Cranfield University at Silsoe

Jana Havránková

The evaluation of ground based remote sensing systems for canopy nitrogen management in Winter Wheat

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Supervisor: Prof. RJ Godwin & Dr. GA Wood

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Abstract

Nitrogen management is a crucial issue in terms of environmental and economical efficiency for winter wheat husbandry. Precision Agriculture in particular Remote Sensing, has been used to determine the variability of the crop. However, to be able to apply the required rate of nitrogen, the calibration of the data with the crop characteristics is critical. Satellite, airborne and ground based platforms are possible to use. Despite the presence of some commercial applications of the satellite and airborne techniques, the ground based systems offer advantages in terms of availability. The most common passive ground based remote sensing system in Europe is the Yara N sensor which has limitations in poor light conditions. Active sensors, using their own energy sources, are now available in the market e.g. the Crop Circle (Holland Scientific) and the Yara N sensor ALS.

The aim of this work was to evaluate the active and passive ground based remote sensing systems for canopy nitrogen management in winter wheat. The work was divided into three sub-experiments. Two were conducted in Wilstead (UK) in 2005 and 2006, with the objective to determine the relationship between sensors output (NDVI) and crop (wheat) characteristics during the growing season and to evaluate their application in field management of winter wheat. The field experiment carried out in Oponice (Slovakia) in 2006 assessed three different management strategies (the real time, near real time and traditional nitrogen management). The results showed that both the active and the passive sensors determine the variability in shoot numbers and total nitrogen content of plants particularly in the early growth stages. The application of Nitrogen using these sensors in the UK saved 15kg N/ha (UK). The nitrogen saved in Slovakia was small (1.5 kg/ha). Use of the sensors enabled a reduction in nitrogen without a negative influence on yield, which increased the Nitrogen use efficiency. In addition to this there were potential environmental benefits through a 52% reduction of the residual Nitrogen in the soil in the UK. In Slovakia there was no significant overall reduction in the total nitrogen used; however, a different application rates was applied to 80% of the field. The overall cost of production in Slovakia using the sensors was increased by 5%. The cost of sensing in the UK was £11/ha which could be offset by the 15 kgN/ha reduction and a potential small increase of yield by 1%.

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1 Introduction

1.1 Background

Precision farming is technology using information about spatial and temporal differences within the field in order to manage site-specific inputs. This can reduce inputs costs, result to higher crop productivity and the decrease of environmental pollution (Godwin et al., 2002a). After Barnes et al. (2000) precision farming involves the integration of Global Positioning System (GPS), Geographical Information System (GIS) and Remote Sensing (RS) technologies which enable this approach. Remote sensing can be used for three aspects of site–specific management.

i, anomaly detection, *e.g.* water stress, disease, or weed infestation;

ii, the correlation of variation in spectral response to specific variables such as soil properties or nitrogen deficiency;

iii, to convert multispectral data to quantitative units with physical meaning such as Leaf Area Index (LAI) into more complex crop models.

The latter two approaches have potential for incorporating remote sensing into decision support systems in a GIS environment. Spectral information is being applied in precision farming practice during the growing season mainly in terms of variable rate fertiliser application (Godwin et al., 2003a; Wood et al., 2003b).

All crop producers deal with nitrogen fertilisation problem. It is an essential issue for winter wheat husbandry. Nitrogen deficiency is characterized in winter wheat by leaf chlorosis, reduced net assimilation and relative growth rates, lower leaf area, phytomass and grain yield (Alley et al., 1996). Over-application can lead to the lodging of the crop and negative environmental impact, *e.g.* leaching or diffuse pollution of excess nitrogen. The characterisation of crop canopies for nitrogen management has, therefore, received much attention (Ložek, 1998; Alley et al., 1996; HGCA, 1997; HGCA, 2000; Godwin et al., 2002).

The management of the spatial and temporal variability of the crop canopy characteristics is a key factor for improving grain yield. The crop requirements or Nitrogen have to be matched as closely as possible by the nitrogen rates and the time between crop data acquisition and management decision making has to be as short as possible. These issues are not only important from an economical point of view, but environmental considerations must also be taken into account. Effort to apply only the necessary amount of fertilisers and chemicals has to be considered. So the accuracy of determining the requirements of the crop plays an important role in site –specific nitrogen management.

Actual nitrogen status, chlorophyll content, and above-ground biomass with connection to nitrogen concentration, LAI and shoot population are used as indicators of nitrogen requirements of the crop (HGCA, 1997). Methods to determine these indicators involve (Wood et al., 2003a) usually taking samples for laboratory analysis, undertaking direct crop measurements or the use of simple hand held devices. This is extremely time-consuming and destructive. Remote Sensing (RS) is one of the technologies which offer potential advantages. Plant nitrogen content and canopy nitrogen deficit can be related to reflectance measurements in green, red and NIR parts of the electromagnetic spectrum. Usually, the crop characteristic obtained by reflectance is then expressed by vegetation indexes. The most wide spread is The Normalized Difference Vegetation Index (NDVI) (Broge & Mortensen, 2002). Recently however Red Edge Inflexion Point (REIP) is used, when multiple wavebands are available (Boegh et al., 2002).

Satellite, airborne and ground-based platform for remote sensing are possible. The initially cost of satellite and airborne images was high and time was lost in processing the images, which delay the variable application of inputs. However, practical applications as SOYL sense (SOYL) or FARMSTAR are available with the acceptable price but still suffer from delays in processing. These applications are, however, despite their rapid expansion, they are not available over the whole of Europe. Therefore ground-based machine-mounted sensors have still advantages. ‘On the go sensors’ must be capable of obtaining data with sufficient accuracy and speed of processing in order to apply the fertiliser in real-time, in one machine pass (Alchanatis & Schimilovitch, 2005). Remote sensing systems can either use the ambient light (passive sensors) or the light emitted from their own source (active sensors) (Gibson, 2000). The main advantages of ground based active optic systems in comparison with passive ones, is that the effect of clouds is minimised and sun angle is not an issue. Using ground based active systems then enables data collection during the night as well as in day light (Morris, 2006).

The most available type at the European market is the passive system N sensor (Yara). Among the active ground based sensors, the Crop Circle system manufactured by Holland Scientific is available and the new N sensor ALS (YARA) with ability to apply the nitrogen real time has been introduced recently. These offer advantages particularly in longer operation day time (Morris, 2006; Yara, 2007). The use of active and passive ground based remote sensing systems, in terms of canopy nitrogen requirements of winter wheat, needs to be assessed and accuracy and operational considerations of these systems need to be explored.

1.2 Aim

To evaluate active and passive ground based remote sensing systems for canopy nitrogen management in winter wheat.

1.3 Objectives

1. To determine the relationship between the outputs of the active sensor (Crop Circle) and the passive sensor (Field Scan) with crop (wheat) characteristics during the growing season.
2. To compare the effectiveness of the both Crop Circle and Field Scan in deciding the N application rate for winter wheat during the growing season.
3. To determine the effectiveness of Nitrogen management systems in both the UK and Slovakia.

1.4 Outline methodology

Three areas of work were planned:

1. A detailed investigation into the performance of sensors in relation with crop physical and chemical conditions. To propose protocols to evaluate the sensors. Field measurements conducted during two growing seasons. Conduct correlation and regression analyses to find relationship between NDVI values and crop characteristics through.

2. A field evaluation of sensors in deciding the nitrogen application rate in comparison with traditional. To propose protocols of the experiment. Analysing the results from the following points of view:
    - nitrogen fertiliser spatial distribution,
    - saving on nitrogen fertiliser,
    - yield analyses,
    - N utilisation analyses,
    - residual N analyses,
    - economical considerations

3. A field assessment of the effect of different levels of input information (real time, near real time and no information) in the nitrogen management. Analysing the results from the following points of view:
    - nitrogen fertiliser spatial distribution,
    - saving on nitrogen fertiliser,
    - yield analyses.

2 Literature survey

This chapter gives the background for the experiments conducted in 2005 and 2006 in Wilstead (UK) as well as in Oponice (Slovakia). It summarizes the statement of the nitrogen management issues and the question of site specific application on winter wheat. Up to date approaches are mentioned to determine the nitrogen applied rate as well as in terms of determining the variability within the field. This section reviews remote sensing platforms with accent to sensors available currently at the market in Europe.

2.1 Nitrogen management for winter wheat crop

Efficient nitrogen (N) fertilization is crucial for economic wheat production and protection of ground and surface waters (Alley et al., 1996). Over application of N produces wheat plants that are not resist to lodging and disease with resulting decreased yields and increased input costs. The potential for enrichment of ground and surface waters with nitrates also increases with excessive N fertilizer applications. However, insufficient N availability to wheat plants results in low yields and significantly reduced profits compared to a properly fertilized crop. Nitrogen fertilizer rate and timing are the major issues to be solved.

Except of the right time-management in nitrogen application the absolute rate applied is critical. Current knowledge and machinery enable to apply the fertilisers spatially variable, what gives the advantage to match the site specific requirements of the crop. Therefore, rapid and non destructive methods are needed to determine the requirements and to be able to obtain this information.

2.1.1 Basics of winter wheat nitrogen management

Winter wheat crop nitrogen requirements differ along with growth stages (Figure 2-1) and the nitrogen uptake changes along a pattern that is depicted by the curve shown in Figure (2-2).

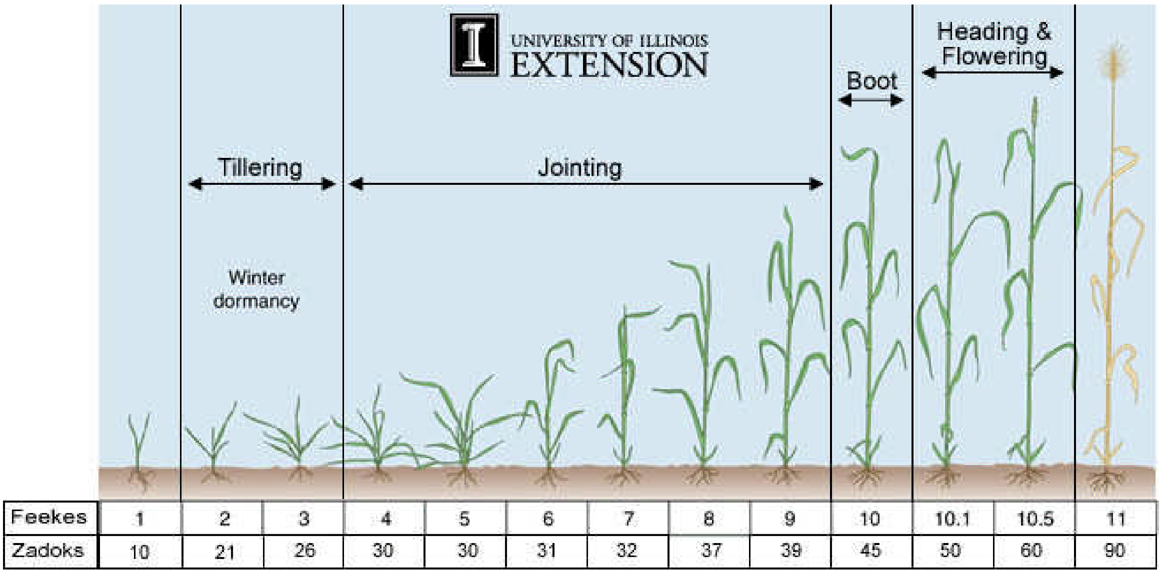

Figure 2-1 Growth stages of winter wheat (University of Illinois, 2007)

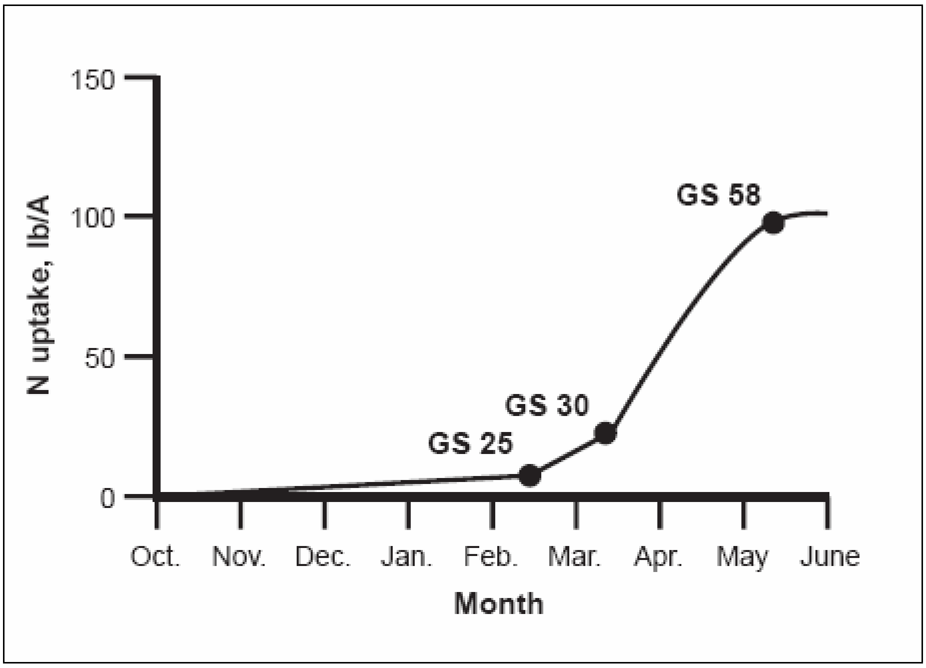

Figure 2-2 N uptake of winter wheat (Alley et al., 1996)

From the Figure 2-2 is evident that the nitrogen management has to ensure that the different requirements for nitrogen during the growth will be satisfied. In order to do so, several techniques have been developed as it is given in following material.

2.1.2 Nitrogen fertilisation strategies used

To be able to optimize the amount of Nitrogen applied, the determination of the crop characteristics, which are used to determine the dose, is essential. Within cereal husbandry there are several techniques which have been used to accurately determine the amount of nitrogen needed by the crop.

The general approach, which is common for winter wheat nitrogen management in many countries, is based in the principle to split the nitrogen dose into four below mentioned applications (Alley et al., 1996; Ložek, 1998). However, the autumn fertilising is omitted in some countries.

- Autumn – to establish the crop and promote the production of fall tillers.
- Early spring – to encourage the development of the crop after winter, the initial N fertilizer application should be as near to the initiation of growth as it is possible. It is important, however, to realize that fields with low tiller numbers should receive the first N applications so that spring tiller production is not delayed due to a lack of plant-available N.
- then the main dose – at GS 30 where the rapid growth starts and so the rapid Nitrogen uptake,
- late application to encourage the protein content in the grain

To estimate the absolute dose, nitrogen concentration in plants in connection with dry matter of plants has been used (Ložek, 1998). The methodology gives exact rates of nitrogen to be applied for Slovakian conditions. The first two applications are based on soil nitrogen available and the nitrogen needed to get certain yield, the later two are based on the plant density combined with nitrogen % content in plants.

The recommendation after Alley et al. (1996) is based on tiller density for early spring fertilisation, and the percentage of Nitrogen in plant tissue for later applications (Figure 2-3).

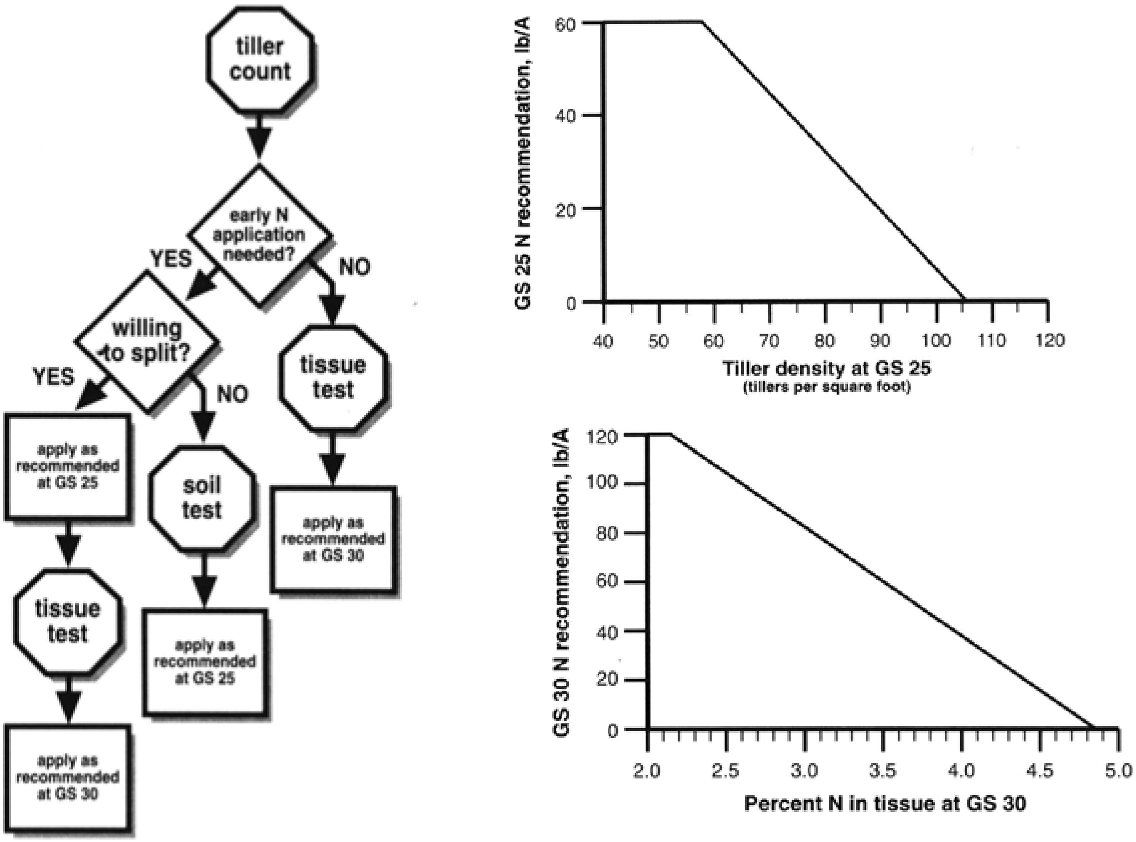

Figure 2-3 Recommendation of nitrogen rates after Alley et al. (1996)

Another approach, used in the UK is based on determination of canopy size. The amount of N is calculated on the base of current canopy size and N in soil (HGCA, 1997) (While: The crop canopy comprises the green leaves, leaf sheaths, stems and ears). Optimum canopy size for wheat growth is estimated to be around six units of green surface per area of ground (or units of Green Area Index – GAI). Variety and plant population determine target the shoot number. Nitrogen management is then used to get the target GAI (HGCA, 2000). To measure the canopy size, expressed as Green Area Index, several destructive and non destructive (SunScan sensor and other) methods can be used (HGCA, 1997).

The above mentioned methods are exact methods to estimate the rate for a given crop. However, they are time consuming and are usually used in practical farming to determine an average rate for the whole field, which would be then applied uniformly.

However, “Precision Agriculture” techniques, which respect the spatial variability of the crop, may have advantages. Here, the rate of nitrogen needs to be determined for a large number of sites in a given field. Therefore new tools to assess spatial variability of the crop nitrogen requirements need to be used. Remote sensing data are then used as a surrogate, which is calibrated by crop characteristic mentioned above (Wood et al., 2003a). The next chapter is aimed to this site specific approach to nitrogen management.

2.1.3 Site specific approach to optimize nitrogen fertilisation

Precision farming (Precision Agriculture or Site Specific Management) is a technology aimed to increasing the productivity together with decreasing the costs, energetic inputs and mineralising of negative environmental impacts. It is defined by many authors (Godwin et al., 2003; Hache, 2003; Frazen, 1999; Shibusawa, 2002; Ehrl et al., 2002; The Centre for Precision Farming, 2004; Rickman et al., 2003; Clark & McGuckin, 1996; Sudduth, 1999; Nozdrovický, 1999). All definitions could be generalised to: "*doing the right operations, in the right way, at the right place and time*".

