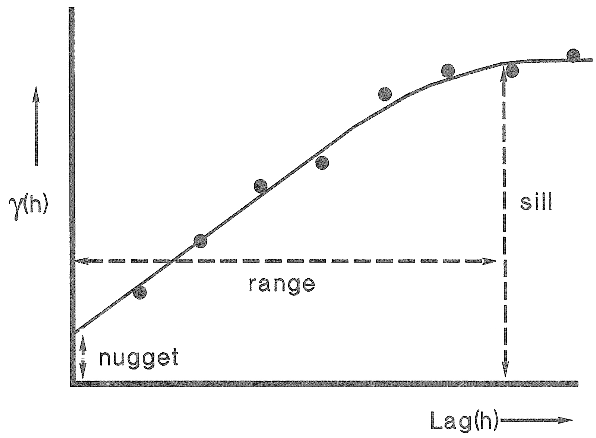

Figure 4. Schematic example of a variogram with range, nugget and sill, where γ(h) is semivariance and Lag(h) is the distance between sampling points.

Often a large number of observations are needed for reliable estimates of variograms used for checking geostatistical relations prior to interpolation. Burrough & McDonnell (1998) suggest 50-100 samples. That is far from the number of soil samples that it is feasible to collect within a normal-sized field in most countries. Other methods for quick and cheap collection of dense data have therefore been tested to replace or complement traditional sampling methods. Variables that can be measured at great density are for instance yield, soil electrical conductivity (SEC), topography and crop or soil reflectance. These can be used for targeting sample points, improving interpolation or in some cases as a direct measure if correlated with the variable of interest. Interpolation can be improved by cokriging, which is a method of interpolating sparse spatial information in cases where correlated parameters are measured at greater density

(Kristensen and Olesen, 1997; Burrough & McDonnell, 1998). Targeted sampling represents a way of reducing sample size and hence costs. Various approaches have been proposed. Olsson, Söderström & Nissen (2003) suggest a method currently used in Sweden, where sample points are selected within grid cells at locations where a SEC map created from few sample points deviates most from a SEC map created from all sample points. Lesch, Strauss & Rhoades (1995) also use an algorithm to select appropriate calibration sites from dense SEC data, to be used for regression-based prediction of soil salinity. A geostatistical approach involves the variance quad tree (McBratney *et al*.,, 1999), where uniform areas are sampled more sparsely and areas with large variation more intensively. In image classification (Thomas, Taylor & Musthill, 1999), satellite images are used to divide the field into zones within which several subsamples are bulked together to get one sample representing the whole zone. Such zones can be managed homogeneously, and are often called management zones. These may also be created, for instance, on the basis of yield data (Lark & Stafford, 1997), SEC (Taylor *et al*., 2003) or both (Halekoh, Greve & Nehmdahl, 2003). Varying management between a few management zones instead of adjusting it to a large number of small grids not only requires fewer soil samples during data collection, but also less advanced technology for management. It should be considered whether to use grid information, management zones or a field average for each field individually, based on the degree of variation and the potential to discern a few homogeneous areas (Söderström, 2003).

Principles of nitrogen supply and crop demand

Principles of optimum nitrogen fertilization

Yield responds positively to N fertilization up to a certain limit, at which some other factor, *e.g*. water, begins to limit crop growth. Too much N may reduce yield due to lodging or more severe fungal infections. This may result in a negative response at higher N levels. The effect of N on yield can be described by response curves expressed as mathematical functions (Figure 5) (Wood, 1980). According to Boyd, Yuen & Needham (1976), the response is best represented by curves with a sharply rising portion, a turning portion and a portion where yield changes little or slowly decreases. Both Sparrow (1979) and Boyd, Yuen & Needham (1976) found no single model to be best for all cases, but many results from fertilization trials were well described by two intersecting straight lines. Data presented in this thesis (Paper IV) were found to be best described by second and third degree polynomials, square root polynomials or the Mitscherlich exponential equation.

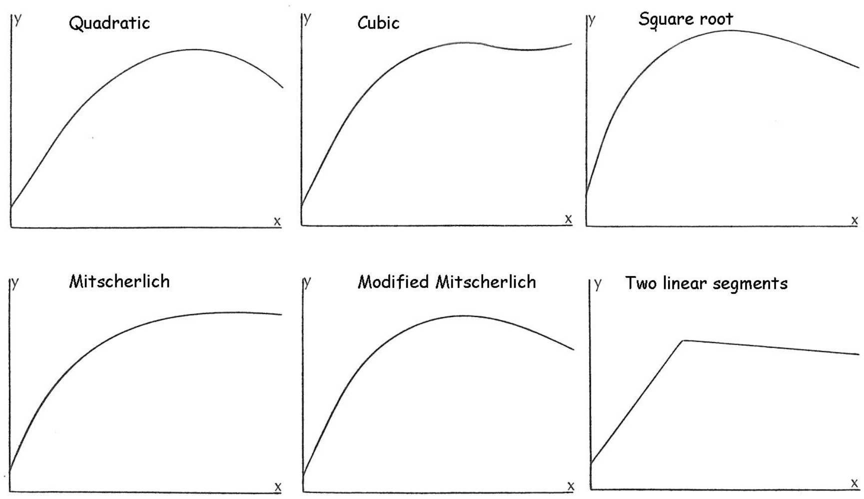

Figure 5. Different functions describing yield response to fertilizer N (reproduced from Wood, 1980).

Principles of net nitrogen mineralization

Fertilizer demand is dependent on the amounts of mineral N supplied to the crop from the soil. The more N the soil supplies to the crop, the less fertilizer N is needed to reach a certain yield level. As an example, economical rates of fertilizer N were calculated on the basis of 39 experiments in Sweden with spring barley, to be reduced or increased by 0.7 kg ha^{-1} as soil mineral N in spring within 0-90 cm depth increased or decreased by 1 kg ha^{-1} (Mattsson, 1990). In addition to mineral N present in the soil at the time of fertilization in spring, N mineralized during the following growing season also contributes to the N supply of the crop. Net N mineralization is usually defined as N mineralization minus N immobilization (Jansson & Persson, 1982). N mineralization refers to the transformation of organic N to mineral N (Figure 6). The process is performed by soil microorganisms that utilize nitrogenous organic substances as an energy source. N immobilization is defined as the transformation of inorganic compounds into the organic state (Jansson & Persson, 1982). Soil organisms assimilate inorganic N compounds and transform them into organic N constituents of their biomass. However, there are other processes that also affect the size of the soil contribution of N to the plant. The inorganic N pool is increased through N fixation and atmospheric deposition and decreased through denitrification, ammonium fixation, leaching and ammonia volatilization (Figure 6). In this thesis, all these processes are included in the definition of net N mineralization. This reduces the chances of finding relationships with soil parameters, but makes N mineralization easier to measure and to relate to crop parameters. In this thesis, net N mineralization (Nm) is defined as soil N taken up by plants (Np) plus residual soil mineral N at harvest minus soil mineral N in spring.

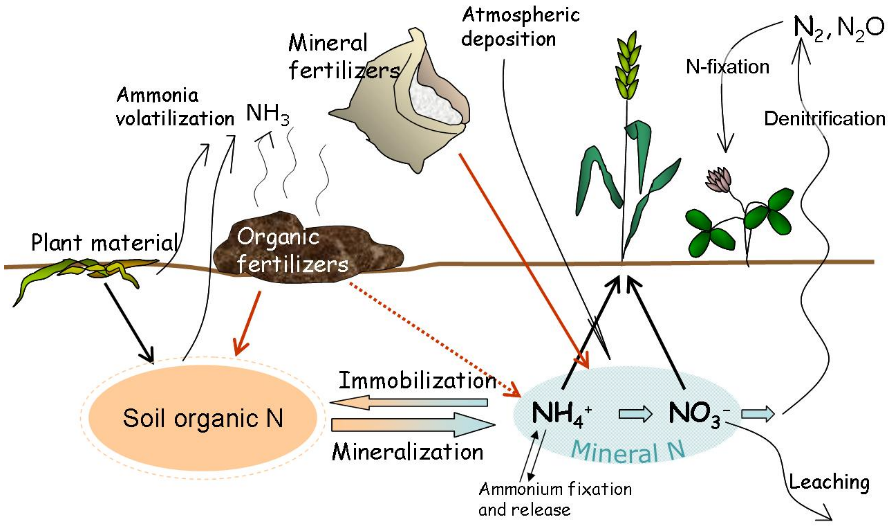

Figure 6. The N-cycle in the soil-plant-atmosphere system, showing the forms and flows of N most important for the N supply to agricultural crops (pictures: Johanna Wetterlind).

Principles of plant water supply

Soil moisture holding capacity accounts for a large proportion of the yield variability between soil types (Moore & Tyndale-Biscoe, 1999). When yield response to increasing amounts of N ceases, some other factor becomes yield-limiting. This factor is frequently water. Unless irrigation is used, potential yield is reached and there is no point in adding more N. The potential water supply from soil to crops is determined by soil texture (pore distribution), rooting depth and groundwater level. Soil texture affects plant available water by its influence on the water holding capacity of the soil. The higher the clay content, the larger the water holding capacity. However, a large fraction of soil water is held beyond the wilting point and the differences in plant available water defined as water held between soil moisture tensions corresponding to 1-150 metre water column (mwc) therefore do not differ considerably between sand and clay (Figure 7). However, rooting is much deeper in clayey soils (Madsen, 1979) and they therefore provide better water supply than coarser soils in dry weather conditions. Changes in soil moisture during the season are due to precipitation, evapotranspiration and drainage. Drainage through clay soils is generally much slower than from sand, due to a lower unsaturated hydraulic conductivity (Hillel, 1982), unless there are cracks in the clay soil that allow rapid flow. This means that clayey soils can hold water above field capacity significantly longer than sandy soils.

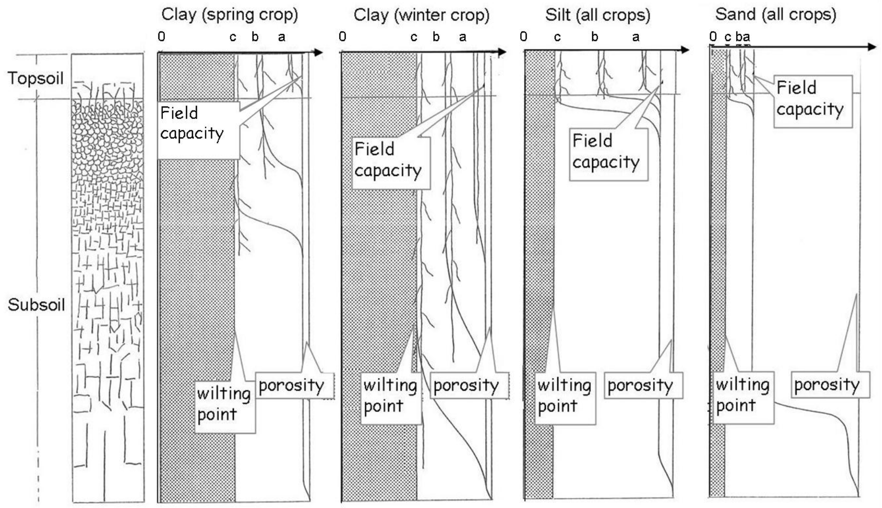

Figure 7. Schematic description of root development and water content at (a) the beginning, (b) the middle and (c) the end of the growing period on soils with different texture (reproduced from Wiklert, 1961).

Measurements of nitrogen supply and crop demand

The experiments presented in this thesis involve determination of optimum N fertilization rates, net N mineralization and plant available water. There are a number of methods available for the determination of each of these variables. Some of them are presented and discussed below. They are mainly methods for research purposes, allowing processes to be studied as they proceed. In practical agriculture, however, it is desirable to estimate the same variables in advance, which, as mentioned earlier, can be a difficult but important task.

Estimation of optimum nitrogen fertilization

Yield response curves for fertilizer N can be created from experiments with increasing amounts of fertilizer N (Wood, 1980). To create yield response curves, fertilization trials with several application rates and replicates are required. On this basis, economically optimum N fertilization can be calculated by identifying where the slope of the curve equals the ratio between fertilizer and grain prices (Figure 8). Fertilization above the optimum implies larger expenses for the extra fertilizer than the income it generates. Similarly, fertilization below the optimum also leads to missed returns from the yield increase that somewhat more fertilizer would have generated. Each plot in an experiment needs a net space of at least 10 m in length if harvested with a plot combine according to current recommendations for field experiments in Sweden (Bergström, 1990), thus corresponding to about 25 m^2. This leads to large areas for trials with several treatments and replicates, which means that measuring within-field variations in optimum N fertilization with this method has severe limitations. There may be equally large variations within and between the experimental areas, and consequently much of the variation found between sites will be considered statistically insignificant, since variations within the areas will be regarded as experimental errors.