Precision Farming technology in nitrogen management is based on estimating the accurate amount of nitrogen fertilizer in terms of the spatial variability within a field. Obtaining this information under or over fertilizing can be avoided (Figure 2-4). This is important from both economic and ecological point of view as well.

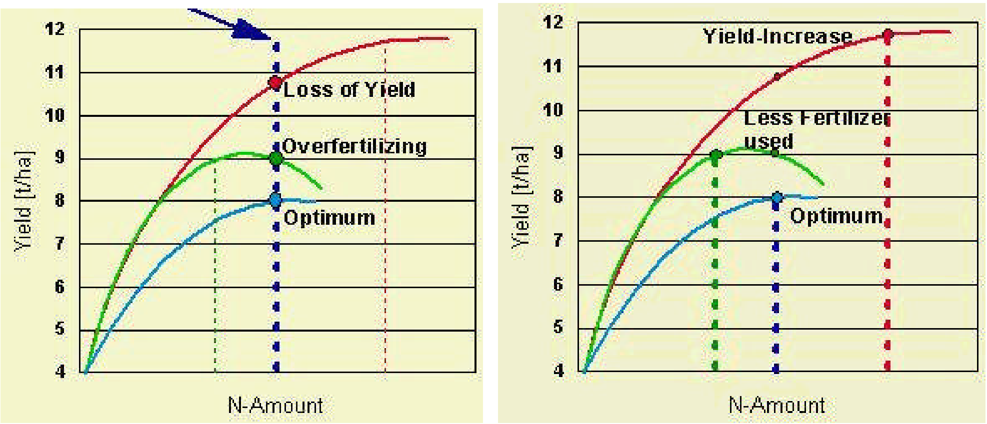

Figure 2-4 Uniform application (left) and Variable application (right) of Nitrogen (Jørgensen, 2002)

New technologies used to determine the spatial variability of crop are based on correlation of the data obtained with crop characteristics used in Nitrogen management (e.g. shoots number or nitrogen content). These data are then calibrated and are referred to the absolute values of nitrogen rates (Welsh et al., 2003; Wood et al., 2003b)

Since the precision agriculture technology was introduced, the research has been aimed to develop new techniques to determine variability in crop properties. The following techniques have been developed:

1. Laser detection: After Schächtl et al. (2005) the principle of laser –induced chlorophyll fluorescence measurement is that the laser light is absorbed by chlorophyll molecules which dissipate the energy by emitting fluorescence light. Authors reported exponential regression between measured values and N uptake. However, as for all measuring systems, the calibration has to be done, where mainly growth stage and cultivars are important parameters which have to be considered. Promising results were reported by (Bredemeier & Schmidhalter, 2005)

2. Crop density and crop resistance sensors (Ehlert et al., 2004) and others have been developed and used currently as well. Ehlert & Adamek (2005) have reported the measurements conducted with mechanical sensor based on physical pendulum, the coefficient of determination was 0.89 for relationship between crop biomass density and the pendulum angle in winter wheat.

3. Radiometers and ultrasonic sensors were used to determine the tiller density and Leaf Area Index (LAI) by Scotford & Miller (2005). Authors used NDVI values together with ultrasonic measurements of height of the crop to create compound vegetation index. The relationship between this index and LAI for winter wheat grown over two seasons reached the R^2 of 0.77. This combined sensing approaches enabled winter wheat to be monitored throughout the growing season, beyond the GS 31 (which has been the limit of traditional spectral reflectance technique). Using this enabled to estimate both tiller numbers and leaf area index to be made without the need of direct ground calibration in the two following seasons.

4. Christensen et al. (2005) introduced the prediction of nitrogen status in wheat under the influence of water deficiency using spectral and thermal information. Authors reported very high prediction ability of crop nitrogen concentration. Identification of water deficiency zones in a given field is crucial before predicting the actual nitrogen content.

5. Spectral reflectance approach, which has had the widest use, is review in the following chapters. The types and platforms of remote sensing system are now reviewed.

2.2 Remote sensing

Remote sensing is defined as acquisition and recording of information about an object without being in direct contact with that object (Gibson, 2000). It is based on the theory of reflectance which is well known and described in several works. In order to understand application of remote sensing technology in agricultural practice together with its opportunities and limitations, it is necessary to understand the basic theory and physical principles. This section describes a basic theoretical overview concerning the remote sensing of vegetation and soil. It is explained which factors need to be considered together with the basic systems and platforms for remote sensing are also described.

2.2.1 Theory of remote sensing

Remote sensing has its physical principle in the theory of electromagnetic spectrum (Figure 2-4) and reflectance of particular wavelengths of this spectrum.

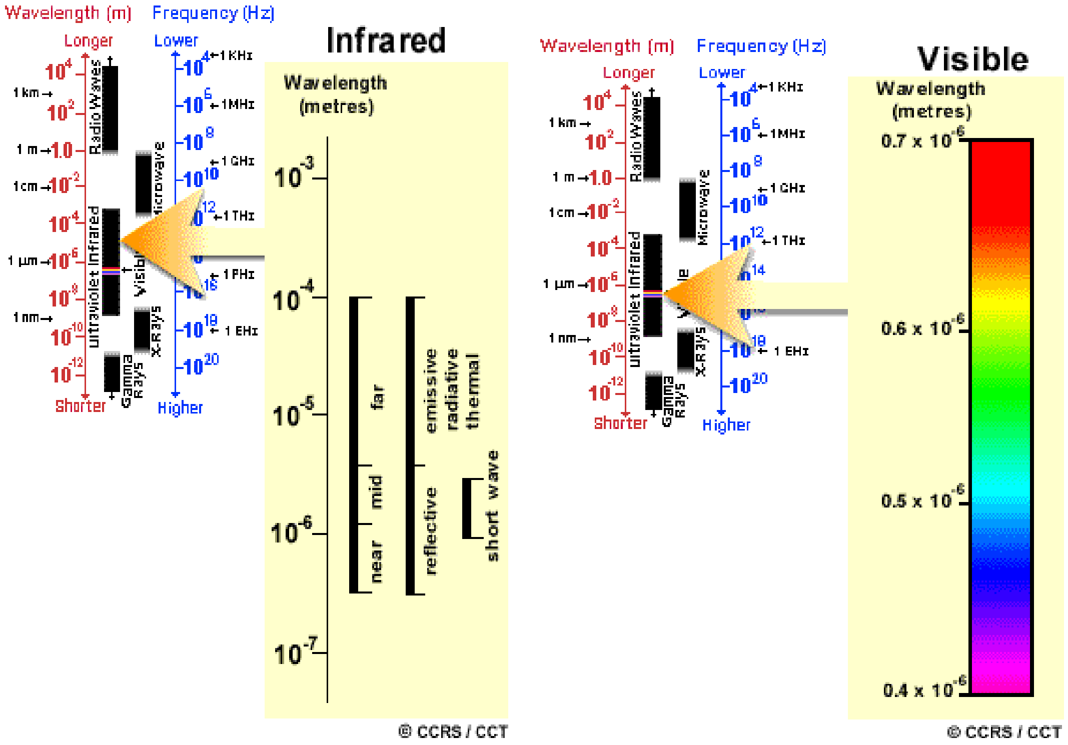

Figure 2-5 Electromagnetic spectrum (CCRS, 2006)

Electromagnetic radiation occurs as a continuum of wavelengths and frequencies from short wavelength, high frequency cosmic waves to long wavelength, low frequency radio waves. The primary physical quantities that can be estimated from remote sensing images constructed from electromagnetic radiation (EMR) are: spectral reflectance (optical remote sensing), surface skin temperature or brightness temperature (thermal remote sensing), back-scatter coefficient (microwave remote sensing). The wavelengths that are of the greatest interest in remote sensing of canopy are visible and near infra red radiation in waveband 0.4 - 3µm (Figure 2-5).

As the energy hits the surface it can be absorbed, reflected or transmitted (Figure 2-6). The degree of each is determined by specific wavelength of the radiation and the physical properties of the body. As a result profiles of surface reflectance can be obtained (Figure 2-7).

Figure 2-6 Reflected, absorbed and transmitted energy

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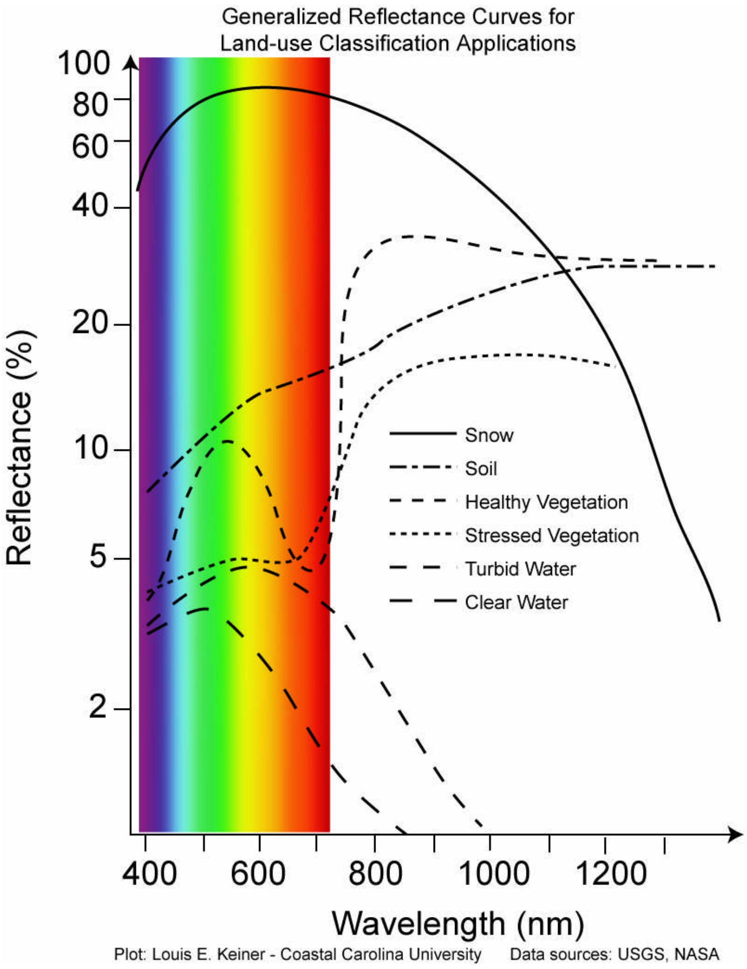

Generalized Reflectance Curves for Land-use Classification Applications

Plot: Louis E. Keiner - Coastal Carolina University   Data sources: USGS, NASA

Figure 2-7 Reflectance curves of several objects (Keiner & Gilman, 2007)

The spectral response of vegetation (Figure 2-7) primarily depends upon the structure of plant leaves. The leaf consists of layers composed of different types of cells (Figure 2 - 8). The cells containing chlorophyll pigment called chloroplasts are responsible for the green appearance of healthy living vegetation. All the colours of visible electromagnetic radiation except green are absorbed, the green is reflected back and the leaf therefore appears green. Other wavelengths of electromagnetic radiation including the infrared are absorbed by this layer too. However, the cells which make the body of the leaf (mesophyll cells) reflect about 60 % of the NIR radiation reaching this leaf layer. Healthy vegetation therefore has a higher and brighter response in the NIR than in the green part of the spectrum. As a leaf dies, cells lose their green pigment. Red and blue light therefore are no longer absorbed by these cells and are reflected back along with the green, and thus dead and dying vegetation appears yellow and brown. Near infrared wavelengths are no longer reflected but are absorbed appear dark or black in the NIR (Gibson, 2000).

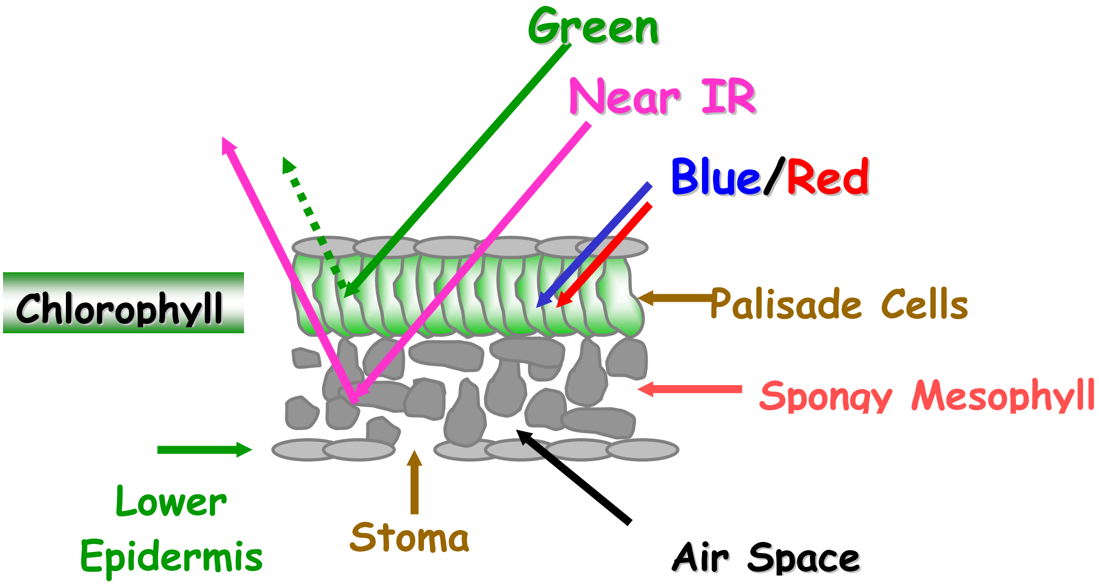


Figure 2-8 Leaf structure (Schepers, 2005)

It was reported by Colwell (1974) that the vegetation canopy reflectance is influenced by (a) leaf hemispherical reflectance and transmittance, (b) leaf area, (c) leaf orientation, (d) hemispherical reflectance and transmittance of supporting structures (stalks, trunks, limbs, petioles), (e) effective background reflectance (soil, rock, leaf litter), (f) solar zenith angle, (g) look angle, and (h) azimuth angle. Pinter et al. (1985) reported that reflectance of excised single leaves from each cultivar of winter wheat were much higher than those observed for the canopy as a whole. Similar results were achieved with maple by Yoder, & Pettigrew-Crosby (1995).

There are significant differences in reflectance of canopy with different structure. Research results presented by Pinter et al. (1985) showed that reflectance of all wavebands were usually higher for planophile than for erectophile canopies of winter wheat varieties. Influence of dew, topography and sensor view angles were also well examined (Pinter et al., 1983; Pinter, 1986, Pinter et al., 1987). The spectral signature obtained by the sensors on remote sensing systems is often a combination of vegetation and soil. In such a situation, the proportion of soil to vegetation cover will greatly influence the resultant signature. The presence of moisture reduces the reflectance across wavelengths. Organic rich soils tent to have a lower reflectance than organic-poor soils (Gibson, 2000). Influence of soil background to canopy spectral reflectance was well examined and described e.g. Broge & Mortensen (2002).

To estimate crop characteristics by remote sensing data, reflectance of selected wavelengths (mostly combination of red and infrared wavelengths) is often transformed to vegetation indices which are well used in praxis. The first of them were introduced in 1960, since then numerous spectra vegetation indices were developed and empirically related to percent plant cover, leaf area and above-ground biomass (Wood et al., 2000). A vegetation index is calculated from the reflectance “ρ” in the red band (typically 0.6 to 0.7 µm) and the reflectance in the near-infrared (typically 0.8 to 1.0 µm). The following are examples of the most frequently used (Broge & Mortensen, 2002):

1. *RVI* (Ratio Vegetation Index) or *SR* (Simple Ratio), which reached value of 1 for soil up to 20 for dense crop.

$$RVI \equiv SR = \frac{\rho NIR}{\rho Red} \tag{1}$$

where: ρNIR reflectance in NIR, %
ρRed reflectance in red area, %

2. The most common is *NDVI* (Normalized Difference Vegetation Index), where the values is in the range form 0 to 1. Typical values of *NDVI* are for soil 0.1 and for dense crop 0.9. The NDVI is more sensitive for more thin crop that the *RVI.*

$$NDVI = \frac{\rho NIR - \rho Red}{\rho NIR + \rho Red} \tag{2}$$

3. The Soil-Adjusted Vegetation Index (SAVI):

$$\frac{\rho \mathrm{NIR} - \rho \mathrm{Red}}{\rho \mathrm{NIR} + \rho \mathrm{Red} + \mathrm{L}} * (1 + \mathrm{L}) \tag{3}$$

This index resembles the NDVI with some added terms to adjust for different brightness of background soil. In principle, the term L can vary from 0 to 1 depending on the amount of visible soil. However, 0.5 works as a reasonable approximation for L when the amount of soil in the scene is unknown.

Correlations between these two sources of data (remote sensed and crop characteristics) have been examined by several researches. Possibilities of determining crop characteristics from remote sensing data were demonstrated. Other scientists concern to find the best fitted equation to describe this relationship. Overview of some findings is below.

Scotford & Miller (2004) demonstrated the possibility to determine LAI and tiller density of winter wheat from remote sensing data, Aparicio et al. (2002) explored relationship between Growth Traits and Spectral Vegetation Indices in Durum Wheat, Wiegand et al. (1992) carried out a multi-site experiment aimed to assess several vegetation indexes in connection with winter wheat characteristics. Boegh et al. (2002) found that there is no correlation between nitrogen concentration and canopy reflectance, but strong correlation with green leaf area index. There is also strong relationship of NDVI with areal nitrogen content of the canopy. The airborne reflectance data in the maximum reflectance bands (550.7nm and 710.9nm) were identified as the most important predictors of canopy nitrogen concentrations on the mass basis. Because the contribution of soil to the far-red reflectance is generally larger than to the green reflectance (r^2=0.78 for ρ550). Serrano et al. (2000) studied the relationships between reflectance based vegetation indexes and canopy variables for wheat. Their research showed that the relationship between NDVI (NDVI = (R_{900} – R_{680})/(R_{900}+R_{680})) and Leaf area index was curvilinear, the relationship between simple ratio SR (SR = R_{900}/ R_{680}) and LAI was linear. As authors report the NDVI demonstrated to be a more sensitive index for low LAI canopies, while SR still increased with increasing LAI. Neither SR nor NDVI showed significant correlation with aboveground biomass. However, both vegetation indexes were significant correlated with leaf Chlorophyll A concentration. Moreover, when expressing the canopy variable as LAI x Chlorophyll A, the degree of correlation increased substantially. Broge & Mortensen (2002) reported that the relationship among all vegetation indexes and the greenness parameter (Green crop area index - GCAI or Canopy chlorophyll density -CCD) were best described by an exponential function, except for the RVI relationship with GCAI. Francis et al. (2004) examined the relationship between crop circle sensor output (NDVI) and chlorophyll content, the R^2 was approximately 0.9, the information were used for controlled application of nitrogen. There were several research works investigating the reflectance of crops under different nitrogen treatments carried out. Hinzman et al. (1986) examined the effect of Nitrogen Fertilization on Growth and Reflectance Characteristics of Winter wheat, where the NIR and the IR/NIR and the greenness index performed to be best for discriminating treatment levels.

The limitation of vegetation indices was also explored. Scotford & Miller (2005) reported that these indexes (calculated from reflectance values of each side of the red edge) are sensitive enough only until the canopy closure, when the crop reaches the leaf area index up to three. Once the canopy closure occurs the response of the vegetation index tends to be relatively flat and any differences in the canopy are not easily measured. In attempting to overcome these limitations, instruments capable of measuring a range of wavelengths are used (for example data which can be used for calculating the shift in the red edge). Selection of the correct wavelengths and bandwidths is also important (Hansen & Schjoerring, 2003). These authors showed that in connection to NDVI the short bands (5 - 10 nm) perform better than broad-bands (>

50nm) using standard Red/NIR and Green/NIR and NDVIs). They reported that more variations are explained if the indices are used in an exponential relationship to the crop variables.

As mentioned above, measurements in visible and NIR region of electromagnetic spectrum for agricultural studies are used. Except of vegetation indices, shifting of “red edge inflex point (REIP)” can be used. The “red edge inflex” point is the point where the electromagnetic spectrum changes from visual to near infra red at a wavelength of approximately 700nm (Scotford & Miller, 2005). REIP symbolizes the boundary of the chlorophyll absorption feature and moves to longer wavelengths with increasing chlorophyll content, which leads to a high correlation between the REIP and leaf chlorophyll content (Boegh et al., 2002). For its determination a three-degree polynomial equation can be fitted to the spectral reflectance data. The wavelength position where the fitted polynomial has its maximum slope is REIP. After Broge & Mortensen (2002) REIP can be defined as the wavelength where the first derivative of the spectral reflectance is the maximum. REIP shifts towards shorter wavelength (blue shift) are associated with decrease in green vegetation density, just as REIP shifts toward longer wavelengths (red shifts) are associated with increase in green plant material.

2.2.2 Types of remote sensing systems

There are two basic types of remote sensing system: passive and active as shown in Figure 2-9.

Passive measures naturally emitted energy (from the Sun, the Earth)**.** Radiation from the Sun interacts with the surface (for example by reflection) and the detectors aboard the remote sensing platform measure the amount of energy that is reflected (Gibson, 2000). An active remote sensing system carries onboard its own electromagnetic radiation source. This electromagnetic radiation is directed at the surface and the energy that is scattered back from the surface is recorded (Gibson, 2000). As the energy source for the active sensors laser diode, Light emitting diode and Xenon lamps can be used (Reusch, 2005)

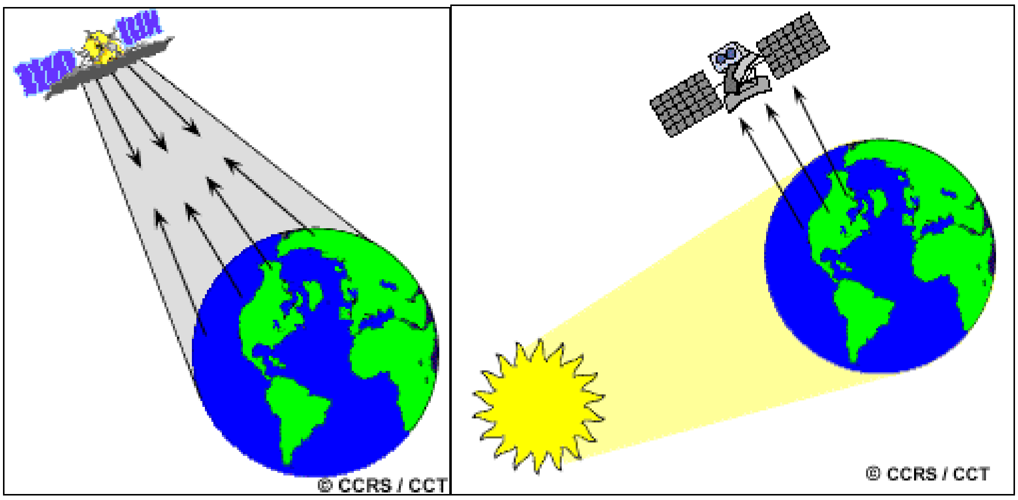


Figure 2-9 Active and passive remote sensing system (CCRS, 2006)

2.2.3 Remote Sensing platforms

For collecting spectral reflectance measurements radiometers, spectrometers or spectroradiometers and digital cameras fitted with optical band pass filters can be used. These can be mounted on a variety of either satellite, aircraft or ground based platforms. Advantages and disadvantages of each platform are summarized in Table 2-1 (Scotford & Miller, 2005).

Table 2-1 Summary of the main advantages and disadvantages of different sensing platforms (Scotford & Miller, 2005)

Parameter	Space	Aerial	Ground
Area covered per scan	Area scanned increases with height of platform		
	typically km^2	typically m^2	typically cm^2
Spatial resolution	As platform height increases resolution coarseness increases		
	1-30 m^2	0.05 – 2 m^2	mm2 to cm^2
Temporal resolution	weeks	days	hours
Affect of cloud cover	Influence of cloud increases with platform height		
	Heavy influenced	Moderately influenced	Not influenced
Affect of illumination conditions	Influence of local illum. conditions decreases with platform height		
	Not affected	Moderately	Heavily
Availability of data to end user	Long delays	Some delays	No delays
Control od end used	Limited	Some control	Full control

Satellite platform

Begiening et al. (2005) introduced the CHRIS (Compact High Resolution Imaging Spectrometer) carried on board a platform called PROBA. They reported that the first analyses of CHRIS data demonstrated that it is possible to extract valuable crop and soil information from space borne hyperspectral data.

Airborne platform

Wood et al. (2003a, 2003b) demonstrated the possibility of airborne data us in cereal production. Images can be obtained using either radiometers or digital cameras. Radiometers produce an electrical signal proportional to the light energy to which it is exposed. The light is filtered to ensure that the radiometer is exposed only to the specific wavelengths required. Digital cameras can be fitted with optical band pass filters (Scotford & Miller, 2005a).

Morris (2006) reviewed the arguments in favour of using aerial images:

- the flexibility of being able to arrange flights at short notice, as required by husbandry considerations,
- the high resolution of the images ,
- the ability to map significant areas quickly and economically,
- the results can be available in a short period of time, (a few days).
- the farmer has some control over the system,
- it is often possible to repeat the taking of images on a short time scale. Arguments against the use of aerial images:
- taking images require clear conditions,
- there is a delay between the images being taken and the farmer receiving them,
- the cost of using an aircraft makes this platform uneconomic for small areas,
- the need to ground calibrate the images.

Aerial sensing is normally organised and the data processed by specialist companies, and the potential for large-scale utilisation of the technology exist (Morris, 2006). Experience from the NI Precision Agriculture project of trying to obtain aerial images from 2001 to 2004 indicated that a combination of cloud cover, mist and availability of suitable cameras made aerial remote sensing impractical under NI conditions (Wilson, 2004). However, there are applications at the market currently as it is described in Section 2.3.2.

Ground based platform

Ground based systems (both active and passive) are currently common for precision agriculture application. They could be used as hand –help, or mounted on a boom. Rundquist et al. (2004) pointed that it is preferable to use sensors as boom mounted rather than hand held because using hand held system for gathering data there is a high variability on reflectance expected and as a result, error in estimating the biophysical characteristics of vegetation could appear. Their results showed that for the NIR reflectance, the standard deviation for hand-held datasets ranged from about 4 to 10%, while those for the boom-collected datasets were between 1 and 2%. Thus, the CVs for the boom-collected datasets were 3-5%in the NIR, but between 15 and 35% for the hand-held samples. Practical application along with the working principle is given in Section 2.3.3.

2.2.4 Introduction to application of Remote Sensing in Agriculture

As it was already mentioned above, precision farming is based on using the inherent spatial and temporal variability in a field as a basis to manage farm operations (Alchanatis & Schmilovitch, 2005). Real time management is essential for determining crop characteristics, which need immediate response (N deficiency, weed control). Remote Sensing is a technology which can allow real-time respectively near-real-time management. Along with these advantages, accuracy of determining these indicators together with variable application of fertilisers or chemicals offers an opportunity to reduce input costs and any negative environmental impact (Godwin, 2003a).

The use of Remote Sensing in precision farming technology is wide; it depends on the platform and system of RS used. Remote sensing systems are used to for determine yield (Freeman el al., 2003; Aparicio et al., 2000). Other applications are in assessing N deficit, weeds, water stress and so on (Scotford & Miller, 2005; Yang et al. 2005; Moran et al., 1997; Tian, 2002; Goel et al., 2003; Barnes et al., (2000), Wood et al., 2003b). Recently experiments were conducted with changes in reflectance of winter wheat in response to macronutrient deficiency (Ayala-Silva & Beyl, 2004), where these data results can be used as an indicator of N, Mg, and Fe deficiencies. However, distinguishing among individual nutrients could be difficult.

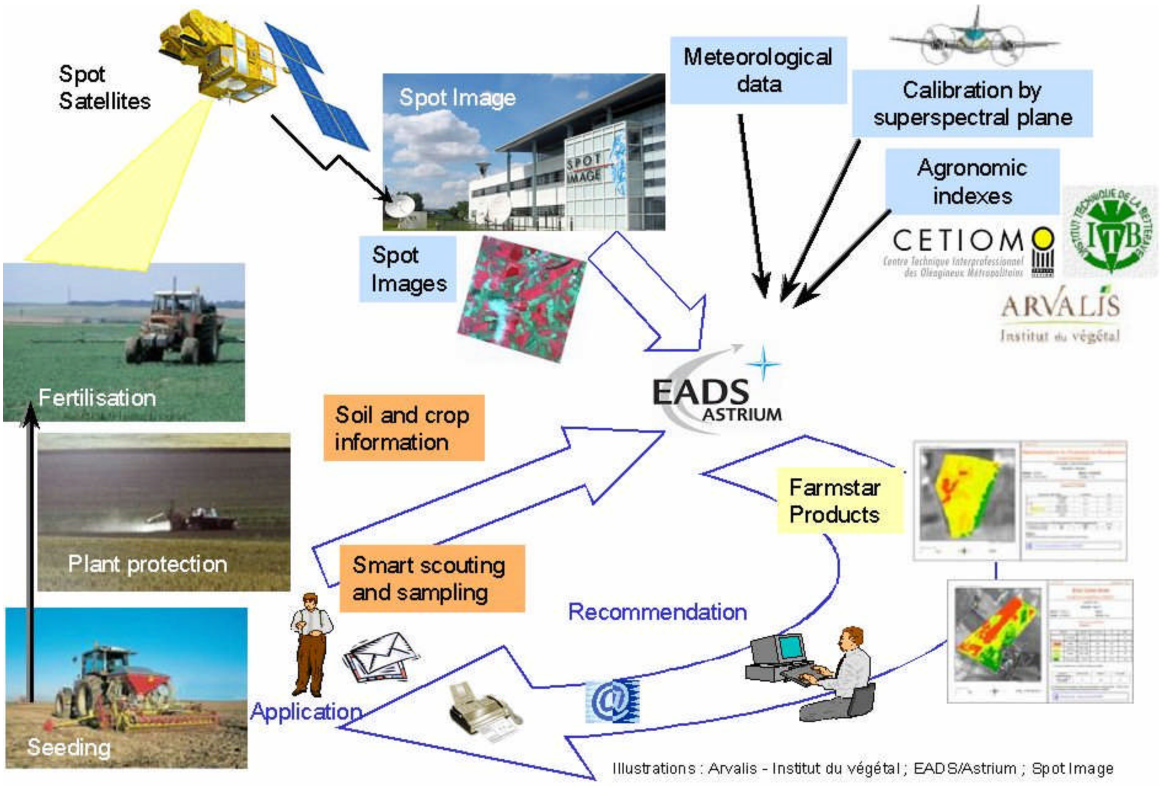
Remote sensing technology is used to determine characteristics of several crops. Mostly grain crops (winter wheat and barley) need to be mentioned (Alchanatis & Schmilovitch, 2005 and others). Relationship between Nitrogen (in Maize plants and in soil) with canopy reflectance described Diker & Bausch (2003) and Daughtry et al. (2000). It was shown that between Nitrogen in maize plants and the Nitrogen reflectance index is linear relationship with $r^2 = 0.78$. Data collected in this research showed that using the 75° view angle was better rather then nadir. Examples are in growing cotton (Zhao et al., 2005), potatoes (Jongschaap & Booij, 2004) and remote sensing assessments to predict the yield and the LAI of alfalfa with greater precision than visual assessments (Guan & Nutter, 2002).

2.3 Practical applications of remote sensing used in nitrogen management up to date

2.3.1 Satellite platform

FARMSTAR

FARMSTAR uses satellite and airborne data, agronomic models and meteorological data to provide timely field-level maps for crops such as winter wheat, barley, oilseed rape, sugar beet and potatoes. The system extracts from satellite images, biophysical parameters such as Leaf Area Index or chlorophyll content at specific growth stages of the crop (Coquil & Borders, 2005). The map-products are designed to provide information at critical growth stages to guide the use of inputs such as plant growth regulator and nitrogen, and aid general farm management decisions (Figure 2-10). FARMSTAR is used in France by more than 10,000 farmers in 2006, and is expanding rapidly in Europe and the world with users in United-Kingdom (FarmStar service was demonstrated over 10,000 ha of wheat, barley and oilseed rape in the UK - Cambridgeshire, Lincolnshire, Berkshire, Oxfordshire, Nottinghamshire and Yorkshire), Spain, Brazil, Argentina. (Infoterra, 2007; Spotimage, 2007). The scheme for winter wheat husbandry is given in Figure 2-14.



Illustrations : Arvalis - Institut du végétal ; EADS/Astrium ; Spot Image

Figure 2-10 The overall system of FARMWORK (Spotimage, 2007)

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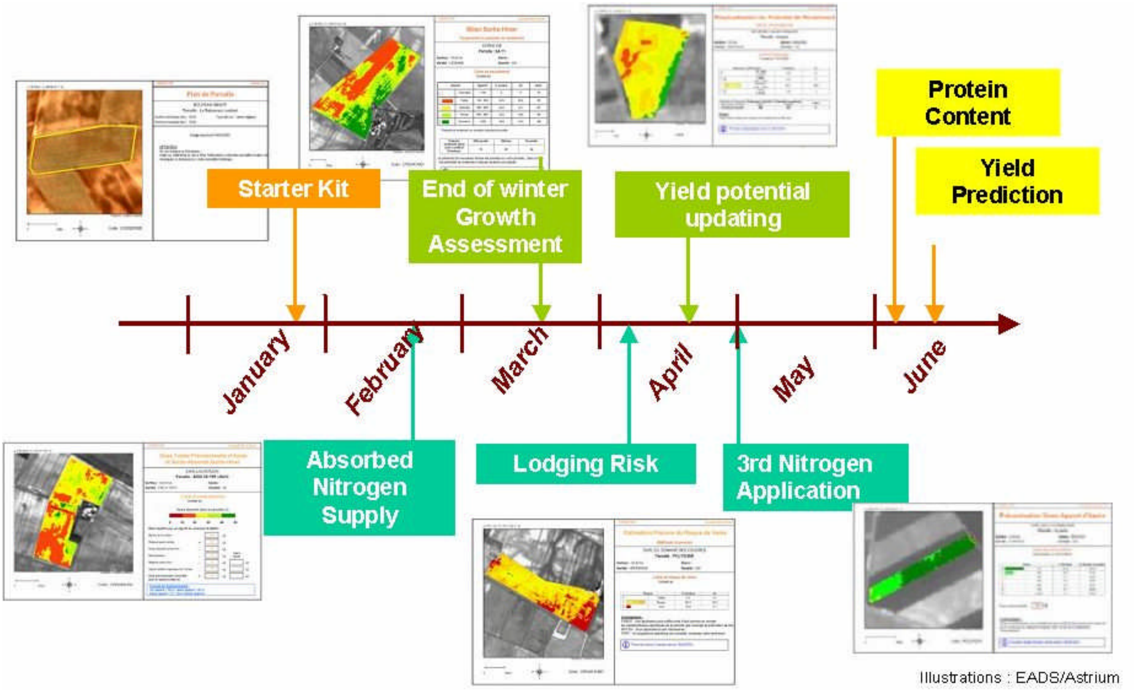


Figure 2-11 Calendar of Farmstar products for winter wheat (Spotimage, 2007)

The company reports, that savings are not systematic but whenever possible they cover the price of the service which is approximately 10 €/ha for wheat. For wheat, an estimate of the average increase in gross margin compared to an equivalent uniform application can be made, giving an estimated increase of about 25 to 35 €/ha. For rapeseed, precise calculations made by the Epis-Centre cooperative following the 2003 campaign led to increase in gross margin (53 €/ha on average, where 83 €/ha for heterogeneous plots) and a reduction in nitrogen budget (Spotimage, 2005)

Coquil & Bordes (2005) reported that base on research made at 600 farms using the FARM STAR system, 88 % indicated saving on Nitrogen of 25 – 50 kg.ha^{-1}.

SOYLsense (SOYL)

The satellite services have improved with a greater frequency of over flights at costs similar to those suggested by Godwin et al. (2003b) for aerial images. As a result, a commercial provider, SOYL, (http://www.soyl.co.uk) undertook a study in 2004 where fields on a series of 10 farms were split into two halves; one half received a uniform application of nitrogen and the other a spatially variable amount applied using the principles recommended by Godwin et al. (2003a), where 9 out of the 10 fields returning a positive benefit from the spatially variable application of nitrogen and an average benefit of £24/ha (Figure 2-12) (Godwin, 2007) .

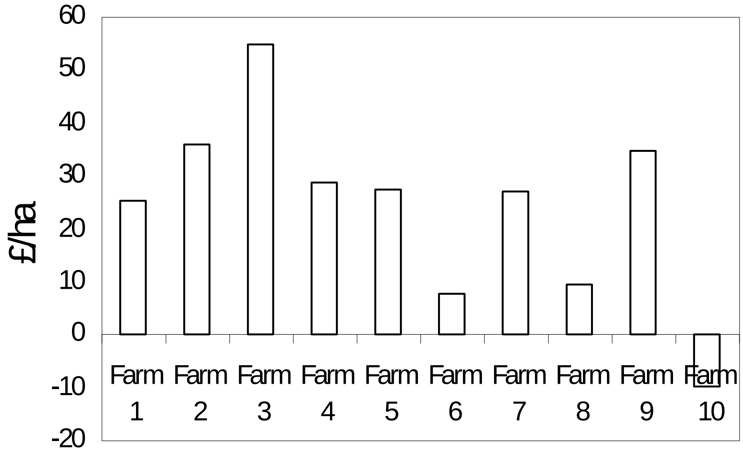


Figure 2-12 Economic benefit of variable nitrogen study conducted in the UK by SOYL.

This commercial service creates crop canopy maps at growth stages 24, 31 and 36. These can be used to target field walking where crop development is behind. Using the HGCA Winter White Canopy Management guidelines, nitrogen application maps are produced (Figure 2-13).

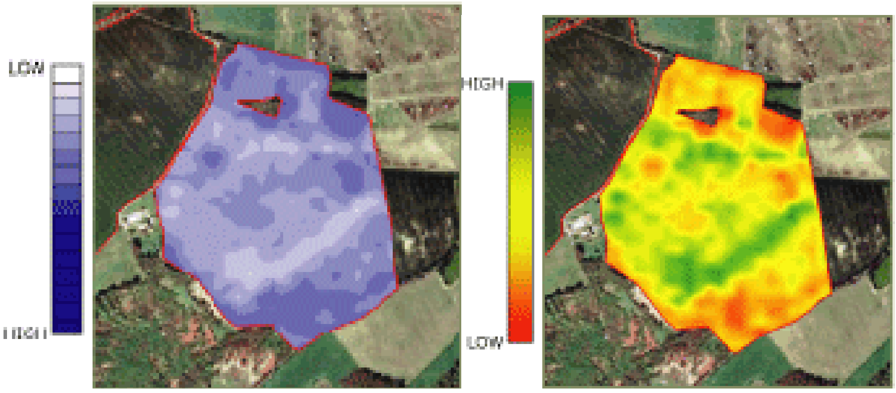


Figure 2-13 Application map and map of biomass provided by SOYL

SOYLsense costs from £4.00 to £7.50 per hectare, the company reported benefits of £15 per ha in 2004, £24 per ha in 2005 and £25 per ha in 2006 (SOYL, 2007).