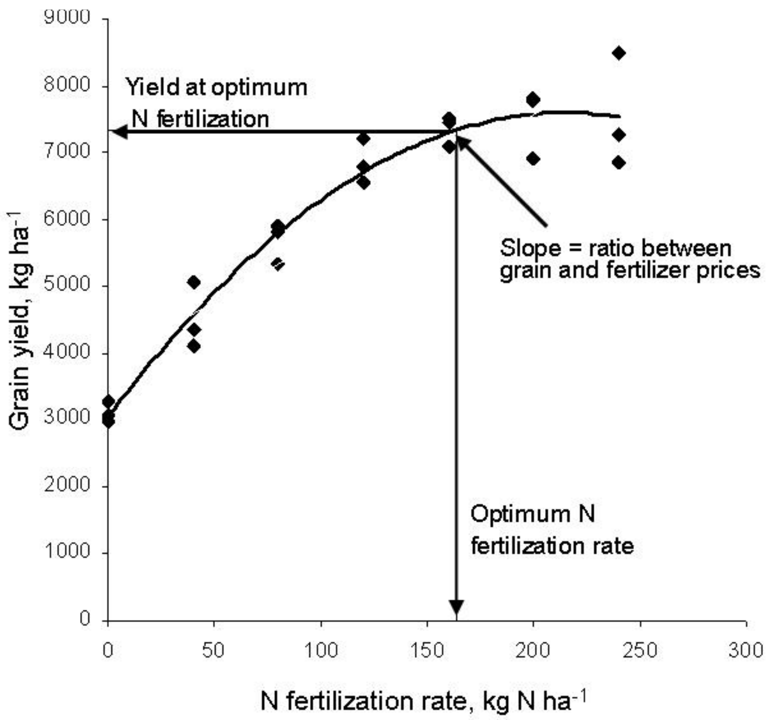

Figure 8. A yield response curve fitted to experimental data on yield at different fertilization rates, where optimum N fertilization rate and corresponding yield can be estimated from the point where the slope of the curve equals the ratio between grain and fertilizer prices.

Estimation of net nitrogen mineralization

Net N mineralization (Nm) can be studied by determining mineral N accumulation in a soil incubated in controlled climatic chambers (Waring & Bremner, 1964; Stanford & Smith, 1972). This may give information about the potential mineralization of a soil, which may be of interest when comparing, for instance, the fertility of different soils. With the goal of developing rapid methods for the estimation of Nm under field conditions, not only incubation methods but also a large number of N availability indices based on chemical extraction methods have been developed (*e.g.* Fox & Piekielek, 1978; Köhler, 1983). However, for measuring the quantity of N mineralized in a soil during a certain period under field conditions, laboratory measurements are unreliable (Köhler, 1983), since mineralization is largely affected by conditions in the field, which cannot be replicated in the laboratory. Moreover, soil preparation before incubation or chemical extraction affects release conditions. One way to study N mineralization is to measure the change in soil mineral N in the rooting zone in uncropped plots covered with a 'roof' that prevents precipitation infiltrating through the soil and thus inhibits N leaching (Scharpf, 1977). A disadvantage with this method is that the absence of precipitation and infiltration of water through the soil profile and the absence of a living root rhizosphere probably influences mineralization processes in the soil. An alternative, described by Köhler (1983) and used in this thesis (Paper II), is to estimate Nm from plant uptake of N in combination with soil-core sampling for determination of soil mineral N in the rooting zone. Plant uptake of soil N can be estimated by sampling plants in plots without N application and analysing them for the N content. Nm during the growing season of a certain crop can be calculated as plant uptake of soil N plus residual mineral N in soil at the end of N uptake of the crop, minus soil mineral N in spring. This method considers N mineralization not only in the topsoil but also in the subsoil as deep as the roots penetrate. It is assumed that Nm in unfertilized plots is equal to Nm in fertilized plots. This may not be quite correct, since priming effects from fertilizer N on mineralization have been observed (Jansson & Persson, 1982). Another disadvantage with this method is that root N must be estimated, as root sampling is laborious and uncertain. A further disadvantage is that Nm is also affected by processes other than mineralization and immobilization, *i.e.* leaching, denitrification, ammonium fixation and release, atmospheric deposition and ammonia volatilization (Figure 6). These processes must either be included in the definition of Nm, or estimated separately. In this thesis, the processes mentioned were included in the definition, since the objective was to investigate how N supply in the soil was affected by different factors and not how the single processes were influenced. This method estimates the actual N supply to plants, but does not give information in advance. The latter is desirable when used for fertilization models. Köhler (1983) tried without success to relate different incubation and chemical extraction methods in the laboratory to Nm measured in the field. Nevertheless, as mentioned earlier, Stenberg, Jonsson & Börjesson (2002) found that NIR can be a reasonable predictor of Nm within a field with large variation in SOM and Nm. The method may be less successful in fields where variation in Nm is dependent on other environmental factors.

Estimation of plant available water

Plant available water (PAW) can be measured in the field or estimated with models. These usually rely on precipitation, evapotranspiration and soil water holding capacity. Maximum amount of PAW is dependent on soil water tension and rooting depth of the crop, which both are largely associated with texture. Several attempts have been made to interpret clay content and soil organic matter content into water holding capacity or PAW (Andersson & Wiklert, 1972; Kritz, 1983; Riley, 1996; Berglund, Berglund & Gustafson Bjureus, 2002). Formulae given in such publications were used in Paper V to calculate maximum plant available water supply at different sites. There are direct and indirect methods of measuring actual soil moisture content in the field and several ways of expressing the result quantitatively. The gravimetric method of measuring mass wetness consists of removing a sample by augering into the soil and then determining its moist and dry weights. This method is simple but destructive and time-consuming. Other methods estimate soil moisture by a calibrated relationship with some other measurable variable. These methods can be divided into volumetric methods measuring volumetric soil moisture and tensiometric methods, which give soil suction or water potential. Both quantities are related through the soil-water characteristic curve specific to each soil (Hillel, 1982). Volumetric soil moisture content can be measured with an impedance measuring technique using an instrument that responds to changes in the apparent dielectric constant (Gaskin & Miller, 1996). Such an instrument, the ThetaProbe (Delta-T devices Ltd., Figure 9), was used in the experiments presented in this thesis for reasons of its low cost and rapid measurements. This and other dielectric techniques, such as Time Domain Reflectometry (TDR), estimate soil water content by measuring the dielectric constant, which determines the velocity of an electromagnetic wave or pulse through the soil. In soil, the value of the permittivity is made up of the relative contribution of each soil component. Since the dielectric constant of liquid water is much larger than that of the other soil constituents, the total permittivity of the soil is mainly governed by the presence of liquid water (Muñoz-Carpena, 2004).

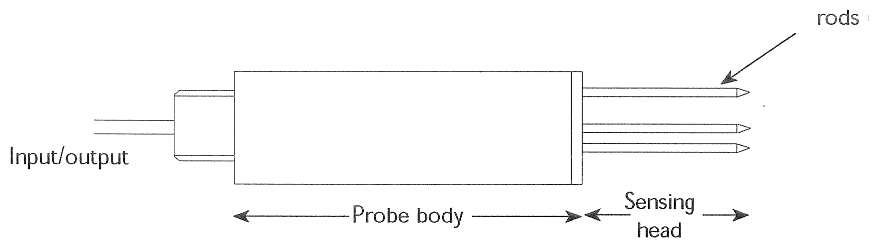

Figure 9. The ThetaProbe (Delta-T devices Ltd.), a soil moisture sensor measuring volumetric soil moisture content using a standing wave measurement technique.

Materials and methods

Experimental site

Field experiments were conducted in 1998-2000 at Ribbingsberg (58°06'N, 12°51'E) in south-west Sweden on a 15-ha field (Figure 10) with large differences in soil texture and considerable spatial variations in grain yield in some years. The crop sequence from 1996 to 2000 was winter wheat-oats-winter wheat-spring barley-winter wheat. The climate in the region is cold-temperate and the weather at the experimental site during the investigation period was comparatively wet.

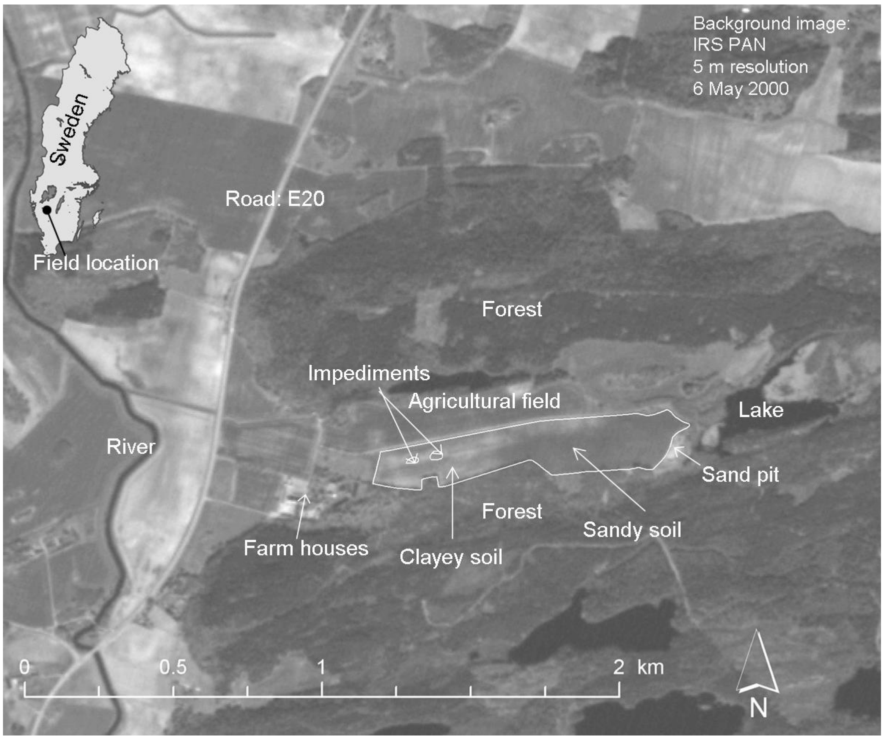

Figure 10. Location of the experimental field on a satellite image taken on 6 May 2000.

The field could be divided into two areas with respect to soil texture (Figures 10 and 11). One is dominated by sandy loams in both topsoil and subsoil (hereafter referred to as sandy soil) and the other by loams in the topsoil and silty clays in the subsoil (hereafter referred to as clayey soil). The clay content varies between 7% and 27% in the topsoil, with a mean of 10% within the sandy area and 23% within the clayey area. The SOM content in the topsoil varies between 2.5% and 4.6%, with a mean of 3.5%. The difference in elevation is 15 m from the highest to the lowest point (Figure 11).

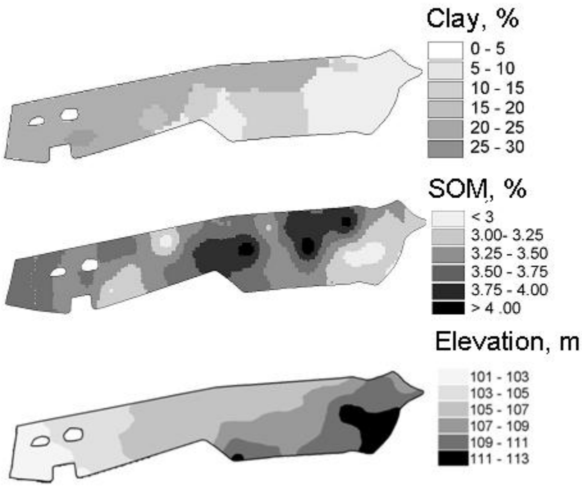

Figure 11. Maps of clay content, soil organic matter content (SOM) and elevation.

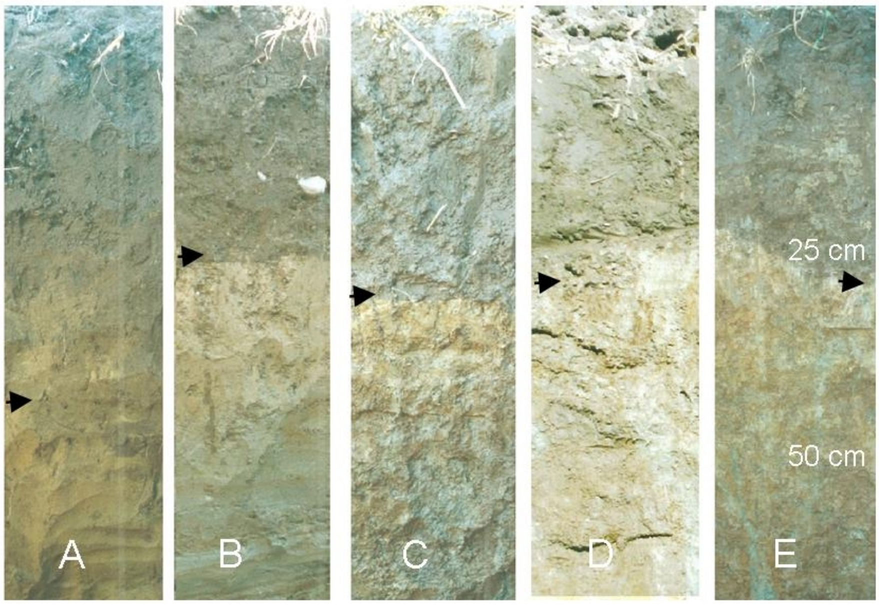

Figure 12. Photographs of soil profiles down to 75 cm depth from five sites (the intensive sites for measurements, see Figure 18) where A and B are sandy soils and C, D and E are clayey soils. The photograph of site D was taken on a different date and therefore has a different colour from that of C and E. The arrows indicate depth of the topsoil.

The sandy soil (A and B) has a weakly developed but distinct B-horizon (upper subsoil) with red colouring (Figure 12). The weak development is natural considering that the soil constitutes a postglacial formation and is thus young, and the coarse material is therefore slowly weathered. The rusty patches interspersed with colourless parts in the clayey soil profiles indicate that they have been affected by high groundwater levels. The topsoil is rather deep at site A and the soil organic matter content is above 1.9% down to 45 cm depth. This is probably due to erosion of topsoil from parts of the field that are positioned uphill from this site. At site B, there were quite a lot of stones and gravel, which may have contributed to lower water holding capacity and more shallow roots than at site A. Sites C, D and E appeared rather similar, although C had a higher groundwater level than the other two sites.

The water holding capacity is larger in the clayey soil, but much of the water is strongly bound and not plant available. The difference in water content between soil water tensions corresponding to a 1 metre water column (mwc) and wilting point (150 mwc) is often considered the plant available fraction. This amount is larger in the sandy soil (Figure 13). However, considering the larger root depth (Figure 13) and shallower groundwater level on the clayey area of this field, the maximum plant available water supply is still greater in the clayey soil.

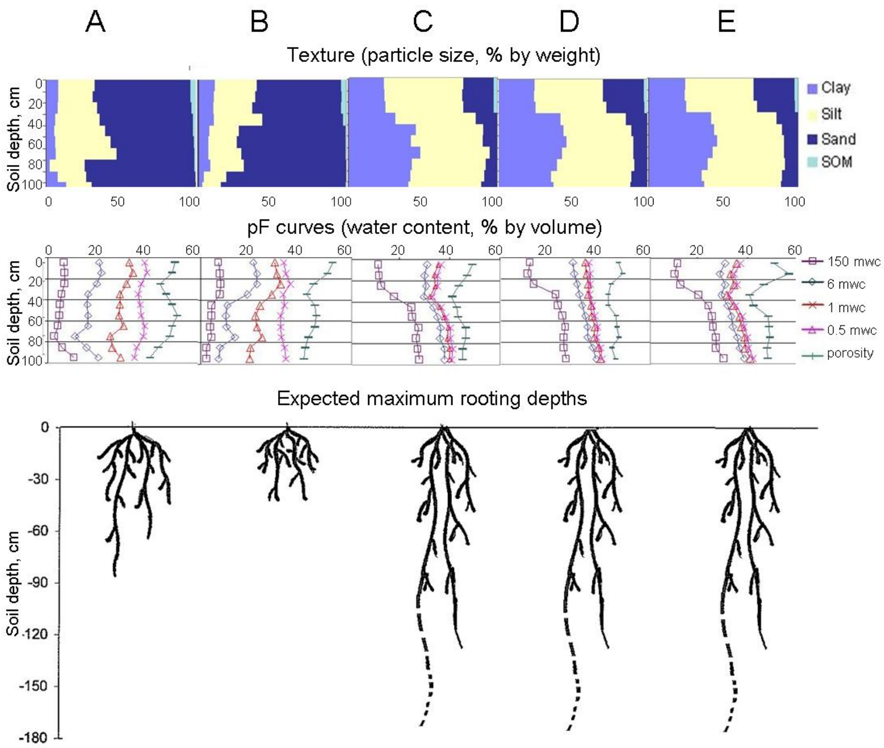

Figure 13. Soil texture, water holding characteristics and expected maximum rooting depths at five sites (the intensive sites for measurements, see Figure 18) where A and B are sandy soils and C, D and E are clayey soils.

The major difference in plant nutrient (P, K and Mg) status within the field was between the clayey and the sandy areas. The concentrations of plant available phosphorous determined as P-AL according to Egnér, Riehm & Domingo (1960) in the topsoil were higher in the sandy soil (Figure 14). This could be due to higher amounts of SOM in the sandy soil and thereby a higher P mineralization. It could also be due to higher yields on the clayey area in the past (*cf.* Shiel, Mohamed & Evans, 1997), meaning that larger amounts of phosphorus may have been removed, but similar amounts to on the sandy area have probably been added with fertilizers. In the upper subsoil, P-AL values are very low on the clayey area. The crop roots have probably penetrated this layer densely and taken up large amounts of phosphorus. This has not been compensated for by fertilizer, since P is not very mobile and would to a large extent have largely stayed in the topsoil. These soil profile phenomena have also been observed in other fields in the area (Fredriksson & Haak, 1995). Deeper down in the subsoil, P-AL values are higher on the clayey area. Here the subsoil seems to be less affected by plant uptake and fertilization. The difference between the clayey and the sandy area in P-AL in the deep subsoil could be due to differences in parent material, weathering rate or leaching.

A similar pattern can be found for K-AL as for P-AL (Figure 14), although it is not as evident. This could be explained by the larger mobility of K than P. Fertilizer K has probably moved from the topsoil to the subsoil to a larger extent, which to some degree may have prevented accumulation in the topsoil of the sandy area and depletion of the upper subsoil of the clayey area. Differences in specific surface area influence weathering rate and therefore differences in K status between the clay soil and the sandy soil may be explained by different degrees of weathering.

Mg-AL values seem to be strongly associated with clay content, and are subsequently much higher on the clayey area, especially in the subsoil where the clay content is large (Figure 14). Mg is a common constituent of clay minerals and therefore the occurrence of Mg-AL, like that of K-AL, is likely to be related to clay due to its weathering rate.

Soil pH does not differ much in the topsoil (Figure 14). However, the topsoil and the upper subsoil are somewhat more acid in the clayey area. In the deeper subsoil, pH levels are higher in the clayey soil than at the same depths in the sandy soil. Nutrient uptake with removal of crops and leaching may have led to acidification historically. A larger nutrient uptake on the clayey area may thereby have contributed to the smaller and opposing differences in pH between the clayey and sandy area in the topsoil, which originally may have had similar differences as in the subsoil. This could also be a result of liming. Due to higher cation exchange capacity in the clayey area of the field, more lime is required to raise the pH there. Therefore, if equal amounts of lime have been applied to the clayey and sandy areas, this may have led to a larger pH increase on the sandy area.

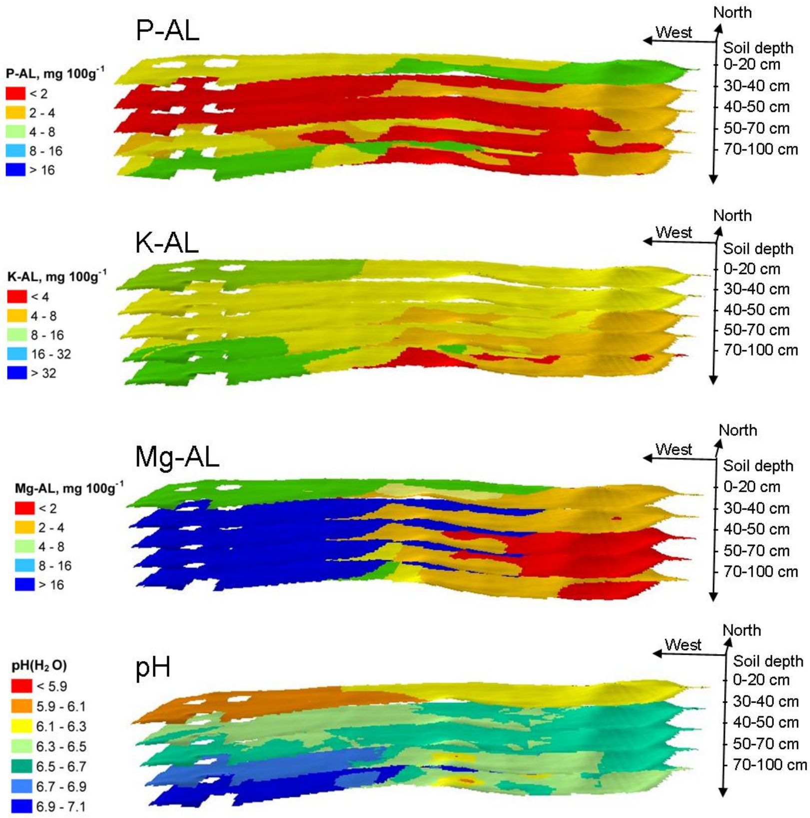

Figure 14. Three-dimensional soil maps of the experimental field showing interpolated values of P-, K- and Mg-status and pH(H_2O) from 39 sample points (Figure 18) at five soil depths.

The weather during the investigation period was rather wet. In 1998, May was quite dry followed by a summer (June-August) that was cooler and wetter than normal (Figure 15). In 1999, May was cool and wet, June wet and July warm. In 2000, May was rather warm followed by cloudy and cool weather in June and July (Figure 15).

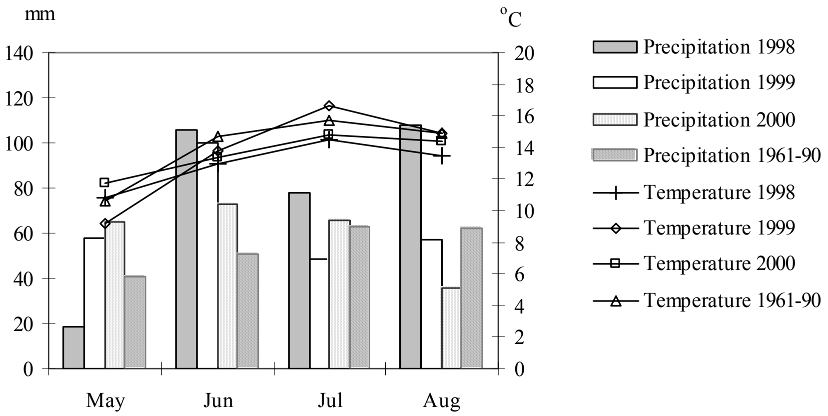

Figure 15. Monthly precipitation and mean air temperature during May-August in 1998-2000 at the experimental field and 30-year average from Lanna Experimental Station

Since all years during the investigation period (1998-2000) were rather wet, yield data from the drier year of 1996 were used to represent the yield situation in a dry year. Since no weather data were collected at the experimental field in this year, weather data from Lanna Experimental Station, positioned 40 km north of Ribbingsberg, were used (Figure 16). The temperature was slightly higher and the precipitation somewhat lower at Lanna in most months during the investigation period (Figure 17).

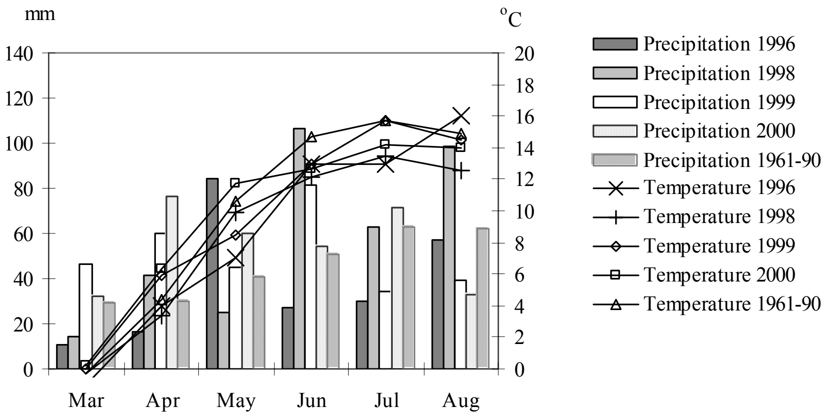

Figure 16. Monthly precipitation and mean air temperature during March-August in 1996 and 1998-2000 at Lanna Experimental Station.

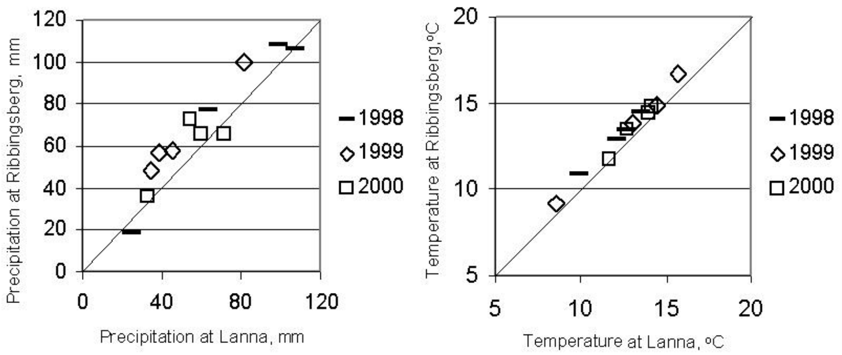

Figure 17. Agreement between Lanna experimental station and Ribbingsberg in monthly precipitation and mean air temperature during May-August in 1998-2000.

Field experiments

Investigations were performed both at five sites (A-E), hereafter referred to as intensive sites, representing different soil types and yield levels, and at 34 other sites, hereafter referred to as extensive sites. The extensive sites were systematically distributed within the field (Figure 18). In addition, some measurements, such as elevation and soil electrical conductivity, were performed at densely throughout the field. Weather data during the growing season were collected at one location in the field.

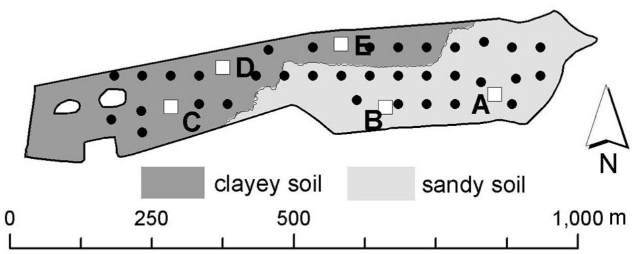

Figure 18. The experimental field divided into one clayey area and one sandy area and with different experimental sites: five 'intensive sites' (A-E) and 34 'extensive sites' for measurements (●).

At the five intensive sites (A-E), annual field trials were conducted using seven treatments with increasing amounts of fertilizer N (Paper IV). The results from these were used to create response curves for the relationship between N application and crop yield and to calculate the economically optimum N fertilization rates. To determine the cause of differences in N fertilization demand within the field, a number of possible growth limiting factors (*e.g.* soil moisture content and disease incidence) as well as crop growth and N uptake during the growing season were recorded at these sites.