2.3.2 Airborne

The effectiveness of airborne images use in nitrogen management was proved in a HGCA project conducted at Cranfield Univesity at Silsoe by Godwin, Wood and others in 2003 the commercial application of this technique have not been adopted in Europe. However, the service ***"Nitrosensing"*** as a part of PREFARM system of MJM Litovel (Czech Republic) (http://www.mjm.cz/HTML/prefarm.html) is a contractor in this area (MJM Litovel, 2007).

Figure 2-14 Aerial system Nitrosensing (MJM Litovel, 2007)

This system use aerial photography (Figure 2-14) taken from 3 to 10 days before the planned fertiliser application. Data are processed and analysed within 48 hours. As a result company provides application maps (MJM Litovel, 2007).

2.3.3 Ground based remote sensing sensors used up to date

Previous chapters described theoretical principles of remote sensing systems generally, together with detail description of RS of crop canopy and determining crop variability. The application of remote sensing in Nitrogen management was introduced in the previous sections. Ground based remote sensing sensors used up to date, with their technical description and working principles, are described in the following chapter.

2.3.3.1 Passive ground based remote sensing sensors

N sensor (Yara)

The N sensor (Field Scan) consists of two diode-array spectrometers, fiber optics and a microprocessor in a rugged housing mounted on the top of the vehicle's roof (Figure 2-15 and 2-16). There are 4 units scanning the reflected light from the crop and another one on the top of sensor measuring the ambient light. Typically an area of approximately 50-100 m² is measured per scan. Viewing Geometry has been designed to meet the following criteria at the same time (Reusch et al., 2003)**:**

- measure a large area (see Figure 3-6),
- have a field of view outside the shadow area of the vehicle,
- avoid large booms etc. to carry the optics and
- be independent of driving, viewing and solar direction.

Figure 2-15 N sensor configuration

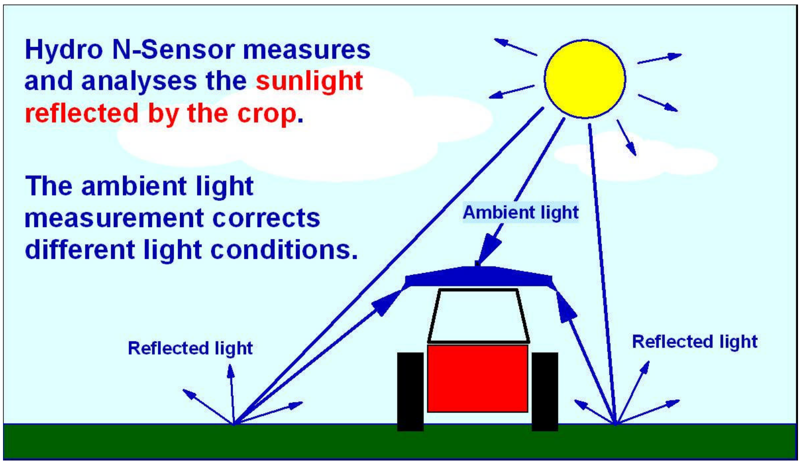
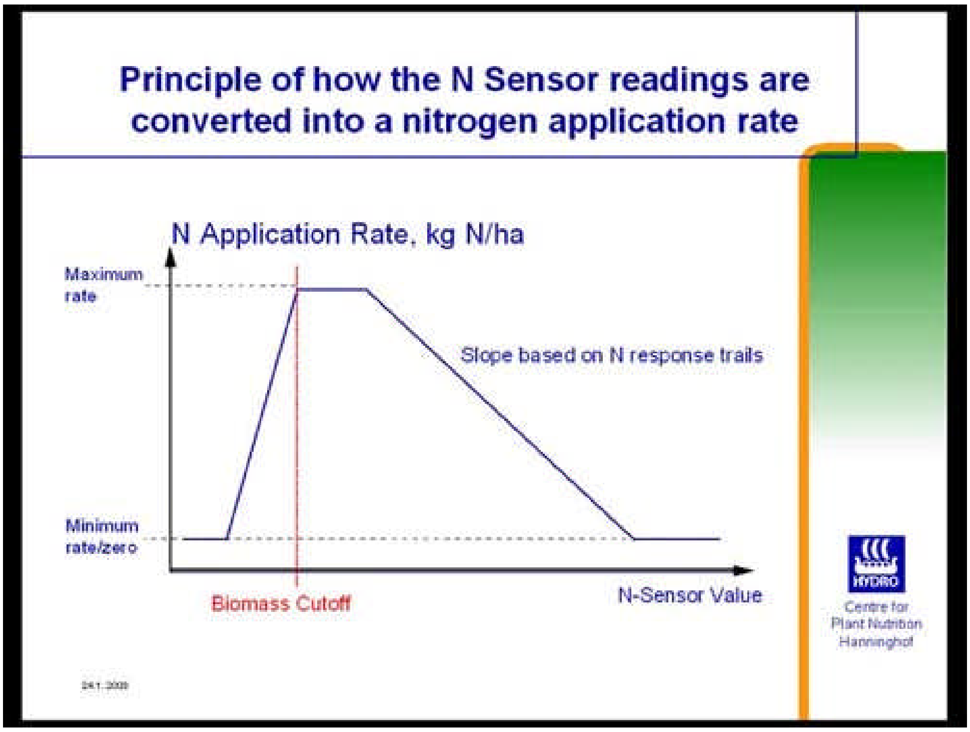


Figure 2-16 Principle of measurement with N sensor (Yara, 2005)

The reflectance at 20 (five user-selectable) wavebands in the 450-900 nm region with a width of 10 nm from four spots located around the vehicle is measured. Wavelengths have been placed in the local green maximum (550 nm) and distributed across the so-called "red edge" (670, 700, 740 and 780 nm). This allows the calculation of all well-known spectral indices like NDVI, SAVI, IR/R, IR/G and the Red-Edge-Inflection-Point (REIP).

Irradiance correction is provided through the reference spectrometer sensing the sky hemisphere in the same wavebands. Though the crop is scanned at an oblique view zenith angle (64° on average), solar azimuth effects are largely avoided by the special viewing geometry. The system is controlled by a user terminal mounted inside the vehicle's cabin. Data is stored on a memory card together with positioning information at a repetition rate of typically 1 second. It can easily be retrieved from the card as simple ASCII data to be further processed in any available GIS package.

N sensor (Field Scan) can work in several operational modes, mode Scanner enable to obtain data of selected wavelengths (where 5 are changeable) reflectance and it is used especially for research purposes. For practical use mainly the mode N application is available, where the sensor on the base of calibration curves (Figure 2-17) and connected to VR applicator is able to manage VR fertilisation.



Principle of how the N Sensor readings are converted into a nitrogen application rate

Figure 2-17 N fertilising curves (Yara, 2005)

Experiences with fertilisation of wheat, barley, maize, potato, onion and oil seed rape are published up to date (Yara, 2006). Feiffer et al. (2003) reported that using the N sensor yield was offset in terms of variability and except of other benefits the efficiency of combine harvesters during the harvest was increased.

Company Leading Farmers (a dealer of N sensor in Czech Republic) reported yield increase of 5% where the N sensor was used (LeadingFarmers, 2006). The results of Ebertseder et al. (2005) confirm the suitability of using N sensor, as the yield was optimal in all fields, however, they recommend improving this technology using the sensor in combination with soil characteristics.

2.3.3.2 Active ground based remote sensing sensors

GreenSeeker (NTech Industries)

GreenSeeker (Figure 2-18) is an integrated system of optical sensor and application system for applying nitrogen. The Unit generates light at two specific wavelengths and measures the light reflected off the target (typically plants in soil). The GreenSeeker^{TM} active lighting optical sensor uses high intensity light emitting diodes (LED's) that emit light at 660 nm (red) and 780 nm (NIR) as light sources. These

LED’s are pulsed at high frequency. The magnitude of the light reflected off the target is measured by a photodiode detector. Electronic filters remove all background illumination. Magnitude of the filtered signal is measured by a multiplexed A/D converter. Measurements are accumulated and averaged over the 0.61-m sensing and treatment distance. The computer calculates reflectance values for red and NIR and calculates the normalized difference vegetative index (NDVI). The sensor is temperature stable.

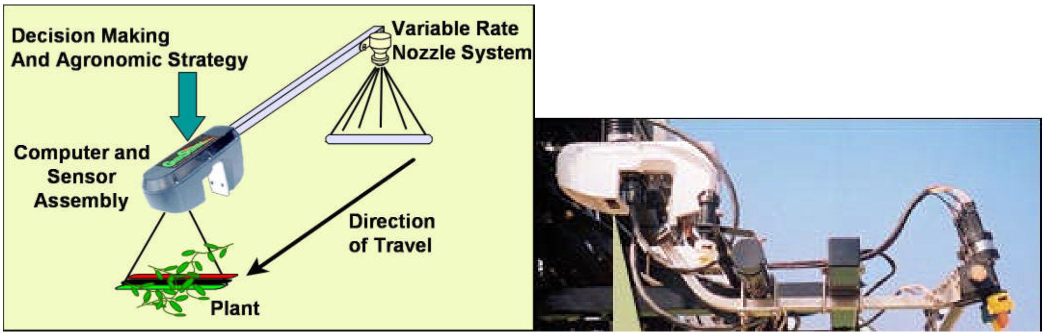


Figure 2-18 Fertilising systems using the GreenSeeker

GreenSeeker sensors have a 0.6m field of view. Optimal sensing height is 0.8 – 1.2 m above the plant. The percent of area coverage you get from each mapping system depends upon the spacing and number of sensors used. The data from the Sensor is transmitted serially to an HP iPAQ, and can later be exported to a desktop computer for analysis. The sensor calculates application rates and determines the combination of the three valves needed to apply that rate. The computer sends this information to a second computer located in the valve control module attached to the sensor. That computer controls the valves (NTech Industries 2005).

Osborne et al. (2007) reported initial results with Greenseeker. Sensor readings (NDVI) collected at Feekes 6 (GS 31) and Feekes 10 (GS 45) showed a significant relationship with plant biomass, N uptake and grain yield, with readings collected at the later growth stage having higher correlation compared to the early sampling date. Authors suggest that existing sensor-based variable nitrogen technology developed for winter wheat could be utilized for estimating in-season N need for spring wheat, but additional testing is necessary. Company “Crop Optics” in Australia reported that the GreenSeeker® system maximizes return on investment in nitrogen. If ideal growing conditions promise a high yield, enough N is applied to achieve that yield. If the environment will not support a large yield, nitrogen will not be wasted. They published that testing has proven that GreenSeeker® generates \$8 to \$10 additional return per acre for winter and spring wheat (on average), and an \$18 per acre average for corn. This is based on higher yields and/or reduced N costs. Research and field data also indicates that some years the savings would be double these amounts (Crop Optics, 2007).

Crop Circle (Holland Scientific)

Crop Circle sensor ASC 210 (Figure 2-19) is the light sensor that can measure plant canopy reflectance on- the-go. It can be mounted at any type of vehicle as well as it can be use as hand-held. Unlike other radiometric light sensors, the Crop Circle ASC-210 is not limited by ambient lighting conditions. It incorporates its own light source technology called PolySource^{TM}. This technology simultaneously emits visible and near infrared from a single LED (light emitting diode) light source. Two sensor models are available: providing yellow/NR (590 and 880 nm) and red/NIR (650 and 880 nm) sensing capabilities. A portion of emitted light from sensor to plant canopy is reflected back to the sensor, this portion is detected by an array of spectrally sensitive photo sensors. Additionally, by modulating the light source (rapidly pulsing the light source on and off many times a second), the ASC 210 can distinguish its own light signal from that of lighting conditions; cloudy skies, full sun, complete darkness or artificial lighting so these effects are minimized.

Figure 2-19 Crop Circle sensor and the GeoScount logger

Sensor can operate from 25 cm to 213 cm. The width of the projected beam when the sensor mounted height ***h*** above a target is defined by the following equation,

$$w = 2.h.\tan\left(\frac{\theta}{2}\right) \approx 0.57h \qquad (4)$$

Where:
θ - is the angular FOV in degrees (≈32 degrees for the ACS-210)
w – in the projected beam width
h – in the height of the sensor above the target

Sample output rate can be set up from one sample per second to 20 samples per second. The data are captured using laptop, PDA or other data acquisition device using a standard RS-232 interface. Data are stores in a comma-deliminated format. The sensor provides classical vegetative index as well as basic reflectance (Holland Scientific 2005a, 2005b, 2005c). Morris (2006) conducted an experiment to determine the maximum distance between successive passes of the sensor. This was undertaken by scanning a field at 4 m centres, estimating the NDVI and then deleting intermediate passes as shown in Figure 2-20. The data shows that the pattern for the variation in the field chosen starts to degrade at about 12 m wide pass widths. This result shows that fitting a sensor on either side of a spray boom at 12m centres will be an economically practical proposition making spatially variable fertiliser application possible in areas with poor weather conditions.

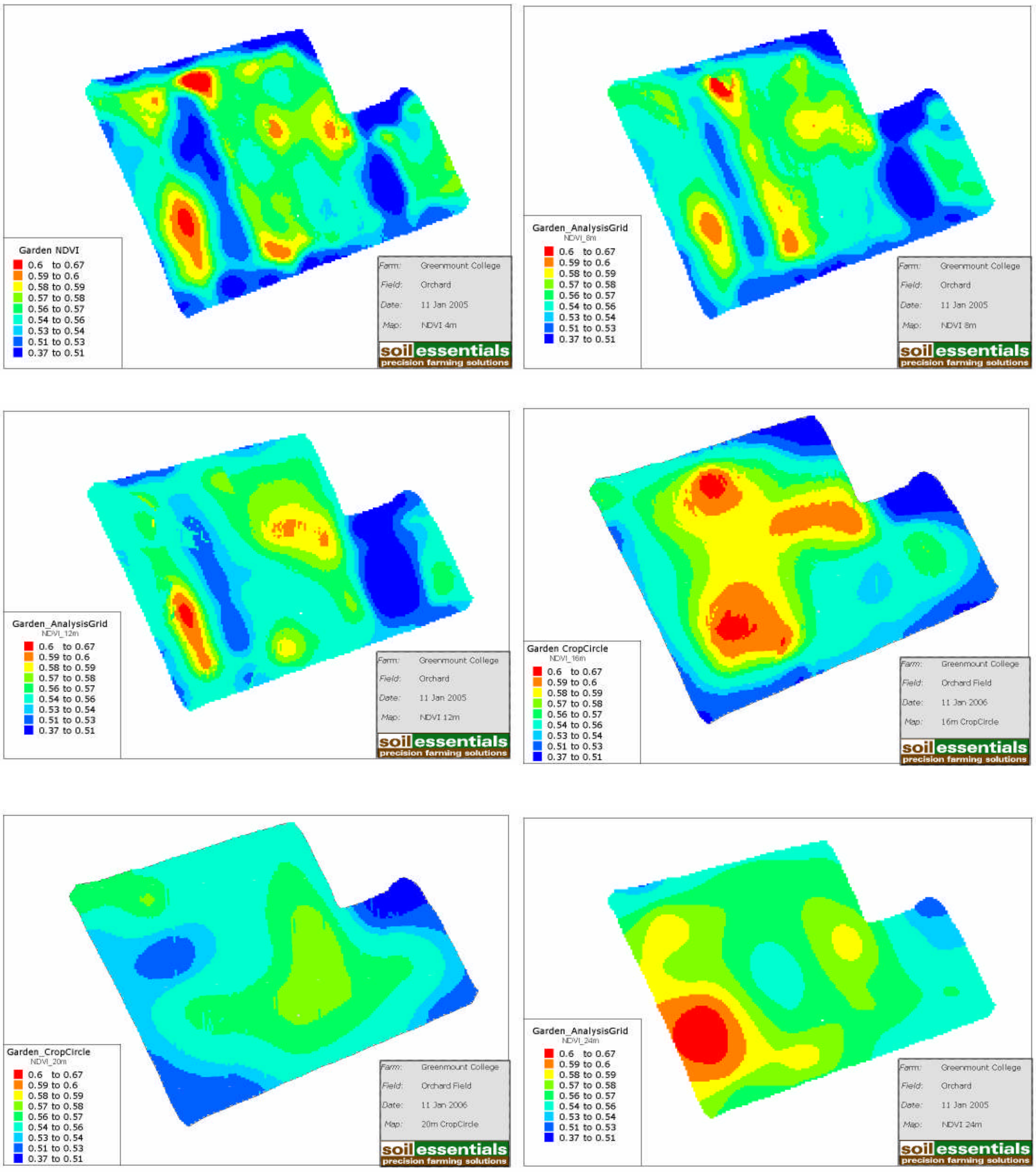


Figure 2-20 NDVI maps based on 4m, 8m, 12m, 16m, 20m, & 24m pass widths using Crop Circle. After: Morris (2006)

N sensor ALS

Reusch (2005) suggested that a combination of two wavelengths both from the upper part of the near –infrared range (> 730nm) were superior to classical reflectance ratios. This was followed by design of a active canopy reflectance sensor with xenon flash lamp as emitter. Unlike the standard commercial laser diodes or light emitting diodes, the xenon flash provides both high pulse energy and good spectral coverage in the desired wavebands. Currently the new active system is available in the market as the N senzor „ALS“ (Figure 2-21) (Yara, 2006; Reusch, 2005)

Figure 2-21 System N sensor ALS (Yara, 2006)

The company has reported that the sensor was successfully tested in growing season 2005 in Sweden and Germany (Yara, 2007).

2.4 Economical and environmental considerations of variable rate technology

To assess the precision farming technology inputs and all benefit has to be included. There were several research projects conducted in order to assess the economical efficiency of precision farming technology. However, results are not consensual for all of them.

Batte & VanBuren (1999) review work of others. They reported that after Swinton & Lowenberg-DeBoer 57 % of assessed operation, using the variable technology brought benefit, Babcock and Pautsch assess 12 farms in Iowa, they concluded that the implementation of variable application and it economic benefit depends on the variability of the field. They found a small increase in return compared to costs of fertilisers, but this was due to the big reduction of fertiliser use in comparison to yield increase. On the other hand, Lu & Watkins (1997) analysed potato farm, where the variable application lead to decrease in returns from production. Kilian (2001) compared the economical effects of conventional and variable technology of fertilising. He concluded that the use of the sensors did not bring any economical benefit due to the high costs of machinery and equipment. He proposed to combine the information from sensors together with information from soil survey. The effects of site specific fertilising on economical efficiency of crop production under Slovakian conditions was assesses by Švarda (Švarda & Findura, 2005; Švarda & Nozdrovický, 2005) and Rataj & Havránková (2006).

To assess the influence of variable application on returns excluding the subsidies and other extra payments to farmers, the only factor which can be changed is yield. At the side of costs several aspects has to be included. The factor which influences the profitability is the size of the farm, respectively the size of the area where the PA technology is used. The size influences the variable costs. The fixed costs increase with increasing of the PA adoption .The costs of PA are given in Figure 2-23.