At each of the 34 extensive sites within the field, areas of 60 m^2 were annually left without fertilizer N application (so-called zero plots). In these plots, plant samples were taken in order to estimate the amounts of soil N available to plants in each season (Papers II & III). The plots were moved slightly from year to year to an undisturbed position, but were still considered to represent the same sites. Fertilized areas of 10 m^2 adjacent to the 34 unfertilized plots were harvested with a plot combine to determine grain yield level at each site (Paper III). The fertilization rates were 160 kg N ha^{-1} in 1998 (winter wheat), 100 kg N ha^{-1} in 1999 (spring barley) and 170 kg N ha^{-1} in 2000 (winter wheat). The fertilizer-N was applied mainly as NO_3-N. Soil P, K and pH status can be considered adequate, *i.e.* no need for liming or fertilization above annual crop demand according to Swedish standards, but Mg-values were somewhat low on the sandy soil according to soil analyzes from 1997 (Figure 14). The annual applications of P and K were approximately 20 and 50 kg ha^{-1}, respectively.

Measurements

In order to explain variations in, and relationships between, yield, protein content and net N mineralization, as well as yield and protein response to fertilizer N, a number of variables were measured within the field during the investigation period.

Weather data

During the growing seasons in 1998-2000 (approximately April-September), precipitation, global radiation, wind speed, relative humidity and air temperature were recorded hourly at the experimental field (Paper V). For other periods, weather data from Lanna Experimental Station were used. Some weather data are presented in Figures 14-16.

Soil texture and nutrients

At each site, composite soil samples consisting of 15 cores were taken from the plough layer (0-20 cm) and 10 cores from different layers in the subsoil to determine soil texture and nutrient content. This is described more in detail in Paper I.

Water holding capacity

Undisturbed soil cores were taken from the topsoil (5-15 cm) at all sites, and from every 10-cm layer down to 100 cm depth at each intensive site, to determine volumetric soil moisture contents at different tensions. This is further described in Paper V.

Elevation

The surface elevation of the field was measured using GPS (Global Positioning System), with a local base station standing on a fixed point and kinematic measurements using a quad motorcycle. This is further described in Papers II and V.

Soil electrical conductivity

Soil electrical conductivity (SEC) was measured using an EM 38 (Geonics Ltd), placed on a sled pulled by a quad motorcycle at 20 m intervals over the field (Figure 19). This is further described in Papers I and V.

Figure 19. The EM 38 equipment with GPS antenna used for measuring soil electrical conductivity (picture: Mats Söderström).

Soil moisture measurements

In the plots with standard fertilization at the intensive sites, volumetric soil moisture contents were measured weekly at different depths (Figure 20) during the growing season using a ThetaProbe (Delta-T Devices Ltd., Figure 9) (Papers IV and V). The groundwater level was measured repeatedly at each site using perforated tubes inserted vertically to one metre depth.

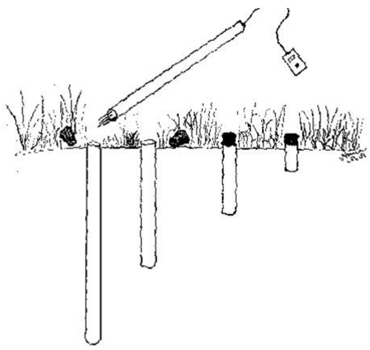

Figure 20. Volumetric soil moisture contents were measured using a ThetaProbe, which was inserted down to different soil depths through 50 mm wide PVC pipes (picture: Anna Nyberg).

Soil mineral nitrogen

At all sites and in all years, soil samples were taken in early spring before the start of the growing season and just after harvest within the unfertilized areas for determination of mineral N (NH_4-N and NO_3-N) (Paper II). For this, 18 cores from the 0-30 cm soil level and 9 cores from 30-60 cm and 60-90 cm depths were mixed to composite samples for each area and depth. The same procedure was followed in plots at the intensive sites, which received standard fertilization rates (Paper IV).

Plant density

The number of spring barley plants per m^2 at tillering (GS 21, growth stage according to Zadoks, Chang & Konzak, 1974), and winter wheat tillers per m^2 at stem elongation (GS 31) and ears per m^2 at milk development (GS 71) were counted in two 1-m long crop row sections within each plot. The row spacing was used for converting the number per row metre into number per m^2.

Root density

Relative root density for each intensive site at the depths 30-60 and 60-90 cm was estimated in 1998 and 1999 through desiccation and ocular examination of the soil samples taken for determining mineral N after harvest. A more thorough examination was performed after harvest in 2000 by digging a 1 m deep pit at each of the five intensive sites and counting the number of roots passing cross-sections of 1 cm x 100 cm at every 10-cm depth.

Weeds and diseases

The frequency of weeds and fungal diseases was observed and graded (percentage of straws infected by eyespot and percentage leaf area covered by leaf blotch) within each plot with standard N application at the intensive sites in 1998-2000 (Paper IV).

Crop growth and nitrogen accumulation in plants

For the determination of crop dry matter production and accumulation of N in above-ground parts of the crop during the growing season, plant samples were taken repeatedly (with 3-6 week intervals) from each plot with standard N fertilization at the intensive sites (Paper IV).

Plant available soil nitrogen

Plant available soil N (Np) was estimated every year at both the intensive and extensive sites. For this, plant samples were taken at ripeness (GS 87-92) from plots without N fertilization and analyzed for total N (Papers II, III and IV).

Yield data

Yield was recorded with a New Holland combine equipped with yield monitor (RDS Ceres) and GPS equipment in 1996, 1999 and 2000. In addition, areas of 10 m^2 were harvested separately with a plot combine at each of the 34 extensive sites in 1998-2000 (Papers III and V).

Grain quality

Grain samples were analyzed for N, dry matter content and thousand grain weights. From N concentrations, crude protein content (CP) was calculated by the conversion factors 6.25 for spring barley (fodder) and 5.7 for winter wheat (bread) (Sosulski & Imafidon, 1990) (Papers III and IV).

Data evaluation

Response curves

The results of yield, CP, plant density and thousand grain weight were used to evaluate the response to N dressing. A cubic polynomial curve was fitted to the yield data to express yield response and to estimate the economically optimum N fertilization rates and their corresponding yields, by identifying the points where the slope of the function equalled the price ratio of grain to fertilizer (Paper IV).

Net nitrogen mineralization

The amounts of soil N available to plants were calculated on the basis of the crop samplings at ripeness with determination of straw and grain biomass and their N contents (Papers II, III and IV). It was assumed that the roots contained 25% of the total amount of N in the crop (Hansson, Pettersson & Paustian, 1987). Net N mineralization was calculated using equation 1 (Paper II):

$$Nm = Np + Na - Ns \qquad \text{(equation 1)}$$

where Nm is net N mineralization, Np is total N in crop at ripeness, Na is residual mineral N in soil at harvest and Ns is mineral N in soil (0-90 cm) in early spring.

Regression

The relationships between net N mineralization and the soil characteristics SOM content, clay content and elevation were calculated by multiple linear regressions (Paper II). Other linear relationships, *e.g.* between net N mineralization, grain yield and grain CP (Paper III) as well as between years (Papers II and III), were simply shown in correlation matrices.

Interpolation

The dense elevation data, SEC data and yield data from 1996 were interpolated using ordinary kriging (Burrough & McDonnell, 1998) to obtain coincident data for the extensive areas (Papers I, II, III and V). Ordinary kriging and inverse distance weighting were used to produce maps for visualisation of variables measured only at the intensive and extensive sites (Papers II, III and V). These interpolated values were not used for any statistical analysis. In Paper I, the performance of different methods for making soil maps from data collected at the intensive and extensive sites was assessed. Interpolated values of clay content, soil organic matter content, pH(H_2O), K-HCl, P-AL, K-AL and Mg-AL were compared with measured values for each interpolation method. Soil electrical conductivity (SEC) data with a distinct border between two different regions were used for dividing the field into two zones. Interpolations were performed both with and without taking this border into account. Interpolations were performed in the geostatistical software GS^+ 5.1a (Robertson, 2000) and the GIS software ArcMap (ESRI). The maps were produced in ArcMap (ESRI).

Soil water balances

Precipitation and potential evapotranspiration in combination with estimated maximum amounts of plant available water at each site were used to calculate daily water balances using an USDA model (Erpenbeck, 1982) adapted to Swedish conditions (Paper V). Potential evapotranspiration was calculated using Penman-Monteith's equation in the software Pgraph (Jansson & Claréus, 1996). Maximum plant available water at each site was estimated from the amount of water held at different tensions and crop rooting data. Rooting depths and effectiveness of water uptake by plants were estimated from clay content and crop at different sites according to Berglund, Berglund & Gustafson Bjuréus (2002). The water balances were then used to estimate number of days with water deficit.

Results and discussion

Within-field variations

Plant available soil nitrogen

The variations in plant available soil N and net N mineralization (Nm) were large both within the field and between years (Figure 21). Nm ranged between 40 and 163 kg N ha^{-1} in 1998, 13 and 81 kg N ha^{-1} in 1999 and 44 and 139 kg N ha^{-1} in 2000 (Paper II). The amounts of soil mineral N in the 0-90 cm layer in spring were small compared to Nm and Np.

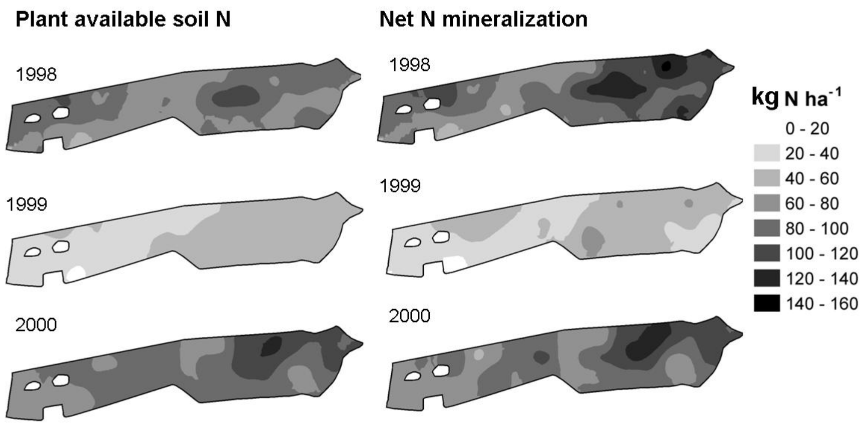

Figure 21. Maps of plant available soil N (Np = plant uptake of soil N) and net N mineralization (Nm = Np – soil N in early spring + soil N at harvest) in different years.

Grain yield and protein content

During the study period 1998-2000, there were within-field variations in grain yield (SD = 800 kg ha^{-1}), but not as large as those in the drier year 1996 (SD =

1400 kg ha^{-1}). Both yield and CP pattern varied between years (Figure 22). The variations in CP within the field were largest in 1999 and 2000 (Figure 22).

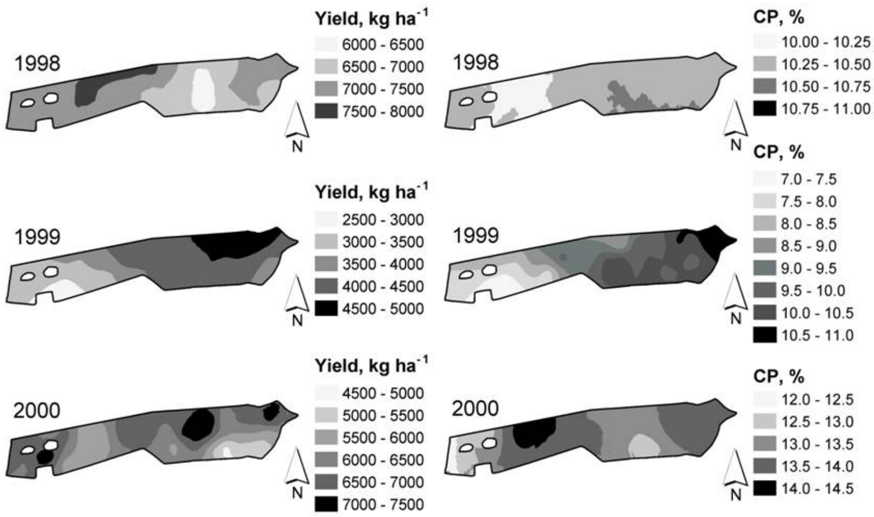

Figure 22. Maps of grain yield (15% water content) and grain protein content (CP, % of DM) in different years.

Soil moisture content

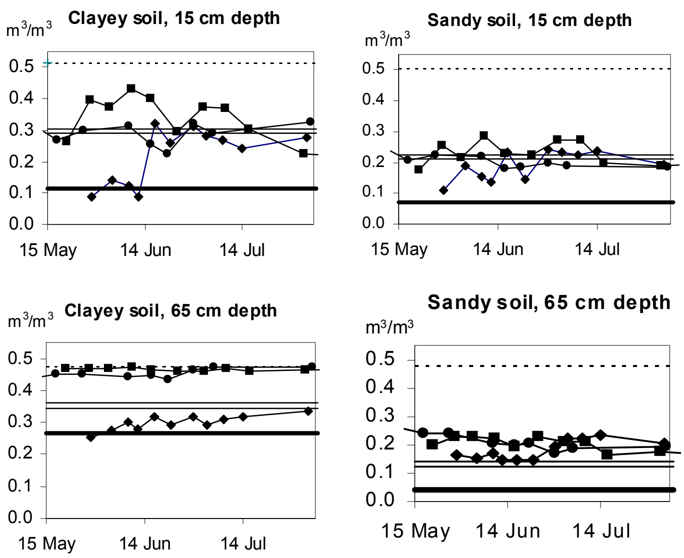

Figure 23. Mean volumetric soil moisture contents (m^3/m^3) at sites on clayey soil (sites C, D and E) and sandy soil (sites A and B) at 15 and 65 cm depths in 1998 (♦), 1999 (■) and 2000 (●), porosity (---) and soil moisture content at 150 (▬) and 6 mwc (═).