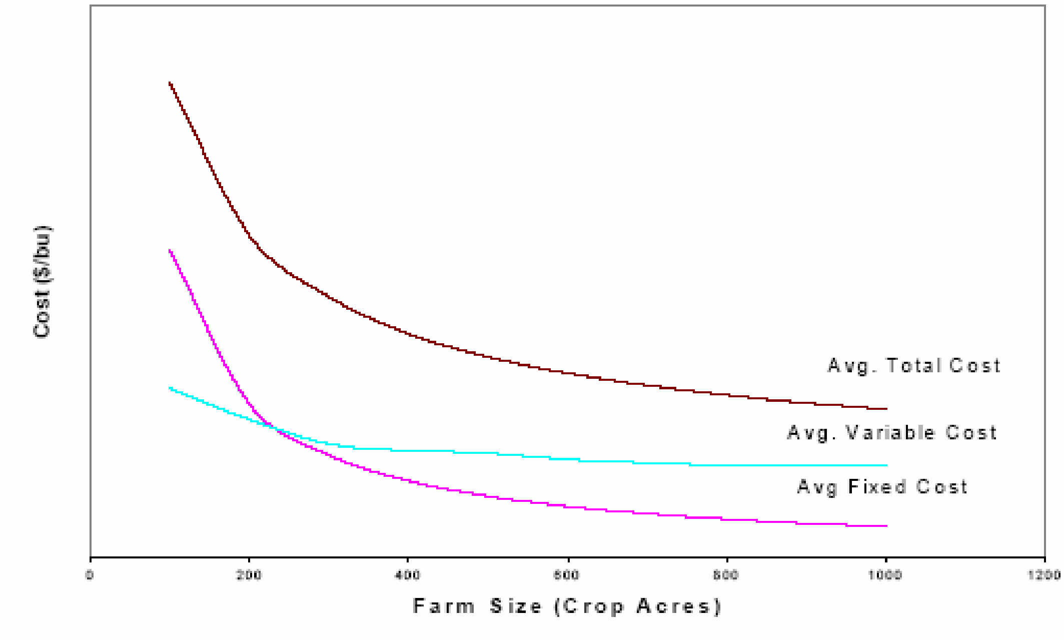


Figure 2-22 Costs of Precision farming technology (Batte & VanBuren, 1999)

An economic analysis of practicing precision farming techniques was conducted by Godwin et al. (2003b). The authors state, that the cost depends on:

- the level of technology purchased, i. e. full or partial system,
- depreciation and current interest rates ,
- the area of crop managed.

The field variability sensitivity analysis for full integrated system from an original equipment manufacturer is given in Figure 2-23 (Godwin et al., 2003b).

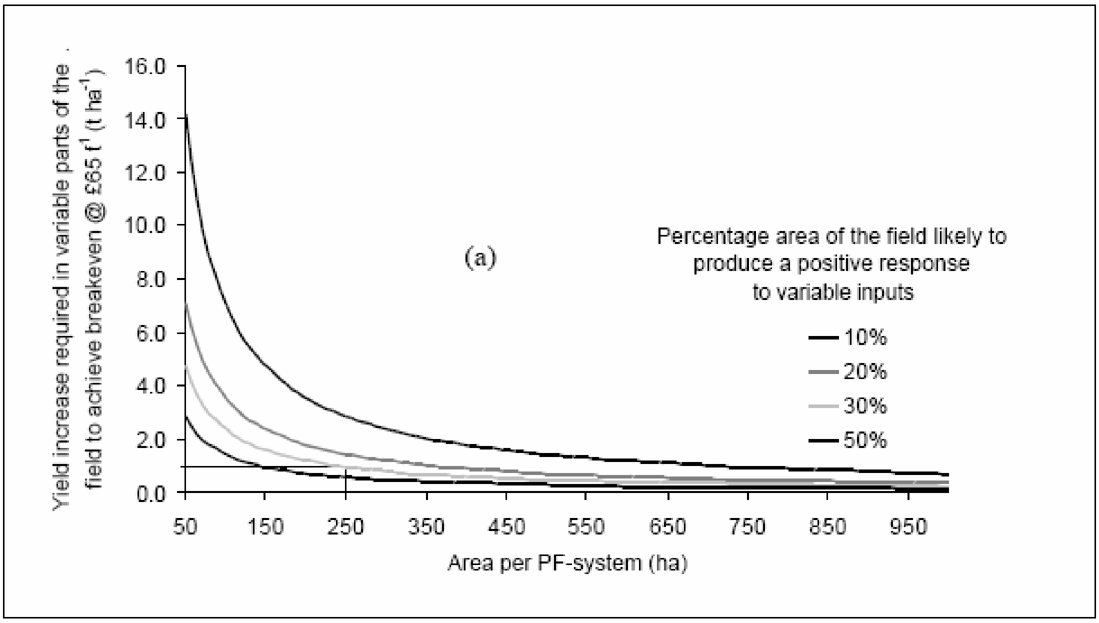


Figure 2-23 Field variability sensitivity analysis for the most expensive PA system (Godwin et al., 2003b)

Godwin et al. (2003) analysed the area needed to obtain the benefits. They reported typically a farmed area of 250 ha, where 30 % of the area will respond to variable treatment requires an increase in yield on the responsive areas between 0.25 and 1.0 t/ha. Also Leiva, Morris & Blackmore (1997) report that for a farm of 150 ha are costs of adopting the PA technology too high and the return of capital is too long, however for a farm of 800 ha with increase of yield by 2 % and costs saving of 8 % is the expected return of capital 5 years.

Alongside the farm size, the efficiency depends on several agro-climate conditions (nutrition need, soil fertility, topography, weather, weeds and so on) Daberkow (1997). Crops differ in terms of input intensity as well. Therefore the technology which reduces inputs is more suitable for crops which require higher amount of inputs. Also, an integrated system is more effective rather than independent technology (Lowenberg-DeBoer, 2003).

The public benefit from precision agriculture technology should result from increasing of input efficiency and reduction of applied fertilisers and herbicides, what should bring a positive effect to environment. This is proved by several research results (Lu & Watkins, 1997; Godwin et al., 2003a, 2003b). Schmerler (1999) reports that variable application in Germany increased the yield by 0,2 to 0,39 t.ha^{-1}, while the savings on Nitrogen were from 2 to 52 kgN.ha^{-1} annually. Author says that because of some restrictions of crop production, there can not be dramatic increase on yield expected. This technology should at fist of all decrease the inputs and enable better environmental efficiency. Pawlak (2003) also stressed that the economic efficiency if influenced by level of machinery costs increase, changes in quantity and quality of production, saving of inputs and environmental benefits. The reduction of fertilisers may lead to reduction of costs and energy used, also improve the environmental impact. The economical benefits of the environmental improvement, traceability and the final product quality of this technology are is not possibility to calculate (Ancev et al., 2005).

The results of research projects differ depending on climate and economical environment of the country as well as growing conditions. Therefore further research is needed in this area to assess the efficiency in central Europe.

The economic efficiency of the use of remote sensing to manage nitrogen is mentioned in section 2.3.3. Generally it can be concluded that all commercial application of all platforms brought benefit. However, their application was not assessed in central Europe conditions.

2.5 Identification of research needs

Having reviewed the above material, the critical issues needing further investigation are:

- The passive N sensor is the most common in Europe; however, there is no or little published evidence of using the active new active sensors Crop Circle and N sensor ALS to manage nitrogen in winter wheat husbandry in European conditions. Therefore, further investigation is needed to evaluate this active sensor compared to the passive in the area of determining canopy nitrogen in winter wheat in field conditions of winter wheat husbandry.
- There is little evidence in the scientific literature reporting data on Precision Agriculture nitrogen management strategies in winter wheat husbandry for central European conditions. These need to be further investigated mainly in terms of possible economic and environmental benefits.

3 An assessment of active and passive sensors

3.1 Introduction

Precision agriculture offers advantages to make nitrogen management more effective (Godwin et al. 2003a). In order to match the spatially variable crop requirements and to use the data in a short period of time, rapid technology is needed. Remote sensing brings advantages as several ground based sensors are available at the market. The most common is the passive N sensor (Yara), however, some new sensors have been introduced namely Greenseeker (N Tech Industries) and Crop Circle (Holland Scientific). The later are active systems as they include their own light source and so are able to minimize the effect of clouds. The methodologies of nitrogen dose determination are based on shoot densities (UK) (HGCA 1997) or the nitrogen content in plants (Ložek, 1998). There is therefore a question of the relationship between the sensors and the crop characteristics, which are used in nitrogen management. The aim of this section was to determine a protocol to assess the two remote sensing systems in comparison with direct crop measurements, to determine the relationship between sensors output (NDVI) and crop (wheat) characteristics during the growing season. The experiments were carried out at winter wheat field at Wilstead (UK) in growing seasons 2005 and 2006.

3.2 Methods

3.2.1 Sensors and methods used for the experiment

Passive system - N sensor (Yara)

The system uses reflectance data of 20 wavelengths (5 of which are selectable) within the range of 450 – 900 nm. The correction of light conditions intensity is done by fifth spectrometer (Figure 3-1). Data are collected at PCMCIA data card with a frequency of 1 Hz.

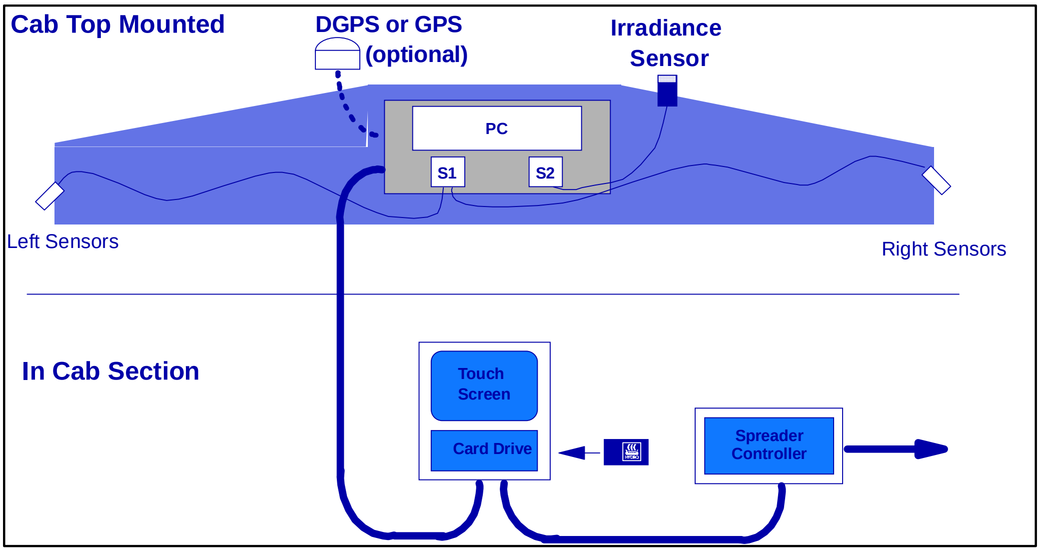


Figure 3-1 N sensor system (Yara, 2005)

N Sensor works in two possible modes:

(a) application – commercial version, where the crop is sensed and Nitrogen is applied in real time, however, agronomic calibration is needed. Using this mode, "index biomass" – unit less number, map of recommended and map of applied Nitrogen is given as an output

(b) scanner (known as Field Scan - FS), to record reflectance values of 25 used wavelengths followed by post processing of the data to produce a map of crop variability

The Field Scan system was used for experiments. To calculate NDVI wavelengths 590 and 880 were used in order to use the same wavelengths as are used by Crop Circle, described below. The N sensor (Field Scan) sensor is described in Section 2.2.3 in more detail.

Active system - Crop Circle ACS 210 (Holland Scientific)

The Crop Circle ACS-210 incorporates its own light source technology called PolySource™. The PolySource™ light source technology simultaneously emits visible and near infrared light (NIR) from a single LED (Light emitting diode) light source with a high frequency. The sensor is then able to distinguish between the reflectance of the combination of its signal and ambient energy, and the reflectance of the ambient energy only. The difference between these two is a reflectance of its own energy emitted. Crop

Circle (CC) provides vegetative index data (e.g. NDVI) as well as basic reflectance information from plant canopies. The sensor can provide yellow/NIR 590nm and 880nm; red/NIR 650nm and 880nm sensing capabilities. Serial data produced by the sensor is captured using a laptop PC, PDA or other data acquisition devices (Holland Scientific, 2005) (Figure 3-2). The length of its footprint, which is scanned by the sensor, is 60% of its height. Sample output rate is programmable for 20 Hz; the default is 6 Hz. The system was connected to PDA and the data were stored using the „Farmworks“ system in the –.csv format.

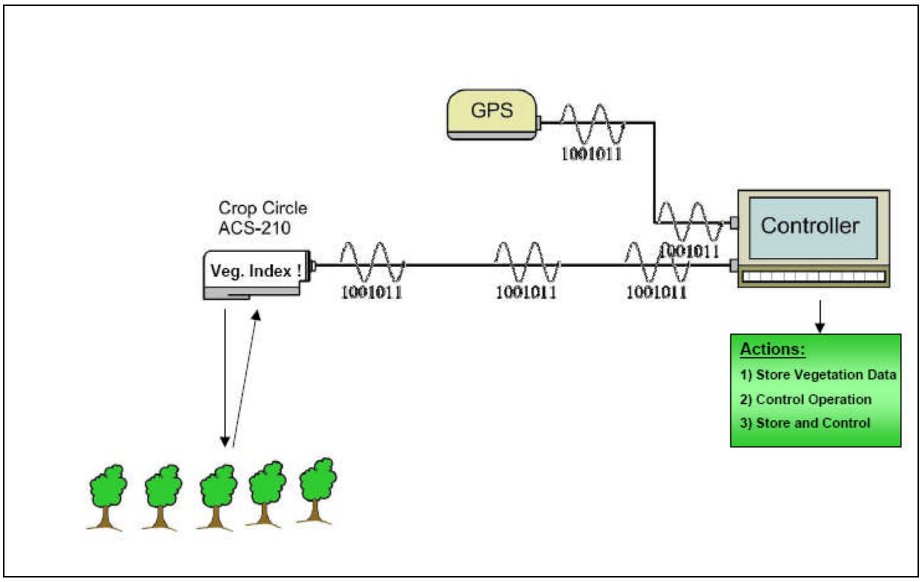


Figure 3-2 Crop Circle system (Schepers, 2005)

3.2.2 Site characterisation and methodology and time schedule

Site characterisation

2005

To be able to assess the two ground-based sensors, a number of sites with the same crop variety but with different crop densities were chosen. In order to be able to use the regression technique, the widest possible range of the predictor (NDVI) was calibrated by crop characteristics. Resulting from Wood’s calibration methodology, where the author uses 8 sites to calibrate the NDVI data (Wood et al., 2003a) and in order to increase the robustness of regression analyses data, 10 sites were chosen. The fields were in winter wheat (Triticum aestivum cv. Malaca) and located in Bedfordshire, UK (0º 26’53” W; 52º 5’16” N).

Experiments lasted for two years. In 2005 the following fields were used, where the agronomical operations were as follows:

1st FIELD
drilled 28. 9. 2004 – Malaca 190 kg/ha
fertilizers 22.3.2005 – 50 kg/ha NPK 0%:30%:20%
4.4.2005 – 100 kg/ha N 32.5%
28.4.2005 – 100 kg/ha N 32.5%

BARN FIELD
drilled 26.9.2004 – Malaca 185 kg /ha
fertilizers 22.3.2005 – 50 kg/ha NPK 0%:30%:20%
4.4.2005 – 100 kg/ha N 32.5%
28.4.2005 – 100 kg/ha N 32.5%

BALANCE field
drilled 24.9.2004 – Malaca 185 kg /ha
fertilizers 22.3.2005 – 50 kg /ha NPK 12%:20%:20%
4.4.2005 – 100 kg /ha N 32.5%
28.4.2005 – 100 kg /ha N 32.5%

2006

To evaluate the two sensors in 2006, a 21 ha field growing Malaca (milling winter wheat) was used (Hawnes End). Historical information (Aerial photographs -see Figure 3-3, and yield map from 2004 - see Figure 3-4) about the fields was obtained. This historical information was used to assess the existing variability of the field. This data were plotted using GIS software.

The field used for the experiment is described in Section 4. Except of the variable application of nitrogen, which was done during the experiment, all treatments were applied uniformly. The following nitrogen applications were made:

- 13.4. 2006 33 kg N /ha uniformly,
- 30.4. 2006 30 kg N/ha uniformly,
- 05.6. 2006 37 kg N/ha uniformly.

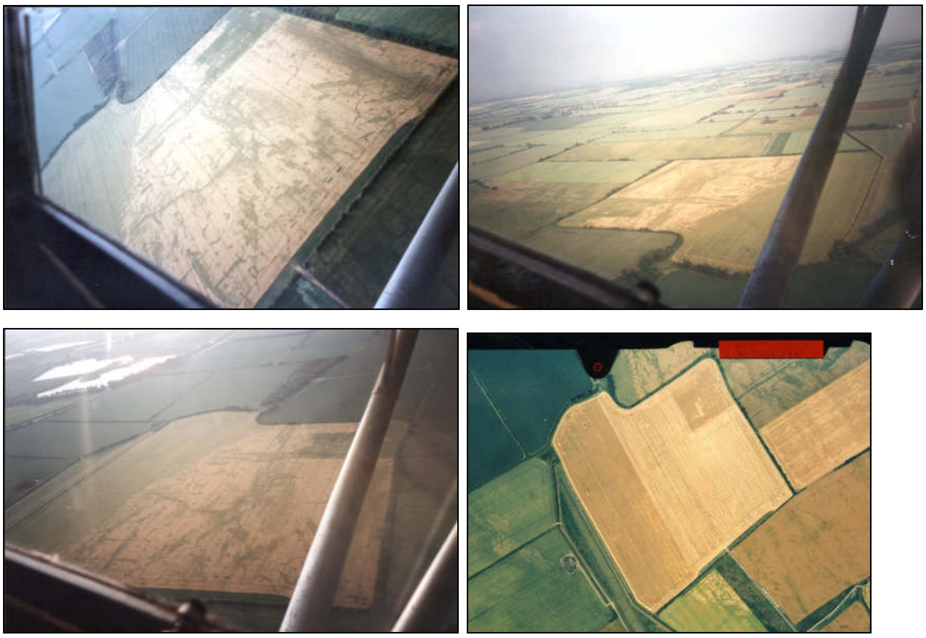
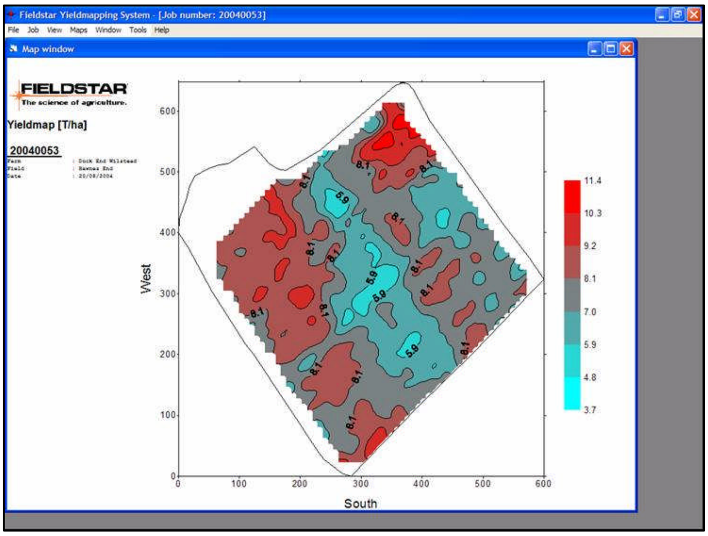


Figure 3-3Aerial photographs of the Hawnes end field from previous growing seasons



Fieldstar Yieldmapping System - [Job number: 20040053]

Yieldmap [T/ha]

20040053

Farm : Duck End Wilstead
Field : Hawnes End
Date : 20/08/2004

Figure 3-4 Yield map from 2004

Methods of initial scanning and time scheduling

In order to obtain information about the variability of the crop and to target sites for the experiment, initial measurements with the selected sensor were carried out at the beginning of the season. Results were plotted using ArcGIS®. In order to target sites across the whole range of NDVI and to get a minimum number for regression analyses the NDVI values were tresholded into 10 (or more in 2006). Each site represents values of one of the intervals. As a result 10 sites with different crop densities were plotted.

At these selected locations three local sub-samples were selected (Wood et al., 2003b):

- after initial fertiliser application (Growth Stage 23 – 29) – early April,
- after main dose (Growth Stage 30 – 32) – early May,
- after final fertiliser application (Growth Stage 37 – 39) – late May.

Methods of scanning at selected sites with both sensors

At each date, the selected sites were scanned simultaneously using CC and FS. The layout of the sub-sampling at each site followed the scanning geometry of the FS, which scans the crop at four areas of crop as shown in Figure 3-5. The exact location of the scan areas were determined by calculation and were then separately scanned using CC.

During the first measurement period the CC was used in ‘hand-held’ mode (Figure 3-7). However, for the second and third scans CC was mounted on the boom of the sprayer and the four sub-scans were scanned in succession (3-8). This was done in order to avoid damaging the crop and to stabilise the position of the sensor above the surface. As the CC sensor works on the base of “inverse distance law”, using the device in the handheld mode (measurement in March) caused the distance between sensor and crop to vary by a few centimetres (approximately 5 cm) and the values could be different for the same crop.

Methodology of the 2006 experiment followed the one in 2005. However, CC was used only as boom mounted and the data were gathered as the machine moved across the field to match the normal practical conditions for sensor use.

The experiment at each targeted site was conducted using the following protocol.

Sensing data:

1. To target and to mark the areas scanned by Field Scan (squares: ABCD) along the dimensions given in Figure 3-5 .The height of Field Scan sensor was 2.7 m. Following the work of Wood (2002) the dimensions of the scanned area are given in Figure 3-6.
2. To scan the targeted site with the Field Scan sensor stationary for approximately 5 minutes.
3. To scan the targeted squares by Crop Circle - the signal between both A and B and C and D was interrupted.

4. The time between scanning with FS and CC should be as short as possible to ensure similar conditions and reflectance signature.

Direct crop measurements:

1. to count shoots - 0.5 m row of plants, 5 replicates at each corner,
2. to count the rows within each square,
3. to take plant samples – 6 plants at each corner at each site.

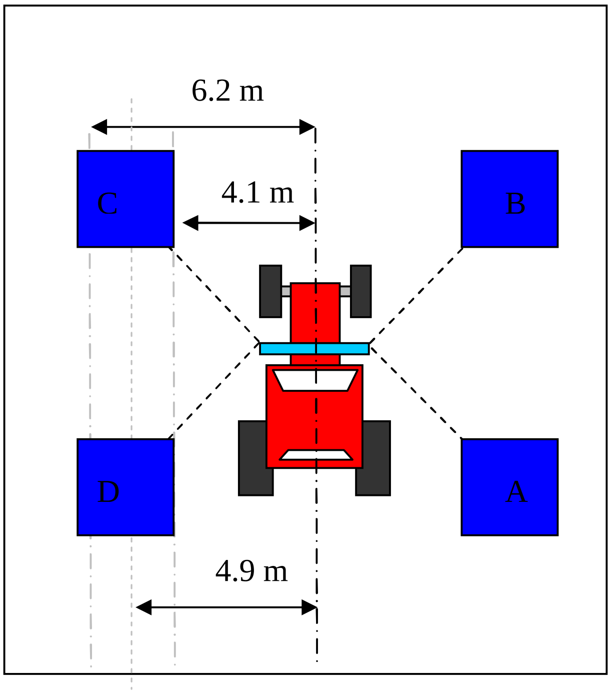


Figure 3-5 Scanning areas of FieldScan (Wood, 2002)

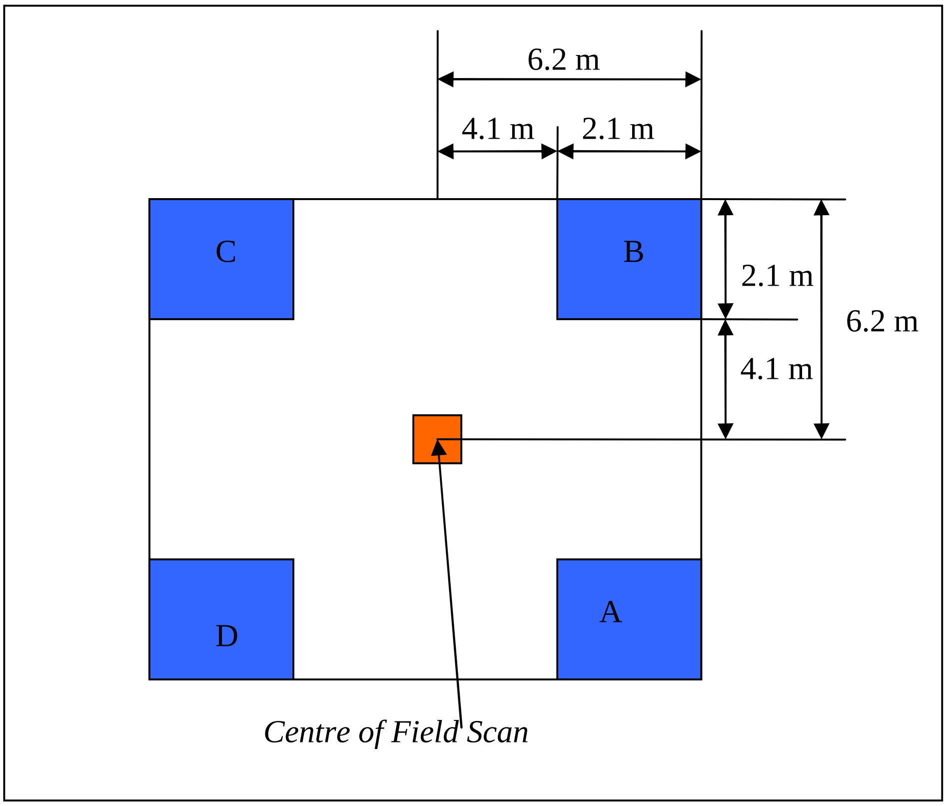


Figure 3-6 Dimensions of targeted site

Figure 3-7 Left – scanning with CC as hand held, Right – Field Scan and the targeted site

Figure 3-8 Scanning at site when using the Crop Circle mounted on the boom

The following crop characteristics were determined about each targeted site:

- number of shoots per m^2 (calculated from data obtained by direct crop measurements)
- dry matter,
- total Nitrogen content per m^2 ($mg.m^{-2}$)
- Nitrogen content in %,
- LAI (Leaf Area Index) was measured by the SunScan device without being successful, what is similar experience to the Wood's (Personal communication).

To obtain information about dry matter and biomass after each field experiment, laboratory analyses were carried out. Samples were weighed wet, and then after 18 hours of drying at 102°C, as a dry sample. The sample was also analyzed to determine the percentage of Nitrogen using CHNOS Elemental Analyser Vario EL III. The data were processed using ArcGIS® and Statistica® software. The total nitrogen content was calculated from the data about dry biomass and % nitrogen of the plants. The data are given in Appendix 3-1.

NDVI values (Equation 1) were derived and used to compare the two systems.

$$NDVI = (\lambda_{880} - \lambda_{590}) / (\lambda_{880} + \lambda_{590})$$

where: NDVI is the normalised difference vegetation index; and λ_{590} and λ_{880} denote the central wavelength (nm) of the spectral wavebands from the sensors.

Each site was characterized by NDVI values from the two sensors and the above mentioned crop characteristics (Appendix 3-1). Correlation and regression analyses were conducted using three dates of sensor data and the physical and chemical crop properties measured in the field and laboratory.

3.3 Results and discussion

3.3.1 Targeting sites

2005

Initial scanning in 2005 of selected fields was undertaken on 8th and 11th March with the Crop Circle sensor mounted on a Quad bike (Figure 3-9). NDVI values obtained were plotted in maps (Figure 3-10). Extreme values, caused by sensor handling or scanning different surface were removed. Results of this scanning were used to target the sites for further measurement.

Figure 3-9 Crop Circle sensor mounted on Quad bike

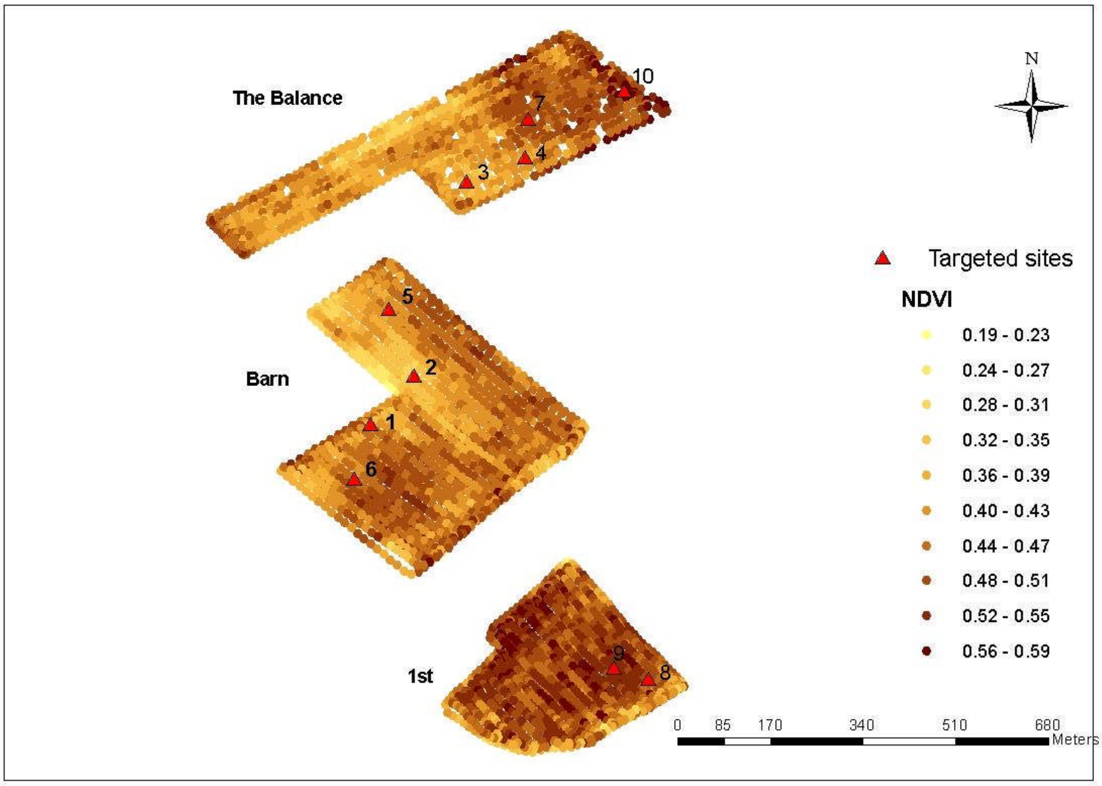


Figure 3-10 Targeted sites for further measurements together with data obtained during initial measurements.

2006

To determine the relationship between sensors output and crop characteristics in 2006 initial measurements were conducted on 13th March 2006. On the base of these data 11 sites were targeted. Following the Wood's rapid calibration technology the NDVI values were divided into 8 intervals. In order to calibrate the data for representative data from the whole field the last three intervals were calibrated with two sites each, giving us 11 sites as a result (Figure 3-11). The second scanning measurement of the whole field was repeated at 30th April 2006. The sites were targeted based on the protocol used in 2005 with the number increased to 15 (Figure 3-12) to improve the spatial distribution of the readings within the field.

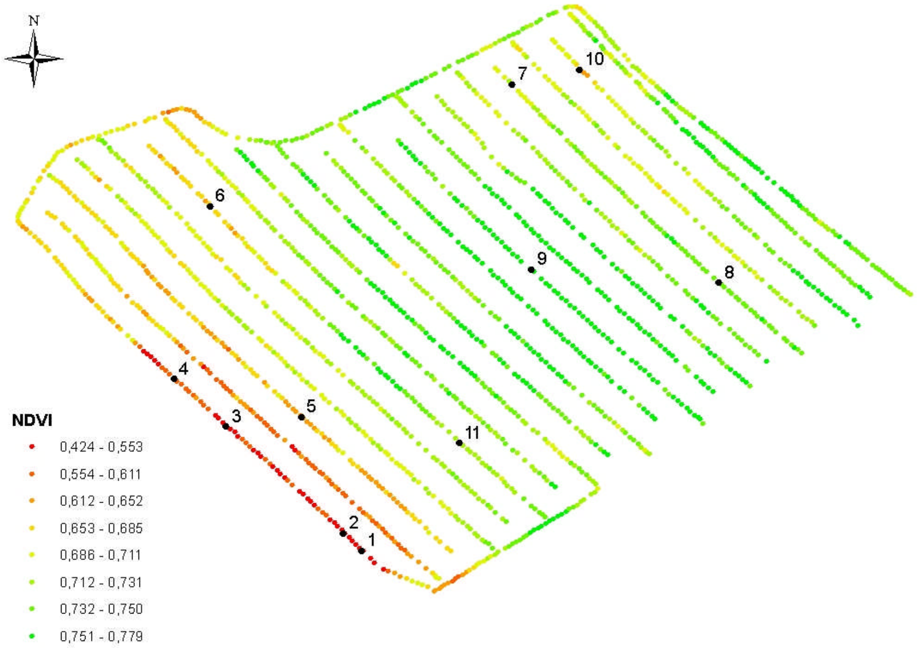


Figure 3-11 Targeted sites for measurements in March 2006

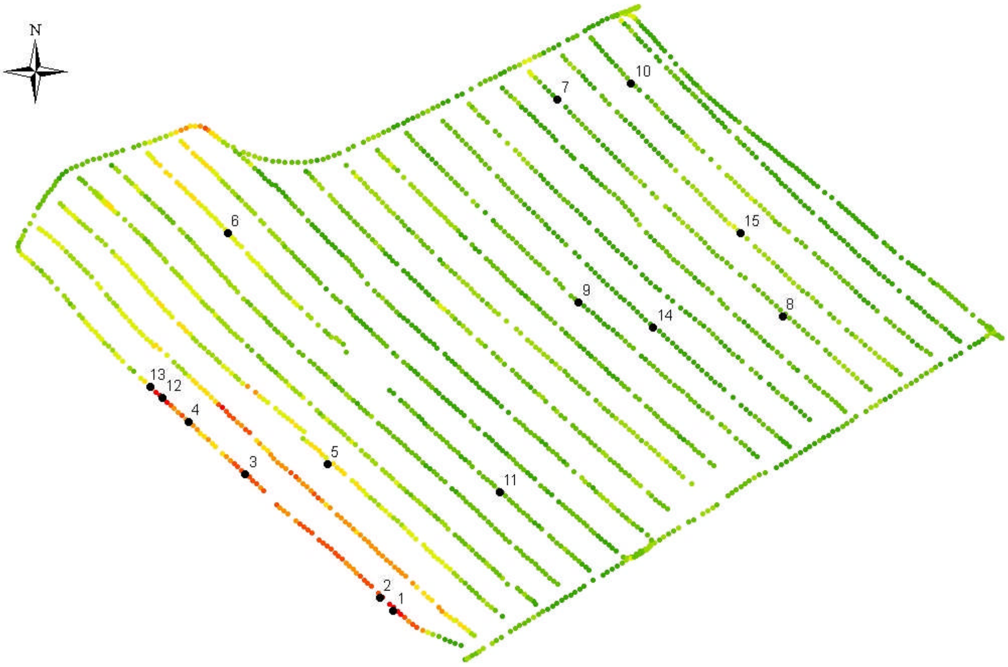


Figure 3-12 Targeted sites for measurements in May 2006

3.3.2 Performance of the two sensors

Measurements were conducted on 11th and 13th March, 2005 with the second measurement on 5th and 6th May and third measurement on 3rd June using both FS and CC sensors. Using CC, four NDVI values corresponding to the four squares of the FS sensor, were calculated, compared with only one average value for each site using FS. Measurements were also conducted on 16th March and 5th May 2006 at 11 targeted sites.

Variability within each site in 2005

CC data were examined in order to assess local variability at each of the 10 sites. As an indicator of this effect the coefficient of variability was used. The results are given in Table 3- 1.

Table 3-1 Coefficient of variability of NDVI data obtained from CC

Site	CV of Crop Circle NDVI, %		
	April	May	June
01	15.75	8.37	7.41
02	11.05	3.92	4.08
03	10.20	8.34	7.66
04	5.35	2.35	4.47
05	16.74	1.42	2.98
06	9.96	5.40	5.71
07	6.21	1.12	3.46
08	9.47	4.30	2.14
09	4.37	2.04	1.84
10	4.97	2.43	3.49

The highest values of variation in NDVI values within each site are in April (from CV of 4.37 to CV of 16.74). These differences could be due to variation in row spacing (introduced during seed drill operation) (Figure 3-13). As the season progressed through May and June, when both the variability within the sites decreased (as the shoots filled the area) and the sensor was mounted on the spray boom, which provided both greater stability and allowed more samples to be taken, i.e. the data set was larger.

Figure 3-13 Site No 6 during the first measurements in April

Performance of the two sensors in 2005 and 2006

The relationship between remote sensing characteristics (NDVI) of the crop and crop characteristics (shoot density, dry matter and nitrogen level given in Appendix 3-1) was determined. The coefficient of determination as well as slope coefficient is summarized in Table 3-2. The detail results of regression analyses are in Appendix 3-2. Results of regression analyses are shown in Figures 3-14 to 3-21, together with the equation for the best fit regression. The NDVI was used as predictor and crop characteristics are the predicted values. This was because we analysed possibilities of sensor use to predict variability within the field. Equally well, the axes could reverse to assess the sensitivity of NDVI to a change in crop characteristics.

The results show that, as expected from other studies (Boegh et al., 2002), the strongest relationship is between NDVI values and crop characteristics such as shoot number, total N in plants and dry matter. The high values of coefficient of determination are given between shoot population per m^2 and NDVI (0.70 for FS and 0.79 for CC in April and similarly 0.52 and 0.73 in May). The relationships for all crop characteristics in April are strong, but the relationships between both sensors and crop characteristics in June are much weaker. These support results published in Broge & Mortensen (2002), Hansen & Schjoerring, (2003), Schmidhalter et al., (2003). However, the slope of line for NDVI and %N in June would be expected to be not significant as the effect of canopy size was removed (Table 3-2).

Table 3-2 Coefficient of determination between NDVI and crop characteristics (*significant value)

Crop characteristics	**RS system**	**Coefficient of determination/ Slope coefficient**				
		April 2005	**May 2005**	**June 2005**	**March 2006**	**May 2006**
Shoot number, no. m^{-2}	FS	0.70* / 2364*	0.52* / 5375*	0.05 / 743	0.55* / 1719*	0.55* / 1748*
	CC	0.79* / 1424*	0.73* / 1398*	0.15 / 747	0.59* / 1863*	0.59* / 1012*
Nitrogen content, mg. m^{-2}	FS	0.62* / 7495*	0.04 / 6710	0.01 / 1494	0.67* / 915*	0.38* / 3220*
	CC	0.77* / 4739*	0.60* / 5853*	0.08 / 2695	0.71* / 985*	0.36* / 1811*
Dry matter content, g . m^{-2}	FS	0.53* / 1708*	0.01 / 960	0.11 / -3439	0.30 / 165	0.40* / 1439*
	CC	0.71* / 1124*	0.57* / 1813*	0.01 / -251	0.37* / 193*	0.44* / 816*
Nitrogen content, %	FS	0.31 / 5.62*	0.18 / 9.63	0.56* / 7.04*	0.49* / 3.93*	0.03 / -0.59
	CC	0.24 / 2.75	0.01 / 0.56	0.28 / 2.86	0.39* / 3.69*	0.05 / -0.40

There is a difference in NDVI between the CC and FS sensors. The slope of best fitting line is similar at any given time (Figures 3-16 to 3-22).The shift of the best fitting line for the relationship of NDVI and shoots numbers is due to the reduction in number of shoots in later growth stages (HGCA, 1997), however, the relationship in June is not significant.

From figures 3-14 to 3-17 it is evident that the FS NDVI has a smaller range of data than the CC NDVI. This is most visible for May and March measurements (Figure 3-14 and 3-15).This may show that the FS sensor did not reflect the variability of the field with the same resolution. This is also evident from Figures 3-18 and 3-20. This fact may be due to the geometry of FS scanning and the footprint which scans an average of a bigger area as well as the oblique angle of sensing.