Soil moisture contents were measured only at the five intensive sites. Since the main differences were between the clayey and the sandy area, the means in each area are presented here (Figure 23). Soil water content was sufficient at all sites most of the time (Figure 21) (Papers IV and V). However, in the beginning of the growing season in 1998, soil moisture contents were close to wilting point (150 mwc) in both the topsoil (15 cm) and subsoil (65 cm) in the clayey area, and below 6 mwc in the sandy area (Figure 23). The winter and spring of 1999 had rather heavy precipitation (200 mm in January-April compared to the 30-year average of 120 mm). Soil moisture contents were very close to full saturation in the subsoil of the clayey soil during the growing season in 1999 and to some extent also in 2000 (Figure 23). This indicates possible oxygen deficiency for plants and aerobic microorganisms.

Impact of clay and soil organic matter content

Impact of clay and soil organic matter content on soil nitrogen supply

With multiple linear regression, the within-field variability in net N mineralization (Nm) could only partly be explained by differences in soil organic matter (SOM) and clay content in the topsoil ($r^2adj = 0.23$***). This was despite the fact that within-field variations in Nm were considerable (Paper II). A stronger relationship between SOM and Nm could be expected, since SOM constitutes the raw material for N mineralization. The moderate variation in SOM may be one reason for the weak relationship obtained. In two studies on nearby fields with larger variation in SOM, the correlation with SOM was better ($r^2 = 0.69$ and $r^2 = 0.83$, respectively) (Börjesson *et al*., 1999; Stenberg, Jonsson & Börjesson, 2002). Another possible explanation for the poor but significant correlation between SOM and Nm in this investigation could be that the properties of the SOM vary within the field, but then more similar patterns of Nm should have been found between the three years. However, N immobilization (Jansson & Persson, 1982) may have varied due to within-field variations in the amounts of crop residues altering the pattern of Nm between years. Areas with unfavourable conditions for mineralization in one year may also have had more organic N available for mineralization in the next year. This statement is supported by the fact that the average Nm for the three years correlated better with SOM and clay content ($r^2adj = 0.34$***) than did annual Nm. In all three years the effect of clay on Nm was negative. This may be partly due to unavailable organic matter trapped in soil aggregates and/or poor oxygen supply to microorganisms due to rainy weather in all three growing seasons. Denitrification may also have contributed to this result.

Impact of clay and soil organic matter content on yield and protein

The influence of clay and SOM on yield and CP varied between years. In 1998, yield correlated positively with clay content (Paper III), which may be explained by the smaller incidence of fungal diseases and the better nutrient status in the clayey area of the field (Paper IV). In 1999, clay content had a negative influence on both yield and CP (Paper III). This was probably due to the limited amounts of plant available soil N (Np) on the clayey area in that year (Paper III), possibly as a result of N losses through denitrification caused by wet conditions observed on the clayey soil in 1999. Water saturation may also have caused oxygen deficit and limited growth of the crop, but yield response curves from 1999 (Figure 24) suggest it was mainly a question of N deficit, since yield was larger when more N fertilizer was added. A strong positive relationship was observed between yield and Np, which suggests that N was limiting yield (Paper III). The higher levels of CP in the eastern, sandy and drier area of the field in 1998 and 1999 were probably due to large Np (Paper II) in combination with limited potential for further yield increases (Paper IV). Higher CP in more coarse textured areas of a field has also been observed by Stewart, McBratney, & Skerritt (2002). In 2000, yield was positively correlated to SOM, but CP was uncorrelated to either clay or SOM (Paper III). The higher yield in areas with larger SOM content in 2000 did not seem to be due to more plant available soil N, since yield and Np were uncorrelated. Fertilizer N favoured yield rather than CP in these areas (Paper IV). This may be explained by a later or slower crop development in areas rich in SOM, as the soil appeared moister and was therefore probably also cooler. Low temperature prolongs the grain filling period and thus increases yield (Spiertz, 1974). In 2000, the field N fertilization rate (170 kg N ha^{-1}) was larger than the optimum N fertilization rate at the intensive sites (Paper IV). Therefore N probably did not limit either yield or CP in 2000. There was no correlation with Np and CP levels were high (Paper III).

Impact of clay and soil organic matter content on soil moisture

The higher the clay and SOM content, the higher the water holding capacity of the soil (Kritz, 1983), which was also evident in this field (Paper V). The differences in soil moisture contents between the clayey and the sandy area were larger than just the difference in water holding capacity. This could be due to differences in hydraulic conductivity and elevation.

Crop response to fertilizer nitrogen

As illustrated in Figure 24, crop response to fertilizer N did not differ greatly between sites, but more between years, especially regarding grain crude protein content (CP) (Paper IV). All three years (1998-2000) were rather moist, and differences between sites due to different risks for drought obviously did not appear. Differences between sites could instead be related to disease incidence in 1998 and Np in 1999 (Paper IV). Disease incidence was significantly more frequent at site B in 1998 and Np was significantly lower on the clayey soil (site C, D and E) in 1999. In accordance with other investigations (Darwinkel, 1983; Gooding & Davies, 1997) the positive yield response to N was due to the N effect on ear density and number of grains per ear in all three years (Figure 24). The reduction of tillers and grain site formation takes place during early stem formation, and the N supply at this stage therefore affects both the number of ears and number of grains per ear (Gooding & Davies, 1997). The number of grains can be reduced at a later stage, up to anthesis, and may therefore be affected by a later N application. In this case the N applied at early stem formation (GS 31) (Figure 25) seems to have been adequate also for later stages, since the number of grains per ear was not significantly increased by the fertilization at flag leaf emergence

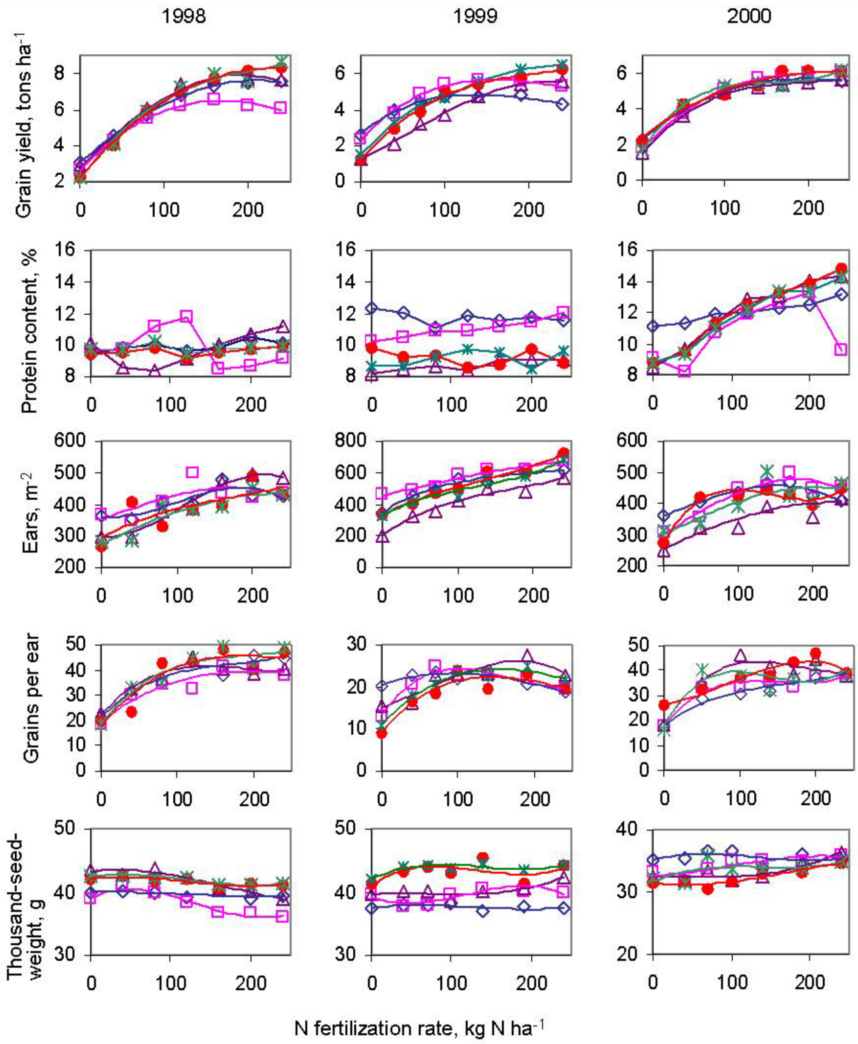

Figure 24. Yield (15% water content), protein content (% of DM), tiller density, ear density and thousand grain weight at different fertilizer N rates at sites A (◊), B (□), C (Δ), D (●) and E (⚹) in different years.

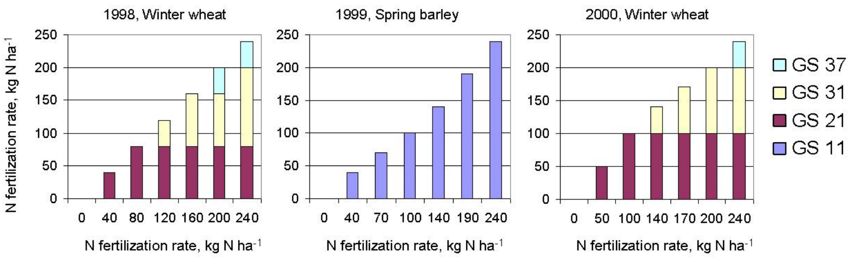

Figure 25. N fertilization rates applied at different growth stages in the field trials in different years, where GS 11 refers to seed development (first leaf unfolded), GS 21 to tillering (main shoot and one tiller), GS 31 to stem elongation (first node detectable) and GS 37 to flag leaf emergence (flag leaf just visible) (Zadoks, Cheng & Konzak, 1974).

(GS 37) (Figures 24 and 25). Thousand grain weight was not affected by fertilization (Figure 24). Thousand grain weight is known to be affected more by variety, weather conditions and diseases (Gooding & Davies, 1997). In 1998, the low thousand grain weight at site B coincided with a larger incidence of diseases, resulting in lower yield response at this site. In 1999, there were lower thousand grain weights on the clayey sites. These coincided with low CP and small amounts of plant available soil N. This may be due to timing of N supply to the crop. The largest increases in CP are obtained by applications at, and after, ear emergence (GS 50) (Gooding & Davies, 1997). Thousand grain weight is also increased by fertilization at late growth stages, especially if flag leaf senescence is delayed (Gooding & Davies, 1997). In 1999, all fertilizer N was applied at emergence (GS 11). On the sandy sites, N may have been supplied by the soil at later stages, whereas the crop on the clayey sites did not receive much plant available N from the soil at all.

Economic optimum N fertilization

The results indicate that some improvements in economic outcome would be possible if optimum N fertilization levels could be predicted site-specifically compared to the uniform application rate chosen (here called standard N fertilization) (Paper IV). In 1998, standard N fertilization was adequate at most sites, but in 1999 the clayey parts of the field would have benefited from higher and/or split N-fertilization rates and in 2000 the same yield and CP level could have been achieved at lower N-fertilization rates (Table 1). However, the improvements observed in this investigation were not of great significance. In a year with drier weather conditions, these improvements would probably be much larger, since yield differences in this field could be much greater in such cases. The effects of N fertilization on CP varied considerably and in an unforeseen way between sites and years. Moreover, the prediction of optimum N fertilization requires that plant-available soil N and yield levels can be estimated prior to N fertilization.

Table 1. Means (SD in brackets) for N fertilization (N, kg N ha^{-1}) and the corresponding grain yields (Y, Mg ha^{-1}, 15% water content) and grain crude protein contents (CP, % of DM) for uniformly applied standard N fertilization rates (kg N ha^{-1}) and optimum site-specific N fertilization rates (kg N ha^{-1}) in different years

	Standard N-fertilization			*Site-specific N-fertilization*		
Year	*N*	*Y*	*CP*	*N*	*Y*	*CP*
1998	160	7.4	9.5 (0.6)	165 (24)	7.5	10.1 (0.6)
1999	100	4.7	9.9 (1.5)	144 (43)	5.4	9.9 (1.3)
2000	170	5.7	12.9 (0.4)	128 (18)	5.4	12.0 (0.6)

Factors affecting optimum N fertilization

Soil nitrogen

As mentioned earlier, in areas of the world where the amounts of soil mineral N in spring are large, this variable has been considered to give good estimates of the demand for N fertilization during the growing season (Scharpf, 1977). In the present investigation, however, annual measurements of within-field variations in soil mineral N in spring gave poor estimates of plant available soil N (Np) (Paper II), possibly due to the small over-wintering amounts of mineral N compared to soil N taken up by plants. Net N mineralization (Nm), however, was more similar in size to Np, indicating that almost the entire amounts of soil N taken up by the crops originated from Nm during the growing season and that it is more important to predict Nm than soil mineral N in spring. The large within-field variations in Nm and Np (Paper II) and their relationship with optimum N fertilization (Paper IV) suggest that the optimum N fertilization rate varied with a standard deviation of at least 20 kg N ha^{-1} during the investigation period. The differences between sites in optimum N fertilization rates were similar, or even larger (SD = 30 kg N ha^{-1}). However, they were not always significant (Paper IV), which may be explained by the size of the trial plots, which in this case were 72 m long to fit 24 x 3 m wide subplots. There may have been just as large within-field variations within the plots as between plots, which would make the variations found between sites insignificant, since variations within the plot would be regarded as experimental errors. This is probably one reason for the insignificance of the differences found in optimum N fertilization rates between the intensive sites (Paper IV), despite the large variations in Nm and yield which were determined in smaller plots at the extensive sites (Papers II and III).