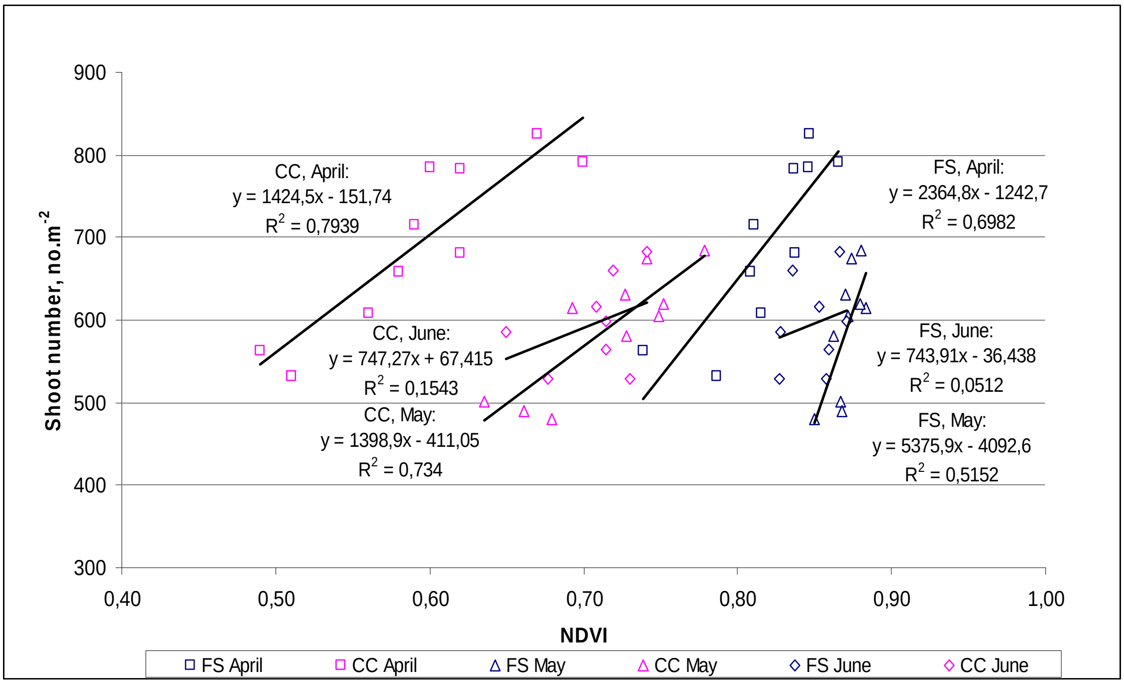


Figure 3-14 Relationship between NDVI from both sensors and shoot population in2005

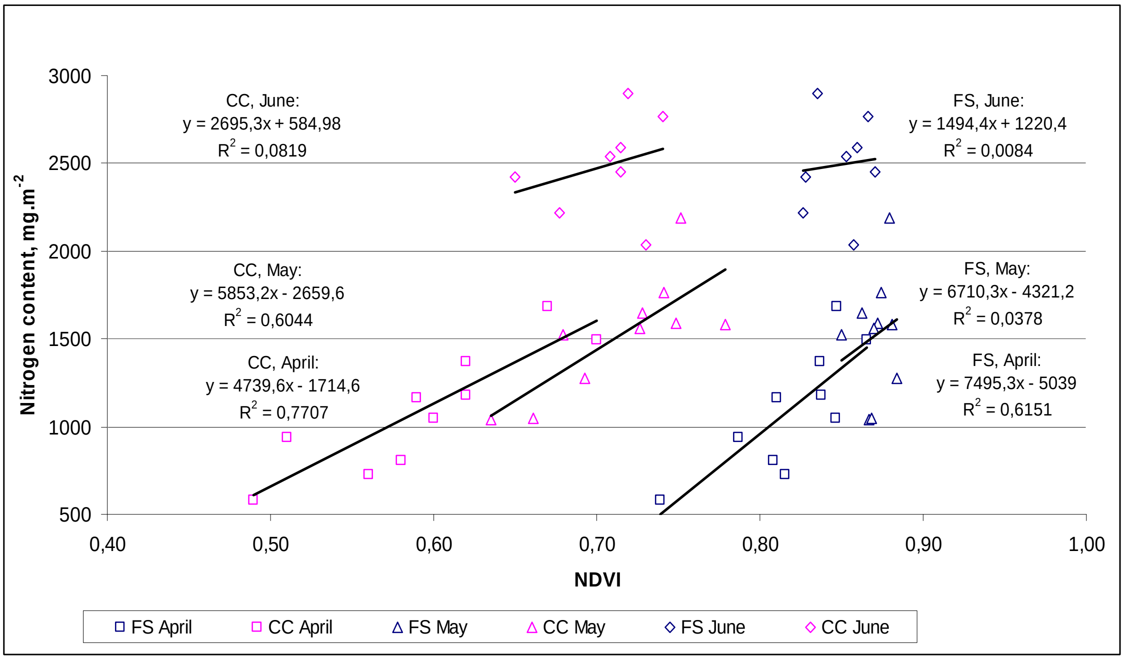


Figure 3-15 Relationship between NDVI obtained from both sensors and total nitrogen content in plants in 2005

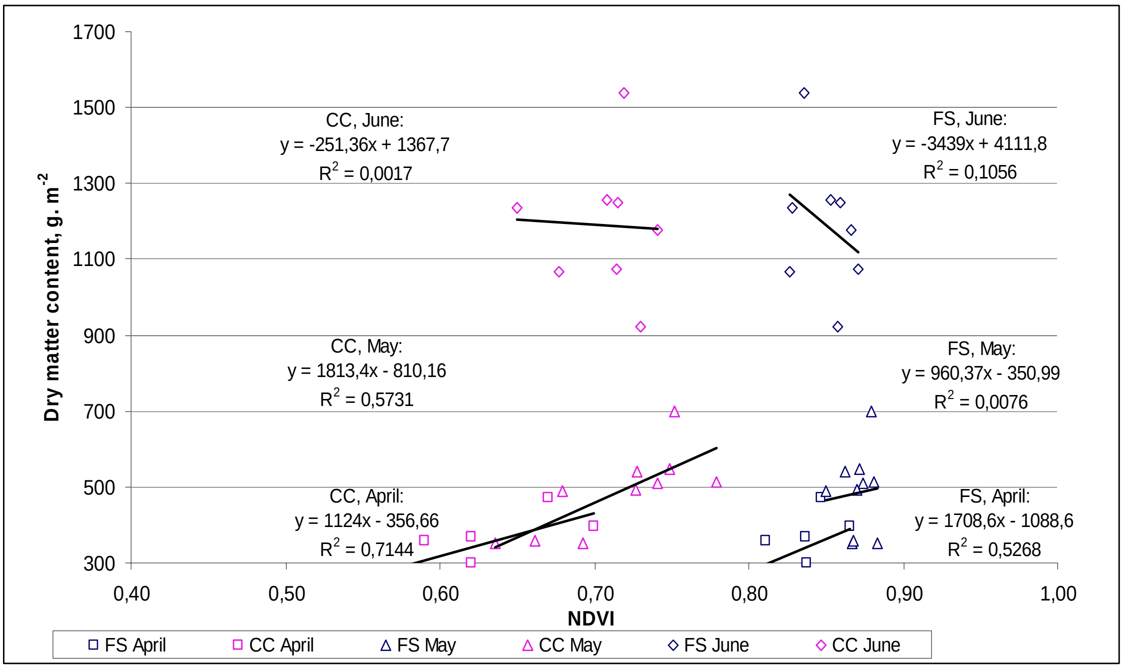


Figure 3-16 Relationship between NDVI from both sensors and dry matter in 2005

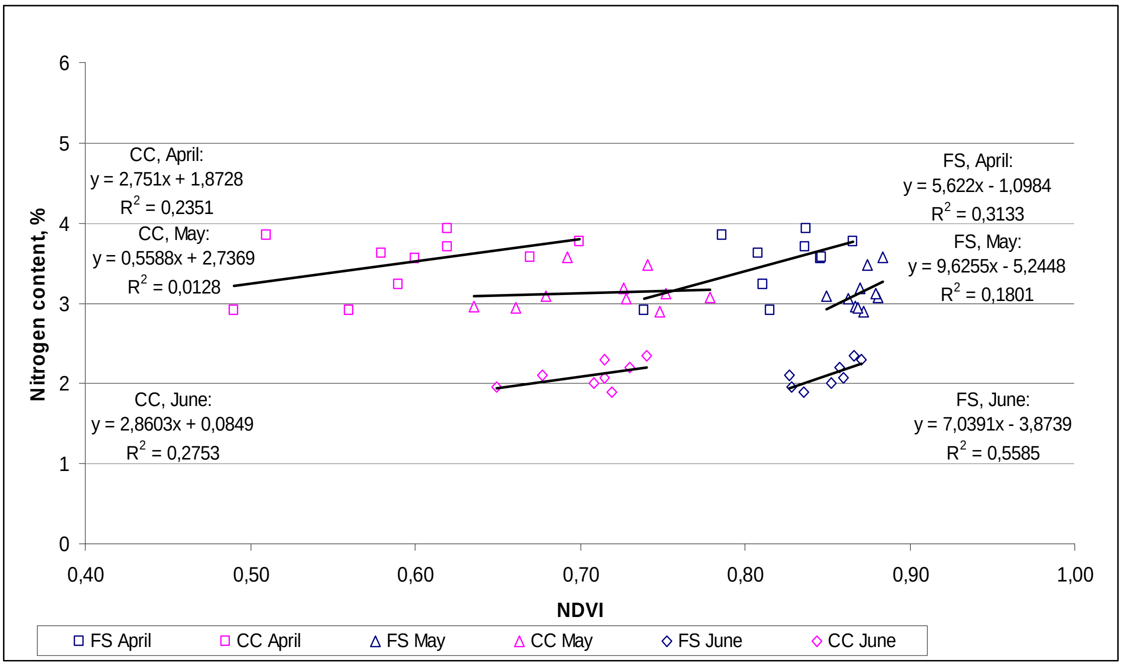


Figure 3-17 Relationship between NDVI from both sensors and nitrogen content (%) in plants in 2005

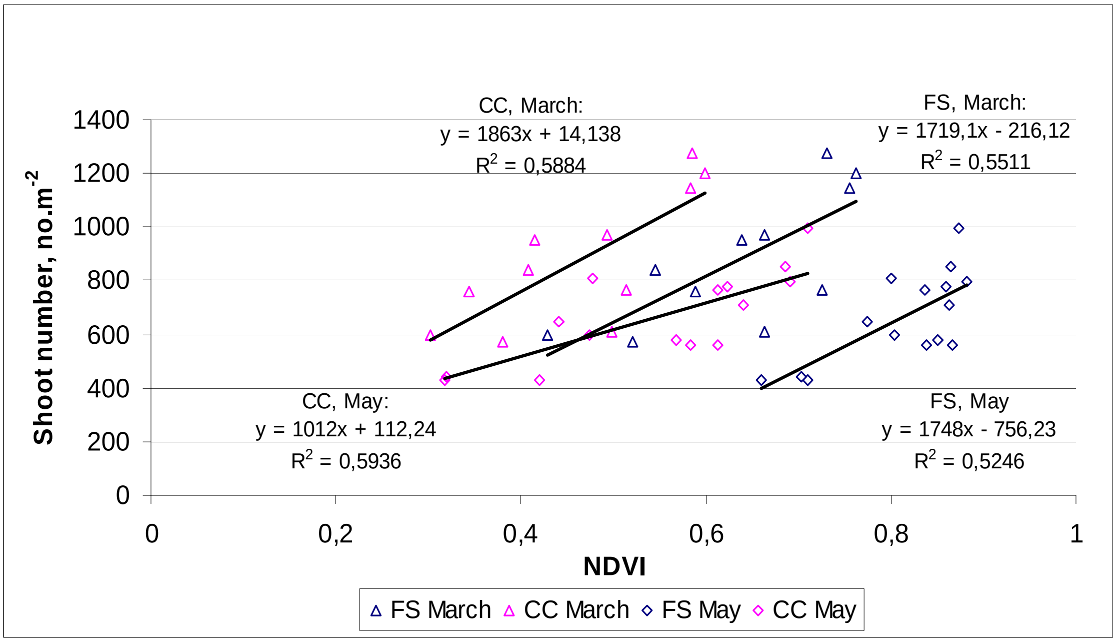


Figure 3-18 Relationship between NDVI from both sensors and shoot number in 2006

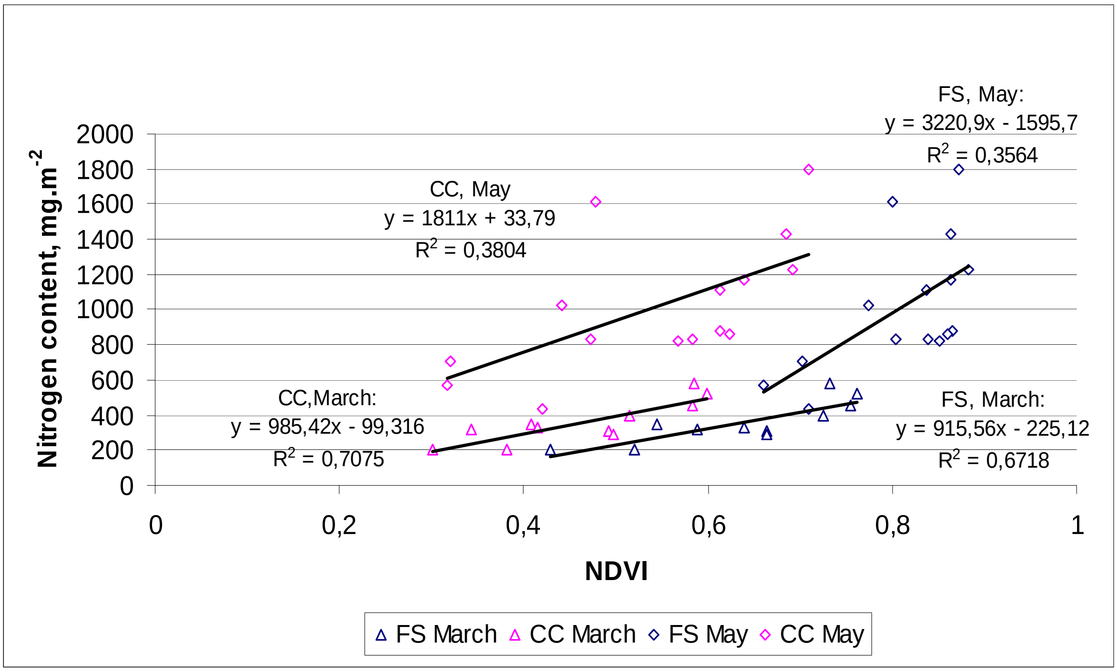


Figure 3-19 Relationship between NDVI from both sensors and nitrogen content in2006

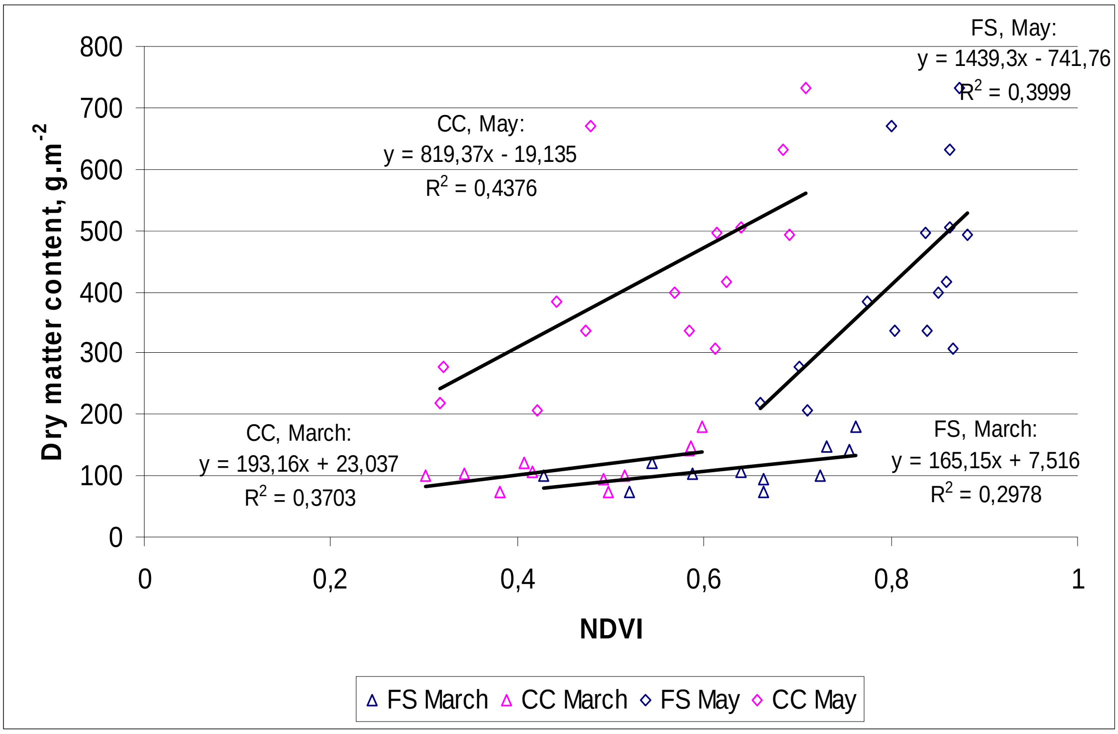


Figure 3-20 Relationship between NDVI obtained from both sensors and dry matter in 2006

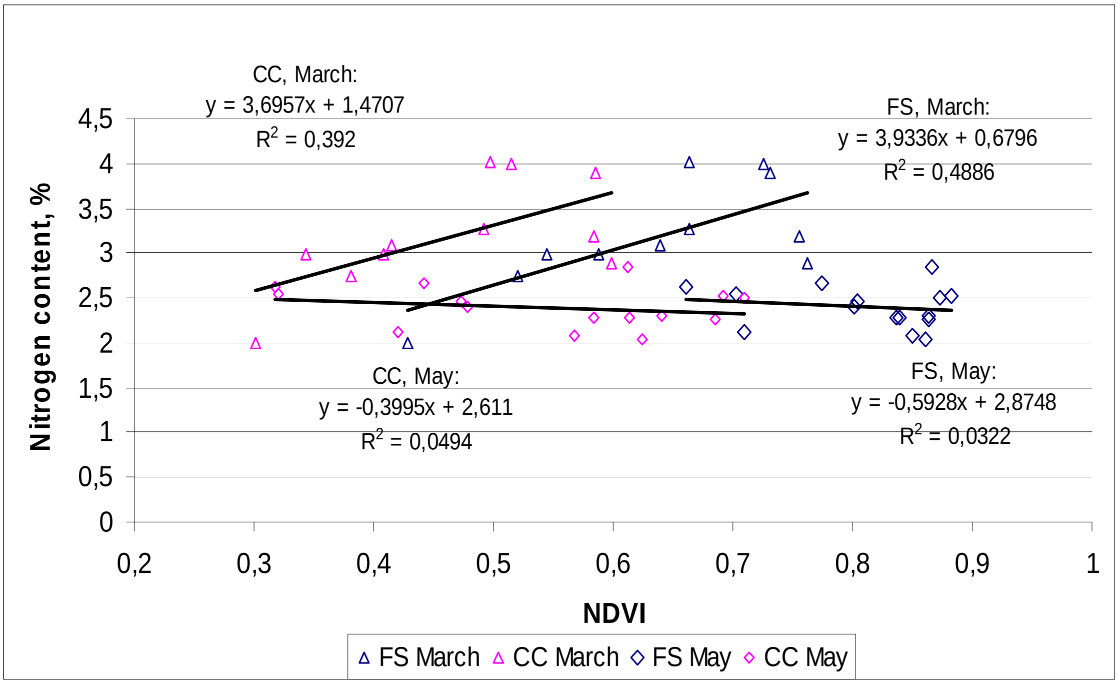


Figure 3-21 Relationship between NDVI from both sensors and nitrogen content in2006

Results from 2006 follow the results from 2005. The best parameter of linear regression analyses were obtained for NDVI vs. shoot number and NDVI vs. total nitrogen content. In March the sensors provided similar data in terms of range width and the slope. Data obtained during measurements in May differ in range, which is smaller for the FS sensor.