Other nutrients and pH

Potassium, phosphorus and pH are not likely to have been limiting for yield, since there were normal amounts in the soil and P and K fertilizers were applied. However, shortage of Mg and other nutrients may have limited yield on the sandy part of the field at larger N fertilization rates. Maximum yields were somewhat lower in the sandy area than in the clayey area in 1999 (Figure 24), which could be a result of limited supply of Mg or other nutrients.

Soil moisture

Heavy precipitation in the beginning of 1999 led to soil moisture contents very close to field saturation on the clayey soil during that growing season. In that year, yields were lower on the clayey soil (Paper V). However, there were no consistent differences in yield at optimum fertilization, but more N was needed at the clayey sites (Paper IV). That was probably due to denitrification caused by waterlogging and limited oxygen supply. In the drier year of 1996, smaller yields were observed within the sandy area of the field with lower water holding capacity (Paper V). In this year water supply may have limited yield in the sandy area. In 1998 and 2000, with moist weather but without waterlogging, the yield response to fertilizer N was very similar, regardless of soil type (Paper IV). Water supply obviously never became a growth-limiting factor in these years. Thus, sufficient water supply may level out yields on soils with large differences in soil texture, if other growth factors are not yield-limiting.

Diseases

There were significant differences in disease incidence between sites only in one year (Paper IV). In 1998, leaf blotch *(Drechslera tritici-repentis* and *Stagonospora* *nodorum)* and eyespot *(Pseudocercosporella herpotrichoides)* were significantly more frequent at site B. The smaller N content in the crop at this site indicates limited uptake or utilization of N. This may have been caused by the eyespot or leaf blotch infections at this site. This is probably the reason for the lower yield response and depressed CP and thousand grain weight at larger N applications at site B. The low CP and thousand grain weight only at larger N application rates (Figure 24) may be due to more severe infections there. A reduced N fertilization rate at this site would have saved fertilizer N, probably without any yield depression and possibly also with improved grain quality. However, this would have required prediction of the eyespot infection. A complementary or alternative measure in such a case would have been site-specific plant protection.

Weeds

The two intensive sites on the sandy area of the field (sites A and B) had higher frequencies of weeds than the other sites in all years, especially of couch grass *(Elymus repens)* at site A (Paper IV). However, no clear effect of weeds on crop response could be detected.

Temperature and radiation

The difference in CP response between 1998 and 2000 (Paper IV), despite the same crop being grown on the field, may be due to differences in both weather and cultivars. The lower temperature in 1998 compared to 2000 may have had an influence, since low temperature favours yield rather than CP (Kalinin, 1986). Johansson & Svensson (1998) found a positive correlation between CP in winter wheat and sun hours in May and June in experiments in Sweden during 1975-1996. There were only small differences between number of sun hours during these months in 1998 and 2000, but considering the earlier development in 2000, sun hours in May may have been more important in that year, whereas sun hours in June may have had a larger influence in 1998. In 2000, crop development was much more rapid, and therefore the latest N application (GS 37) was closer in time to grain filling, which should have favoured CP.

Methods for mapping soil variables

In Paper I, the performance of different methods for making maps of measured values of clay content, soil organic matter content (SOM), pH(H_2O), K-HCl, P-AL, K-AL and Mg-AL were assessed. According to cross-validations, where interpolated values were compared with measured values, averages from two zones divided by a distinct border (Zones) gave better prediction for most variables than interpolation without considering the border (IDW, OK and COK) (Figure 26). With the border taken into account, cokriging with SEC as a covariable (COKt) improved the prediction, whereas the improvements with ordinary kriging (OKt) and inverse distance weighting (IDWt) were insignificant (Figure 26). Direct interpretation of soil electrical conductivity (SEC) by a simple linear regression model (REG) gave rather good predictions of clay content (Figure 26). In general, even the simplest interpolation method improved the prediction compared to field average (Figure 26). For fields with distinct borders between different regions within the field, transformation of data may obviously be necessary prior to interpolation. The use of averages in such regions may obviously be a better alternative than interpolation of the whole field without respect to the regions. SEC can be used both for classification of a field into smaller regions and as a covariable in cokriging of a number of soil variables.

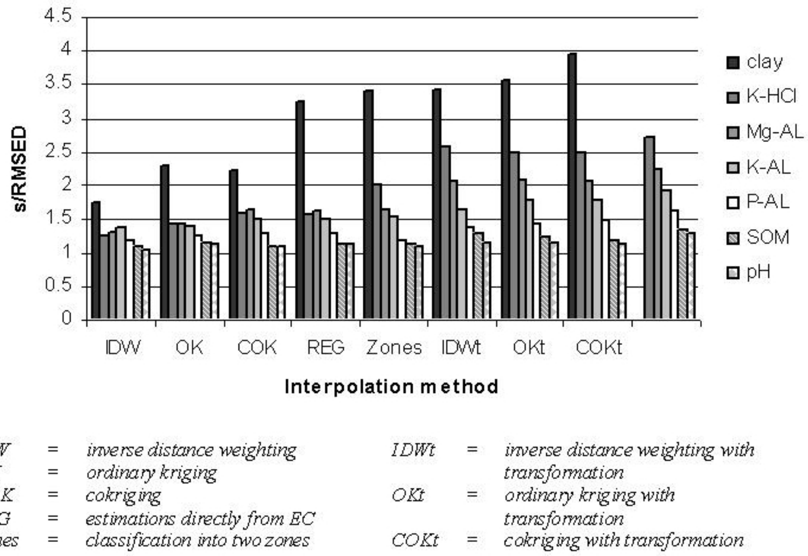

Figure 26. Average s/RMSED-value (ratio of the standard deviation to the error of prediction from the ideal 1:1 line) for each variable and method for mapping where a s/RMSED ratio greater than one indicates that the method improved the predicted map compared to field average.

Maps for decision support

Yield maps and protein maps

CP maps may indicate where N supply has been sufficient. If growing conditions were expected to be similar between years, indicating that historical data could be used to determine N fertilization demand, more N should be applied in areas with low CP if there is a correlation with yield, regardless of the direction (Table 2). When N is limiting for both yield and CP, as in 1999 in this field, CP and yield are likely to be positively correlated. When N only limits CP, as in 1998 in this field, CP and yield are instead negatively correlated. In either case, fertilization demand is higher in areas with low CP. If the correlation is positive, however, the mean rate should probably be increased and if the correlation is negative the mean rate should probably remain if mean CP is reasonable, or be lowered if mean CP is high. When there is no correlation between yield and CP, fertilization according to the CP map should not be recommended. Here areas with both low yield and CP could be identified, to find where other management measures should probably be adjusted. Alternatively, these areas should be fertilized with less N, since the crop in those areas probably cannot utilize larger doses effectively. See further Paper III.

Table 2. Schematic description of how the relationship between yield and crude protein content (CP) indicates N status in the field and what measures should be taken if the relation could be predicted

Relationship between yield and CP	Adequacy of N supply	Measure to be taken
Positive correlation	N is limiting yield and CP	Average N should be increased. More N should be applied where yield and CP are low.
Negative correlation	N is mainly limiting CP	Average N supply is probably sufficient. More N should be applied where CP is low and less where CP is high.
Uncorrelated	CP and yield are limited by some other factors other than N	Identify areas where both CP and yield are low and find out what factor is limiting.

Soil N maps

As mentioned earlier, the within-field variation in Np in this field was large and should therefore have a considerable impact on the within-field variation in fertilizer N demand (Paper II). However, the spatial pattern in Np varied between years, and can only partly be explained by stable soil parameters such as clay and SOM (Paper II). The pattern of Np is therefore difficult to predict with satisfactory precision from these parameters alone without seasonal adjustment. In other fields, where SOM is spatially more variable and is better correlated with Np (Stenberg, Jonsson & Börjesson, 2002). SOM maps may be more useful. However, this requires maps that are detailed enough to make a reliable interpolation. As shown in Paper I, the simple interpolation of sparse SOM data is not much better than a map of field average. However, SOM and probably also Np can be predicted by a method based on near infrared reflectance (NIR) of the soil (Stenberg, Jonsson & Börjesson, 2002). Online measurements of NIR would provide the possibility to achieve dense data, which would be interesting in fields with larger variations in SOM. If not used by itself, it could be complementary to measurements of crop N status with spectrometers, such as the Yara N-sensor. However, this requires split N application. In Sweden, split N application is currently common in most crops in areas with large precipitation and high risk for N losses, but in drier areas it is more restricted to winter crops and potatoes.

Maps of risk for drought and waterlogging

Soil electrical conductivity (SEC) was well correlated with clay content, which is known to strongly affect the water holding capacity of a soil (Andersson and Wiklert, 1972). SEC is also directly affected by actual soil moisture content in the field (McNeil, 1980), and may therefore be a fairly good estimator of within-field variations in water holding capacity. Elevation influences drainage and groundwater level and thereby soil moisture content. Areas with lower elevation are likely to be wetter and hills may be drier than could be expected from their soil texture. The relationships between SEC and yield, as well as between elevation and yield in different years (Figure 27), indicate that areas with high values of SEC and low elevation were subject to waterlogging in wet years and areas with high elevation and those with low SEC were subject to drought in dry years (Paper V). Therefore, SEC and elevation may be used to divide the field into zones with different risks of drought and waterlogging (Paper V). The drought risk map could be implemented in practical agriculture for variable N fertilization within the field. However, this requires that a certain year can be classified as wet, dry or intermediate prior to fertilization, which will be difficult unless the fertilization is split and there is an application later in the growing season when the grower knows more about the weather in the year in question. In dry years, less N is motivated in the zones with a risk of drought, since optimum yields would be depressed by water limitation. In wet years, more N and/or split applications are needed to achieve high yields in zones with a risk of waterlogging, due to reduced soil N mineralization (Stanford & Epstein, 1974) and increased risks of N losses through gaseous emissions and leaching (Stevenson & Cole, 1999). However, the risk of leaching may also justify a low input of N in such areas. SEC and elevation would also be useful in other arable fields where drought and/or waterlogging affect potential yield. An advantage with SEC and elevation is that they can be sampled densely at a reasonable cost. If yield data are available, they could be used to check relationships with SEC and elevation.

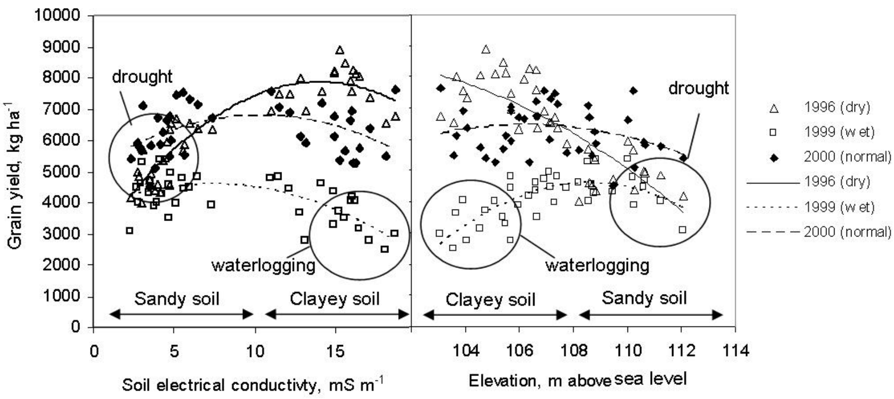

Figure 27. Grain yields in 1996, 1999 and 2000 versus soil electrical conductivity (SEC) and topography at the 39 sites.

Management zones

As shown in Paper I, even if interpolation of most variables yielded improvements compared to field averages, within this particular field with its distinct borders between different regions, the use of averages in each region was a better alternative for most variables than interpolation of the whole field without respect to the borders. Dividing the field into management zones can also have other advantages compared to using grid data. For instance, it requires less complicated equipment for application of inputs, and only the most important variation is accounted for. Management zones can be defined by multivariate classification based on data with great spatial density. As described above, management zones classified with respect to different risks of drought and waterlogging could be based on SEC, elevation and grain yield, whereas it appears possible to classify management zones based on differences in soil N supply on the basis of NIR data. Consequently, it may be possible to identify zones based on both different risks for drought and soil N supply by multivariate classification from all these variables (SEC, elevation, grain yield and NIR).

Conclusions

Potential for site-specific N fertilization

The spatial variation in plant available soil N (Np) (Paper II) and in yield in years with varying soil moisture conditions (Paper V) indicates that there is a potential for site-specific N management of this field. Site-specific N fertilization in the field studied may improve yields or reduce fertilizer N doses (Paper IV).

Potential to predict site-specific fertilizer N demand

Plant available soil N (Np) and net N mineralization (Nm) were significantly correlated to SOM and clay in this field. However, the correlation was too weak in this field to use these variables for prediction of Nm or Np.

Soil electrical conductivity (SEC) and elevation were able to explain yield depression caused by both drought and waterlogging. SEC and elevation would therefore be applicable for classification of the field into risk zones for drought and waterlogging, useful in site-specific N fertilization (Paper V). However, one major restriction is that at the time of fertilizer application, the farmer generally does not know what the weather will be like in the future. This will always be a restriction for N fertilization unless there are great improvements in weather forecasting or unless irrigation is used. There should still be greater potential for improvements in yield returns and the ability to achieve the desired protein content if each zone is treated separately.

Protein and yield maps together revealed how N demand varied spatially in relation to fertilizer N applied (Paper III). They could thereby be used to analyze where more or less N should have been applied to optimize returns. However, the maps of yield and protein varied between years, and historical information may not be valid from one year to the next.

Np and grain yield can evidently vary widely from year to year, due to various unforeseen conditions. Within-field variations in fertilizer N demand are not only affected by Np and plant available soil moisture, but also by diseases and other growth limiting factors (Paper IV).

Potential to map soil parameters

Interpolated maps from sparsely sampled soil variables had smaller errors than field averages in this field, but larger errors than averages within each of two zones, unless the borders between the zones were considered in the interpolation (Paper I).

The potential to relate easily measured variables with great spatial density, such as SEC, to the risk for drought and waterlogging, and perhaps in the future also to dense NIR measurements that can be related to Np, provides the opportunity to divide fields into management zones (Paper V).

Future research

On the basis of the knowledge presented in this thesis, indicating that plant available soil N, potential yield and thereby N fertilization demand vary considerably within fields, attention should be directed to research on how to predict these variables. The results of this thesis indicate that these variations to some extent connected to within-field variations in plant available soil moisture and soil organic matter. It is also shown that the effects are difficult to predict due to dependence on unforeseen weather conditions. Methods for prediction should therefore involve seasonal adjustments, which for instance could be based on measurements of the current status of the crop, recent weather data or weather forecasts. Research could perhaps focus on how soil and plant data should be combined for more accurate estimation of fertilizer N requirements. For example, N-sensor data on current N status in the crop could be complemented by soil NIR data on expected net N mineralization during the rest of the growing season.

Conventional soil analysis can be very expensive and time-consuming, and therefore samples are taken comparatively sparsely, which leads to soil maps with low spatial resolution or large uncertainty. Future research should therefore focus on how to achieve more detailed spatial resolution. This would require measuring equipment with the potential for dense measurements at low cost to be developed and tested. Some success in this area has already been achieved, regarding *e.g.* soil electrical conductivity (SEC) and near infrared reflectance (NIR) measurements, but much work remains before such measurements are both readily made and easily interpreted for site-specific measures. For example, the usefulness of SEC to create management zones needs further evaluation.

Even though interpolated maps may have less error than field averages, they may not always be much more correct than a map divided into zones. Comparisons of different methods for creating management zones versus continuous maps with regard to error and cost could provide a basis for future sampling and management strategies.

This thesis and other research in the area deal mostly with fertilization using mineral fertilizers. However, knowledge about spatial variations in fertilizer demand is relevant both for conventional farmers using mineral fertilizers and for organic farmers using only organic fertilizers. Even though it may already seem difficult to achieve high precision in dosage and timing of organic fertilizers, there may be greater motivation for organic farmers to optimize fertilization in this way, since the supply of organic fertilizers is usually restricted.

References

Andersson, S. & Wiklert, P. 1972. Markfysikaliska undersökningar i odlad jord. XXIII. Om de vattenhållande egenskaperna hos svenska jordarter (Water-holding properties of Swedish soils). *Journal of agricultural land improvement* 25, 2-3, 143 pp (in Swedish).

Berglund, K., Berglund, Ö. & Gustafson Bjuréus, A. 2002. Markstrukturindex – ett sätt att bedöma jordarnas fysikaliska status och odlingssystemets inverkan på markstrukturen (Soil structure index, a method to evaluate the physical status of the soil and the effect of the farming system on soil structure). Sveriges lantbruksuniveritet, Uppsala. *Avd. f. lantbrukets hydroteknik, Avdelningsmeddelande 02:4,* 132 pp (in Swedish).

Bergström, T. 1990. Några aspekter på vad som är lämplig parcellstorlek. (Some aspects of a suitable plot size) SLU, Institutionen för Lantbruksteknik. *Nytt om Försöksteknik 1990*, 2, 2-4 (in Swedish).

Berry, J.K. 1999. *The Precision Farming Primer.* Berry & Associates, Spatial Information Systems, Inc., USA. www.innovativegis.com/basis/pfprimer

Blackmore, S. & Moore, M. 1999. Remedial correction of yield map data. *Precision agriculture* 1, 53-66.

Blackmore, S., Godwin, R.J. & Fountas, S. 2003. The analysis of spatial and temporal trends in yield map data over six years. *Biosystems engineering* 84, 455-466.

Börjesson, T., Stenberg, B., Lindén, B. & Jonsson, A. 1999. NIR spectroscopy, mineral nitrogen analysis and soil incubations for the prediction of crop uptake of nitrogen during the growing season. Plant and soil 214, 75-83.

Boyd, D.A., Yuen L.T.K. & Needham, P. 1976. Nitrogen requirements of cereals. *Journal of agricultural science*, Cambridge 87, 149-162.

Burrough, P.A. & McDonnell, R.A. 1998. *Principles of Geographical Information Systems. Spatial Information Systems and Geostatistics*. Oxford University Press, New York, N.Y. 333 pp.

Christensen, S. & Olesen, S.E. 2003. Use of spatial – temporal data and future precision farming. In: Lindén, B. & Olesen, S. E. (eds.) *Implementation of precision farming in practical agriculture,* DIAS report, plant production 100, 91-98.

Dalsgård Bjerre, K., Nistrup Jørgensen, L. & Secher, B.J.M. 1998. Disease map and site-specific fungicide application. *Dansk Planteværnskonference 1998, DJF report* 3, 131-144.

Darwinkel, A. 1983. Ear formation and grain yield of winter wheat as affected by time of nitrogen supply. *Netherlands journal of agricultural science* 31, 211-225.

Earl, R., Taylor, J.C., Wood, G.A., Bradley, I., James, I.T., Weine, T., Welsh, J.P., Godwin, R.J., & Knight, S.M. 2003. Soil factors and their influence on within-field variability, part I: Field observation of soil variation. *Biosystems engineering* 84, 425-440.

Egnér, H., Riehm, H. & Domingo, W.R. 1960. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II. Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung (Investigations on soil chemical analysis as a basis of the evaluation of plant nutrient status of soils II. Chemical extraction methods for phosphorous and potassium determination). *The annals of the Royal agricultural college of Sweden 26*, 199-215 (in German).

Ehsani, M.R., Upadhyaya, S.K., Slaughter, D., Shafi, S. & Pelletier, M. 1999. A NIR technique for rapid determination of soil mineral nitrogen. *Precision agriculture* 1, 217-234.

Erpenbeck, J.M. 1982. Irrigation Scheduling – A Review of Techniques and Adaptation of the USDA Irrigation Scheduling Computer Program for Swedish Conditions. Swedish University of Agricultural Sciences, *Department of Soil Sciences, Division of Agricultural Hydrotechnics, Report 127*, 135 pp.

Esala, M. & Leppanen, A. 1998. Leaching of ^{15}N-labeled fertilizer nitrate in undisturbed soil columns after simulated heavy rainfall. *Communications in soil science and plant analysis* 29, 1221-1238.

Fox, R.H. & Piekielek, W.P. 1978. Field testing of several nitrogen availability indexes. *Soil science society of America journal* 42, 747-750.

Flowers, M., Weisz, R., Heiniger, R., Tarleton, B. & Meijer, A. 2003. Field validation of a remote sensing technique for early nitrogen application decisions in wheat. *Agronomy journal* 95, 167-176.

Flowers, M., Weisz, R. & Heiniger, R. 2003. Quantitative approaches for using color infrared photography for assessing in-season nitrogen status in winter wheat. *Agronomy journal* 95, 1189-1200.

Fredriksson, L. & Haak, E. 1995. Svenska åkermarksprofiler (Swedish arable soil profiles). *Kungliga Skogs- och Lantbruksakademiens tidskrift* 134, 116 pp (in Swedish).

Gaskin, G.J. & Miller, J.D. 1996. Measurement of soil water content using a simplified impedance measuring technique. *Journal of agricultural engineering research* 63, 153-160.

Gerhards, R. & Christensen, S. 2003. Real-time weed detection, decision making and patch spraying in maize, sugarbeet, winter wheat and winter barley. *Weed research* 43, 385-392.

Godwin, R.J. & Miller, P.C.H. 2003. A review of the technologies for mapping within-field variability. *Biosystems engineering* 84, 393-407.

Goedeken, M.W., Johnson, G.V., Raun, W.R. & Phillips, S.B. 1998. Soil test phosphorus crop response projections to variable rate application in winter wheat. International soil and plant analysis symposium, Minneapolis, USA, August 1997. *Communications in soil science and plant analysis* 29, 1731-1738.

Gooding, M.J. & Davies, P.D. 1997. *Wheat Production and Utilization, Systems, Quality and the Environment* (CAB International, Wallingford, UK) 355 pp.

Gustafsson, K. 1999. Models for precision application of lime. In: Stafford, J. (ed) *Precision agriculture ´99*, 175-180.

Guyot, G. 1990. Optical properties of vegetation canopies. In: Steven, M. D. & Clark, J. A. (eds.) *Applications of remote sensing in agriculture*, Butterworths, Sevenoaks, Kent, UK, 19-43.

Halekoh, U., Greve, M.H. & Nehmdahl, H. 2003. Concepts of field management zones based on soil and landscape properties. In: Lindén, B. & Olesen, S. E. (eds.) Implementation of precision farming in practical agriculture, DIAS report, *Plant production 100*, 35-41.

Hansson, A.-C., Pettersson, R. & Paustian, K. 1987. Shoot and root production and nitrogen uptake in barley, with and without nitrogen fertilization. *Zeitschrift für Acker- und Pflanzenbau* 158, 163-171.

Hamid Muhammed, H. & Larsolle, A. 2003. Feature vector based analysis of hyperspectral crop reflectance data for discrimination and quantification of fungal disease severity in wheat. *Biosystems engineering* 86, 125-134.

Hillel, D. 1982. *Introduction to Soil Physics*. Academic Press Inc. 364 pp.

Jansson, S.L. & Persson, J. 1982. Mineralization and immobilization of soil nitrogen. In: Stevensson, F. J., Bremner, J. M., Hauk, R. D. & Keeney, D. R. (eds.) Nitrogen in Agricultural Soils, *Agronomy 22*, Madison Wisconsin USA, 229-252.

Jansson, P-E. & Claréus, J. 1996. *Pgraph v.1.3. User's Manual.* Department of Soil Sciences, Swedish University of Agricultural Sciences. 66 pp.

Johansson, E. & Svensson, G. 1998. Variation in bread-making quality: Effects of weather parameters on protein and quality in some Swedish wheat cultivars grown during the period 1975-1996. *Journal of the science of food and agriculture* 78, 109-118.

Kalinin, N.I. 1986. Change of spring wheat grain quality under the effect of air temperature. *Soviet agricultural sciences* 1, 16-18.

Köhler, J. 1983. *Eignung von Metoden der Bodenanalyse zur Erfassung der N-Nachlieferung von Lössböden und zur Bemessung der Stickstoffspätgaben zu Winterweizen.* Dissertation Universität Hannover. 146 pp.

Kristensen, K. and Olesen, S.E. 1997. Mapping root zone capacity by cokriging aerial photographs and point measurements of available soil moisture. In: Stafford, J. (ed.) *Precision Agriculture ´97*, 793-802.

Kritz, G. 1983. Physical Conditions in Cereal Seedbeds. A Sampling Investigation in Swedish Spring-sown Fields. *Reports from the Division of Soil Management, Department of Soil Sciences, Swedish University of Agricultural Sciences 65*, 187 pp.

Lark, R.M. & Stafford, J.V. 1997. Exploratory analysis of yield maps of combinable crops. . In: Stafford, J. (ed.) *Precision Agriculture ´97*, 887-903.

Lesch, S.M., Strauss, D.J. & Rhoades, J.D. 1995. Spatial prediction of soil salinity using electromagnetic induction techniques. An efficient spatial sampling algorithm suitable for multiple linear regression model identification and estimation. *Water resources research* 31, 387-398.

Lillesand, T.M. & Kiefer, R.W. 2000. *Remote Sensing and Image Interpretation.* Fourth edition. John Wiley & Sons, Inc., New York, USA. 724 pp.

Link, A., Panitzki, M. & Reusch, S. 2002. Hydro N-Sensor: Tractor-Mounted Remote Sensing for Variable Nitrogen Fertilization. In: *Proceedings of the 6th International Conference on Precision Agriculture and other Precision Resources Management*, July 14-17 Minneapolis, SAS-CSSA-SSSA, Madison, WI., USA, 1012-1018.

Machado, S., Bynum, E.D., Archer, T.L., Lascano, R.J., Wilson, L.T., Bordovsky, J. Segarra, E., Bronson, K., Nesmith, D.M. & Xu, W. 2000. Spatial and temporal variability of corn grain yield: site-specific relationships of biotic and abiotic factors. *Precision agriculture* 2, 359-376.

McNeil, J. D. 1980. Electrical Conductivity of Soil and Rocks. Tech. Note TN-5. Geonics Ltd. Mississauga, Ont., Canada. 20 pp.

Madsen, H.B. 1979. Jordbundskartering og bonitering belyst ved hjælp af jordens vandretention, bygs rodudvikling og simuleret planteproduktion. (Soil surveying for evaluating soil capability on the basis of soil water retention, root development of barley and simulated plant production.) *Folia geographica Danica 10*, 203 pp (in Danish).

Mattsson, L. 1990. Effect of the inorganic soil nitrogen level on fertilizer nitrogen requirements by spring barley grown on regularly manured soils. *Swedish journal of agricultural research* 20, 141-145

Mattsson, L. & Thylén, L. 1994. Skördevariationer - en konsekvens av ojämnheter i alven? (Yield variations - a consequence of unevenness in the subsoil?) *Kungliga Skogs- och Lantbruksakademiens tidskrift* 133, 85-89.

McBratney, A. Whelan, B.M., Walvoort, D.J.J. & Minasny, B. 1999. A purposive sampling scheme for precision agriculture. In: Stafford, J. (ed.) *Precision Agriculture ´99*, 101-110.

Mengel, K. & Kirkby, E.A. 1987. *Principles of Plant Nutrition*. International Potash Institute, Bern, Switzerland, 687 pp.

Misselbrook, T.H., Smith, K.A., Johnson, R.A. & Pain, B.F. 2002. Slurry application techniques to reduce ammonia emissions: Results of some UK field-scale experiments. *Biosystems Engineering* 81, 313-321.

Moore, G.A. & Tyndale-Biscoe, J.P. 1999. Estimation of the importance of spatially variable nitrogen application and soil moisture holding capacity to wheat production. *Precision Agriculture* 1, 27-38.

Muñoz-Carpena, R. 2004. Field devices for monitoring soil water content. *Bulletin 343, the Department of Agricultural and Biological Engineering*, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

Müller, S. & Görlitz, H. 1984. Nutzung der Bestimmung des anorganischen Bodenstickstoffs bei der N-Düngung. (Using Determination of Soil Mineral Nitrogen for N Fertilization.) *Fortschrittsberichte für die Landwirtschaft und Nahrungsgüterwirtschaft, Band 22, Heft 7,* Akademie der Landwirtschafts-wissenschaften der DDR, Institut für Lndwirtschaftliche Information und Dokumentation Berlin. 36 pp (in German).

Naturvårdsverket. 1997. Kväve från Land till Hav, Huvudrapport. (Nitrogen from Land to Sea, Main report) *Swedish Environmental Protection Agency*, Report 4735, 113pp (in Swedish).

Olsson, D., Söderström, M. & Nissen, K. 2003. An automated method to locate optimal soil sampling sites using ancillary data. Werner, A. & Jarfe, A. (eds.) *Programme book of the joint conference of ECPA-ECPLF*, Wageningen Academic Publishers, 649.

Ortega, R.A., Westfall, D.G., Gangloff, W.J. & Peterson, G.A. 1999. Multivariate approach to N and P recommendations in variable rate fertilizer applications. In: Stafford, J. (ed) *Precision Agriculture ´99*, 387-396.

Osborne, S.L., Schepers, J.S., Francis, D.D. & Schlemmer, M.R. 2002. Detection of phosphorus and nitrogen deficiencies in corn using spectral radiance measurements. *Agronomy journal* 94, 1215-1221.

Pennock, D.J., Walley, F.L., Solohub, M.P., Hnatowich, G. 1999. Yield response of wheat and canola to a topographically based variable rate fertilization program in Saskatchewan. In: Robert, P. C., Rust, R. H. & Larson, W. E. (eds*.), Proceedings of the 4th International Conference on Precision Agriculture*, 797-805.

Reusch, S. 1997. Entwicklung eines reflexionsoptischen Sensors zur Erfassung der Stickstoffversorgung landwirtschaftlicher Kulturpflanzen. (Development of a reflectance sensor for the establishment of nitrogen support of agricultural crops.) Dissertation. *Forschungsbericht Agrartechnik des Arbeitskreises Forschung und Lehre der Max-Eyth-Gesellschaft Agrartechnik im VDI (VDI-MEG) 303*, Kiel, 157 pp (in German).

Riley, H. 1996. Estimation of physical properties of cultivated soils in southeast Norway from readily available soil information. *Norwegian journal of agricultural sciences* 25, 51 pp.

Robert, P.C. 2002. Precision Agriculture: a challenge for crop nutrition management. *Plant and soil* 247, 143-149.

Robertson, G.P. 2000. *GS$^+$, GeoStatistics for the Environmental Sciences, Version 5*. Gamma Design Software, Plainwell, Michigan. 384 pp.

Russell, C.A., Angus, J.F., Batten, G.D., Dunn, B.W. & Williams, R.L. 2002. The potential of NIR spectroscopy to predict nitrogen mineralization in rice soils. *Plant and soil* 247, 243-252.

Scharpf, H.-C. 1977. *Der Mineralstickstoffgehalt des Bodens als Maßstab für den Stickstoffdüngerbedarf.* (The mineral nitrogen content of soil as a measure for the nitrogen fertilization demand.) Dissertation Universität Hannover. 172 pp (in German).

Shiel, R.S., Mohamed, S.B. & Evans, E.J. 1997. Planning phosphorus and potassium fertilization of fields with varying nutrient content and yield potential. In: Stafford, J. (ed.) *Precision Agriculture ´97*, 171-178.

Siman, G. 1974. Nitrogen status in growing cereals with special attention to the use of plant analysis as a guide to supplemental fertilization. *The annals of the Royal agricultural college of Sweden, Uppsala*. 54 pp.

Söderström, M. 2003. Systems of soil mapping in precision agriculture. In: Lindén, B. & Olesen, S. E. (eds.) Implementation of precision farming in practical agriculture, *DIAS report, plant production 100*, 17-25.

Söderström, M., Nissen, K., Gustafsson, K, Börjesson, T., Jonsson, A. & Wijkmark, L. 2004. Swedish farmers' experiences of the Yara N-sensor 1998-2003. In: *Proceedings of the 6th International Conference on Precision Agriculture and other Precision Resources Management,* July 2004, MN, USA, in press.

Sosulski, F.W. & Imafidon, G.I. 1990. Amino acid composition and nitrogen-to-protein conversion factors for animal and plant foods. *Journal of agricultural food chemistry* 38, 1351-1356.

Sparrow, P.E. 1979. Nitrogen response curves of spring barley. *Journal of agricultural science, Cambridge* 92, 307-317.

Spiertz, J.H.J. 1974. Grain growth and distribution of dry matter in the wheat plant as influenced by temperature, light energy and ear size. *Netherlands journal of agricultural science* 22, 207-220.

Stanford, G. & Smith, S.J. 1972. Nitrogen mineralization potentials of soils. *Soil Science Society of America journal* 36, 465-472.

Stanford, G. & Epstein, E. 1974. Nitrogen mineralisation-water relations in soils. *Soil Science Society of America journal* 38, 103-107.

Stenberg, B., Jonsson, A. & Börjesson, T. 2002. NIR-technology for soil analysis with implications for precision agriculture. *Near Infrared Spectroscopy: Changing the World with NIR.* NIR Publications, Chichester, UK, 279-284

Stenberg, B., Jonsson, A. & Börjesson, T. 2004. Use of near infrared reflectance spectroscopy to predict nitrogen uptake by winter wheat within fields with high variability in organic matter. *Plant and soil*, in press.

Stevenson, F.J. & Cole, M.A. 1999. *Cycles of Soil, Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients*. Second edition. John Wiley & Sons, Inc. 427 pp.

Stewart, C.M., McBratney, A.B. & Skerritt, J.H. 2002. Site-specific Durum wheat quality and its relationship to soil properties in a single field in northern New South Wales. *Precision agriculture* 3, 155-168.

Swinton, S.M., Jones, K.Q., Miller, N.R., Schabenberger, O., Brook, R.C. & Warncke, D.D. 2000. Comparison of site-specific and whole-field fertility management in Michigan soybeans and corn. In Robert, P. C., Rust, R. H. & Larson, W. E. (eds.) *Proceedings of the 5th International Conference on Precision Agriculture*, published on a CD.

Taylor, J.C., Wood, G.A., Earl, R. & Godwin, R.J. 2003. Soil factors and their influence on within-field crop variability, Part II: Spatial analysis and determination of management zones. *Biosystems engineering* 84, 441-453.

Thomas, G., Taylor, J.C. & Musthill, T. 1999. A purposive sampling scheme for precision agriculture. In: Stafford, J. (ed.), *Precision Agriculture ´99*, 191-200.

Timlin, D., Pachepsky, Y., Walthall, C. & Loechel, S. 2001. The use of a water budget model and yield maps to characterize water availability in a landscape. *Soil tillage research* 58, 219-231.

Viscarra Rossel, R.A. & McBratney, A.B. 2000. A two-factor empirical deterministic response surface calibration model for site-specific predictions of lime requirement. *Precision agriculture* 2, 163-178.

Waring, S.A. & Bremner, J.M. 1964. Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. *Nature* 201, 951-952.

Wiklert, P. 1961. Om sambandet mellan markstruktur, rotutveckling och upptorkningsförlopp. (About the relationship between soil structure, root development and course of drying.) *Journal of agricultural land improvement 14*, 221-240 (in Swedish).

Wood, J. 1980. The Mathematical Expression of Crop Response to Inputs. *Proceedings of the International Potash Institute Colloquium 15*, Wageningen 1980, 263-271.

Wood, G.A., Welsh, J.P., Godwin, R.J., Taylor, J.C., Earl, R. & Knight, S.M. 2003. Real-time measures of canopy size as a basis for spatially varying nitrogen applications to winter wheat sown at different seed rates. *Biosystems engineering* 84, 513-531.

Zadoks, J.C., Chang, T.T. & Konzak, C.F. 1974. A decimal code for the growth stages of cereals. *Weed research* 14, p. 415-421.

Acknowledgements

I carried out the investigation presented in this thesis with the help of a lot of people, who contributed in different ways. Thank you all!

The Swedish Board of Agriculture, the Foundation for Agricultural Research and SLU, thank you for funding this work.

Börje Lindén, my main supervisor, thank you for initiating this project, for your good and faithful support, for all the time you spent reading through my work and for returning ink-filled papers of good and encouraging comments concerning scientific, pedagogic or grammatical issues.

Kerstin Berglund, my second supervisor, thank you for your part in initiating this project and for being a good support concerning different postgraduate matters. Thank you for all those papers you sent about soil physics and hydrology. It was a pleasure writing together with you and thank you also for all your useful comments on my work.

Mats Söderström, my third supervisor, thank you for your patient support with ArcView and other GIS software. You provided many good comments on the thesis and I really enjoyed writing Paper I together with you - a long but educational process. Thank you also for bringing Holger Nehmdahl and the EM38 equipment to the experimental field. The soil electrical conductivity data were very useful.

Sören Nyman, host for the field of investigation, thank you for so patiently letting us fill your field with plots, interfere with your management and visit your field, sometimes several days a week, for three whole years. Hopefully you will find the results interesting and useful in your management. Few farmers have such detailed information on their fields.

Anna Nyberg, thank you for good company during the otherwise so boring sessions of soil moisture measuring and for good support when I've struggled with the computer.

Lena Engström, thank you for helping me with the weather station in the worst of weathers, for good cooperation during threshing at Bjertorp and for supervision concerning production biology of winter wheat.

Maria Stenberg, Bo Stenberg, Christina Lundström and Johanna Wetterlind, thank you for joining our otherwise so small division. When you came along, there were suddenly twice as many people to ask for help.

Bo Stenberg, thank you for good advice concerning statistics and cross validations and for introducing me to the software Unscrambler.

Johanna Wetterlind, it was a pleasure to have you as room mate when you wrote your Master's thesis. Thank you for good support when I've struggled with ArcGIS and for introducing me to the software FuzMe.

Rolf Tunared, thank you for perfect management of the field trials and efficient organization of the soil sampling.

Knud Nissen, thank you for doing the difficult job of running the combine without cutting within the plots at the 39 sites and making yield maps from the recorded yield data. Thank you also for teaching me about the Yara N-sensor.

Håkan Svantesson, thank you for perfect fertilization of the field.

Thank you all field assistants from Lanna and Mats Rosqvist, Bibbi Manngård, Lars Johansson, Niklas Ingvar-Nilsson, Håkan Andersson, Daniel Gustafsson, and anyone else that gave me a hand when I needed help with field measurements.

Berit Larsson, thank you for providing weather data from Lanna.

Sölve Johnsson and Johan Roland, thank you for bringing Börje to Skara, for forming the Department of Agricultural Research Skara and for employing me in 1998.

Kjell Gustafsson, Anders Jonsson, Börje Lindén, Per-Åke Sahlberg and all others involved, thank you for bringing about the project "Precisionsodling i Väst", without which this investigation may never have been initiated. The network of people provided by this project, and later by "Precisionsodling Sverige", has been very valuable for the investigation. Thanks also to all of you others within the project who have contributed to my work in any way.

Mattias Frick, AnalyCen, thank you for introducing me to, and letting me borrow, the GPS equipment and for exporting the data for me.

The staff at Bjertorp, thank you for kindly letting me use your drying facilities and threshing equipment for plant samples taken at harvest.

Anders Larsolle, thank you for lending me your cropscan and instructing me on how to run it.

Mary McAfee, thank you for checking the English in all my papers and the thesis so quickly and at such short notice.

The referees at the Department of Soil Sciences, Ingvar Nilsson, Olle Andrén and Martin Larsson, thank you for valuable comments on the thesis.

Per-Erik Jansson, thank you for supervision concerning calculations of potential evapotranspiration.

Pernilla Tidåker, thank you for valuable information concerning changes in N losses due to recycling of nutrients from society.

Örjan Berglund, thank you for making the water modelling so much easier with the Excel macros you wrote.

Jan Eriksson, thank you for helping me with description of soil profiles and soil classification.

Jan-Erik Englund and Thomas Börjesson, thank you both for advice concerning statistical analyzes.

I also would like to thank Crown Princess Victoria for showing interest in site-specific fertilization and giving comments on my work when visiting our campus in August 2001.

My parents, parents-in-law and sister-in-law, thank you for looking after the children for a while when I needed some more time at work.

My husband Karl, thank you for being patient when I had to work a lot and for telling me to stop when I needed a break. Thank you also for helping me with soil sampling when I was short of field assistants and for giving me the farm advisor's views on my results.

My boys Markus and Erik, thanks to you I could extend my PhD-period by two years by spending some time at home with you. By doing that I got four of my papers accepted before printing this thesis. I also got frequently reminded that life is so much more than site-specific nitrogen fertilization.