Because the active sensor scans a smaller area, and it is recommended to use one at each side of the sprayer (Morris, 2006), compared to an average number for both sides of the tramline obtained by Field Scan (Figure 3-5), these may be an advantage in more precise determination of variability within a field. Moreover, according to experiments conducted by Morris (2006) where authors repeated the measurement of selected sites during a long period of time and for different ambient light conditions, it has an advantage of possible longer working period. However, the relative performance in terms of determining the variability in shoot number and nitrogen content (mg/m2) of the two sensors was not significantly different (Figures 3- 14, 3-15, 3-18 and 3-19). The relative performance of the Field Scan in May (Figure 3-16 and 3-17) may be caused by the oblique angle of the sensor, which causes that it saturates sooner rather than active system using the nadir view. As the nitrogen per m^2 is a function of dry matter and Nitrogen content in %, its relationship with NDVI follows the similar pattern.

As there is not similarity in slope between the given dates and years, calibration of data obtained from ground based remote sensing sensors should be done for each time separately. However, in terms of their design and practical use, the relationship should be universal for any given variety.

3.4 Conclusions

1. There are strong relationship between NDVI values and winter wheat crop characteristics. The strong relationships is particularly between NDVI and shoot number (0.69 for FS and 0.79 for CC) and total N (0.61 for FS and 0.77 for CC) in April and May (Table 3-2), with a reduction in June when canopy size is a maximum and the NDVI saturates.

2. The active sensor (CC) has an advantage resulting from its footprint size and possible longer working time; however the relative performance of the two sensors was not significantly different when determining the variation in the winter wheat canopy.

3. The oblique angle of FS will measure a greater apparent depth of canopy than CC and, consequently, will reach saturation sooner. This could explain the relative performance of the sensors especially in May (Figure 3-16, 3-17).

4 Field evaluation of sensors effectiveness in Nitrogen management

4.1 Introduction

The ability of both, the Crop Circle and the Field Scan sensors, to determine the variability of crop nitrogen requirements as well as shoot density was proved in the previous section. The NDVI output data can be calibrated by these crop characteristics. The field evaluation of the effectiveness for two sensors in nitrogen management is described in the following chapter, where the sensors were assessed in practical field conditions compared to uniform nitrogen management. The effect of variable application on yield was determined. Furthermore, environmental and economical analyses were conducted.

4.2 Methods

4.2.1 Sites characterisation and time schedule

The field experiments were conducted in experimental winter wheat (Triticum aestivum) field in Wilstead (22 ha) (lat 52.854444, long 0.448055), Bedfordshire, UK.

The experiment was scheduled for the dates of nitrogen fertilisation, used in winter wheat husbandry (see Section 2.1). Because the fertiliser for this experiment was available only for the main dose, the other application was controlled by the farmer and nitrogen was applied uniformly. The applications of nitrogen at this field were on the following dates at following rates:

➢ First application	13.4. 2006	33 kg N /ha uniformly
➢ Main application	30.4. 2006	30 kg N/ha uniformly
	15.5. 2006	80 – 150 kg N/ha variably
➢ Final application	05.6. 2006	37 kg N/ha uniformly

The main dose was split into two as there were problems with fertiliser delivery and the crop requirements were urgent.

4.2.2 Sensors and methods used for experiment

A strip design was used in these experiments to apply nitrogen (Figure 4-1); all other procedures (seeding, application of chemicals) in this field were completely controlled by the farmer attempting to apply in a uniform manner. Conventional farm machinery was used to apply nitrogen along the 24 wide strips with three nitrogen treatments based on:

a) the variation in the estimated tiller density from the active sensor Crop Circle - CC,
b) the uniform treatment - agronomist's best practice rates,
c) the variation in the estimated tiller density from the passive sensor Field Scan - FS.

This strategy was designed so, the uniform treatment is in the middle of the variable treatments and the paired comparison can be done. This pattern was repeated for the whole field.

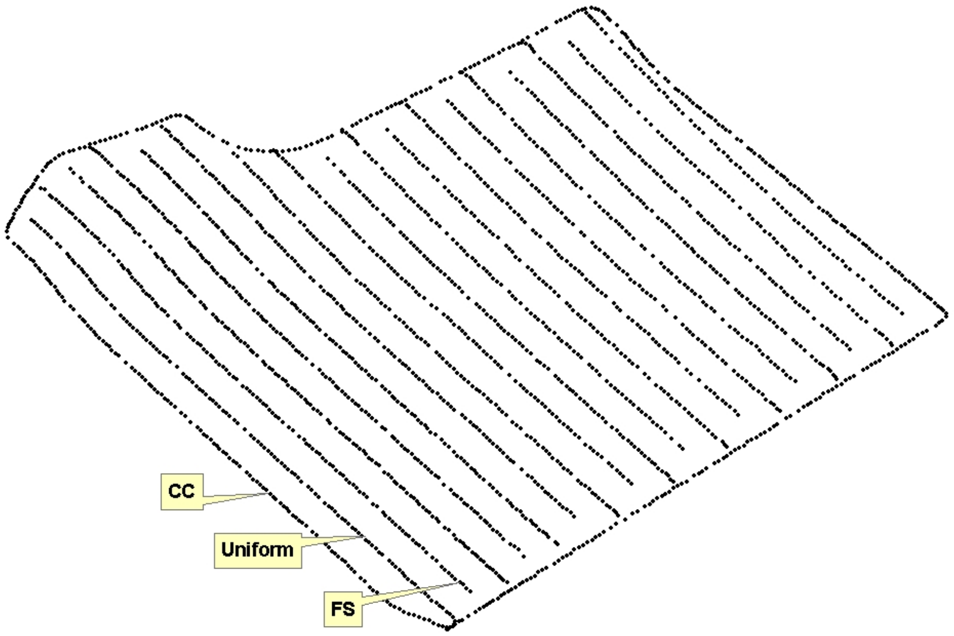


Figure 4-1 Design of the experiment

The following steps were taken to apply nitrogen:

- to scan all fields with both sensors simultaneously,
- to perform the calibration of the NDVI values obtained from field measurements of tiller density at targeted locations of the field from poor to dense crop, as described in the previous section and introduced by Wood et al.(2003a),
- to divide the field into strips (where the width of strips was given by the tramline spacing) allocating the CC, UNIFORM and FS based methods to each strip alternately,
- to divide each strip along its length into zones of different tiller densities – different NDVI values (above, under and on target) after Godwin et al. (2003),
- to calculate the nitrogen rates for each zone based on HGCA methodology (HGCA, 1997),
- to apply nitrogen.

Yield was used as an indicator of variable nitrogen management effects. The field was harvested with a combine harvester Massey Ferguson 7276 equipped with a yield monitoring system. The yield obtained was analysed from these aspects:

- total yield per field,
- total yield per strips,
- variability of yield along strips.

Nitrogen efficiency and nitrogen residuals in soil were analysed as well. An economical analysis was conducted to determine costs and benefits of nitrogen application to improve yield only. The economic benefits of environmental aspects are difficult to calculate at the current time.

4.3 Results and discussion

4.3.1 Nitrogen application

The field was scanned on 5th May 2006 by both the CC and the FS simultaneously. Basic statistics of NDVI values of CC measurements are given in

Table 4-1, with respect to treatments used for the experiment. The map of NDVI values is given in Figure 4-2. Basic statistics of NDVI values of FS measurements are given in Table 4-2, the data are plotted in Figure 4-3.

Table 4-1 Basic statistics of NDVI values obtained by Crop Circle (5th May 2006)

Parameter	NDVI values obtained by Crop Circle		
	CC	Uniform GB	FS
Mean	0,61	0,62	0,62
Standard deviation	0,09	0,08	0,07
Minimum	0,23	0,31	0,35
Maximum	0,78	0,79	0,77
Coefficient of variability, %	15,52	13,20	10,93

CC – tramlines which belong to treatment based on CC values
Uniform– tramlines which belong to uniform treatment
Field Scan - tramlines which belong to treatment based on FS values

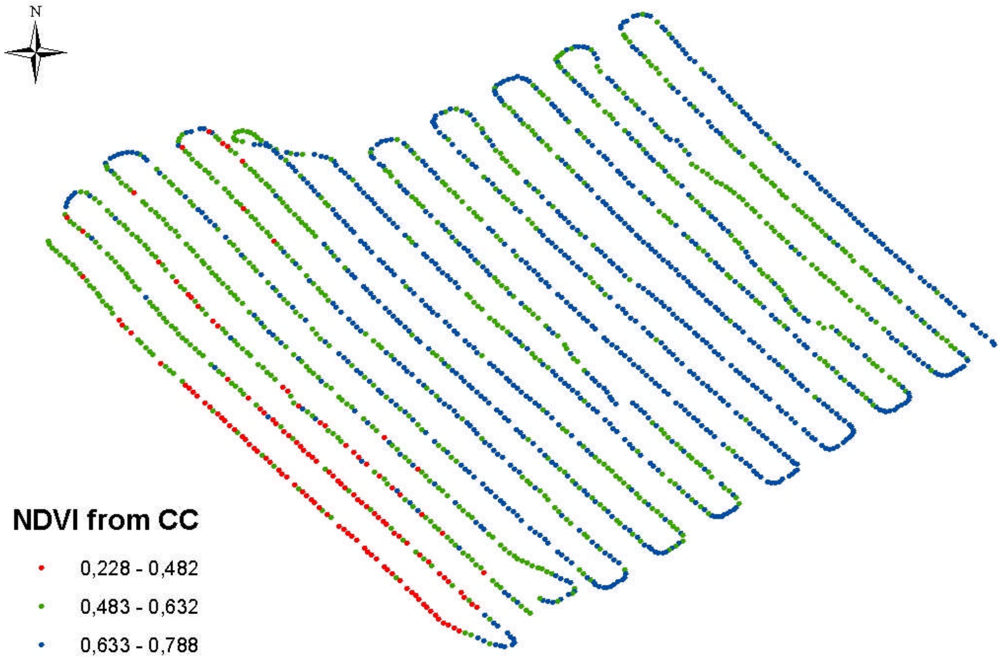


Figure 4-2 NDVI values obtained by Crop Circle (5th May 2006) (red-below target, green – on target, blue – above target crop)

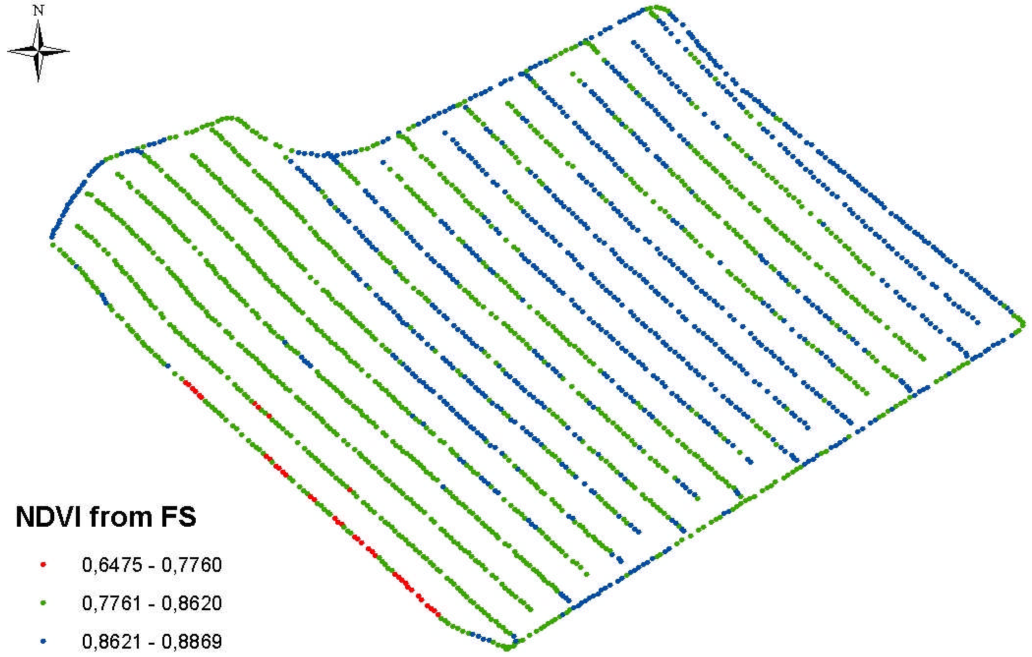


Figure 4-3 NDVI values obtained by FS (5th May 2006) (red-below target, green – on target, blue – above target crop)

Table 4-2 Basic statistics of NDVI values obtained by Field Scan (5th May 2006)

Parameter	NDVI values obtained by Field Scan		
	CC	Uniform	FS
Mean	0.85	0.85	0.86
Standard deviation	0.03	0.019	0.01
Minimum	0.65	0.75	0.79
Maximum	0.88	0.88	0.89
Coefficient of variability, %	3.53	2.27	1.51

The NDVI data obtained from both sensors were ground calibrated by numbers of shoots, following the methodology given in Section 3 and introduced by Wood et al. (2003a). The equations of linear regression for this relationship were $y=1012x+112.24$ with $R^2=0.59$ for the Crop Circle sensor and $y=1748x-756.23$ with $R^2=0.52$ for the Field Scan sensor. The threshold values and nitrogen rates (Table 4-3) were estimated based on Practical guidelines “Precision farming of cereals” (Godwin et al., 2003) and personal communication with agronomist (Parrish, 2006). Crop density of below 600 / m^2 was considered as below target, 600 – 750 shoots on target and above 750 - above target. However, estimation of the threshold values is critical as the areas of above, on and below the target may change and so the design of the fertiliser application map. This could have significant influence to the overall efficiency of the sensors performance.

Table 4-3 Parameters and total amounts used during the experiment at Wilstead

Tiller density	<600 tillers per m^2		600 – 750 tillers per m^2		>750 tillers per m^2	
N rate	150 $kg.ha^{-1}$		115 $kg.ha^{-1}$		80 $kg.ha^{-1}$	
Method \ area	%	ha	%	ha	%	ha
CC	5	0.38	46	3.29	49	3.54
Uniform	-	-	100	6.16	-	-
FS	-	-	55	3.42	45	2.75

The Nitrogen rates were determined for each category of tiller density and the fertilising scenario was design (Figure 4-4). Fertiliser Extran 37% N (Yara) was applied on the crop with the Spra Coupe sprayer. The total amounts of fertiliser applied are indicated in Table 4-3.

On the base of the experiment conducted, it can be concluded that both the CC and FS system saved on nitrogen, compared to the UNIFORM practice. Lower rates of nitrogen were applied on 49% and 45% of the area of the active and passive-based strips (Table 4-3, Figure 4-4), respectively; higher nitrogen rates were applied on 5% of the area using active system (Figure 4-5). Savings of 15 $kgN.ha^{-1}$ were obtained with variable nitrogen management (Table 4-4).

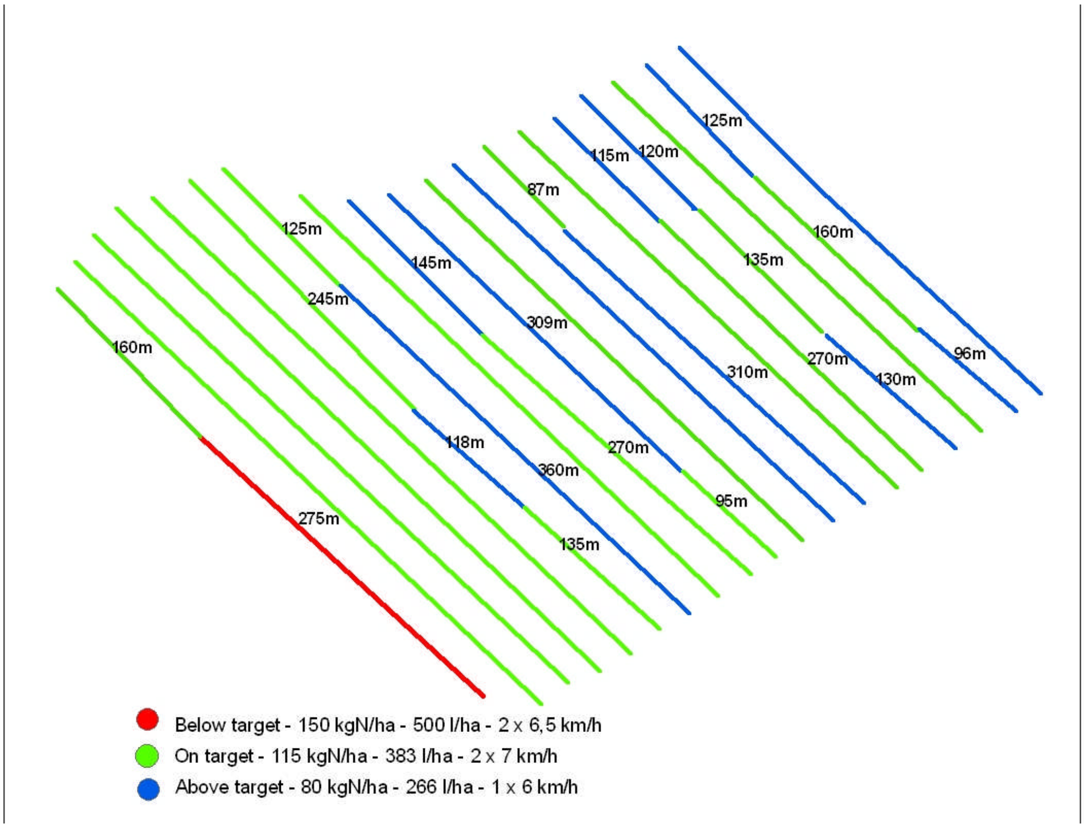


Figure 4-4 Experimental fertiliser application design

Table 4-4 Saving on nitrogen during the experiment in Wilstead

	Crop Circle	Field Scan
Saving on nitrogen for all field, kg	110	96
Saving on nitrogen/kg.ha^{-1}	15.3	15.6

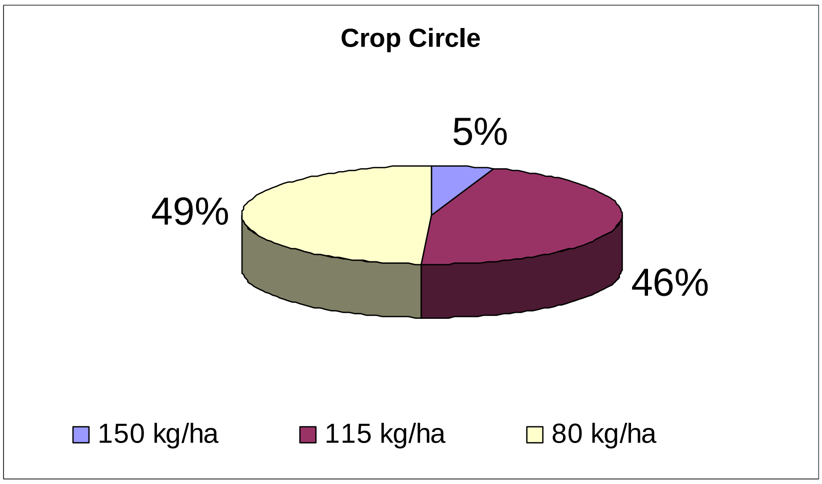


Figure 4-5 Analyses of nitrogen dose applied based on CC NDVI data

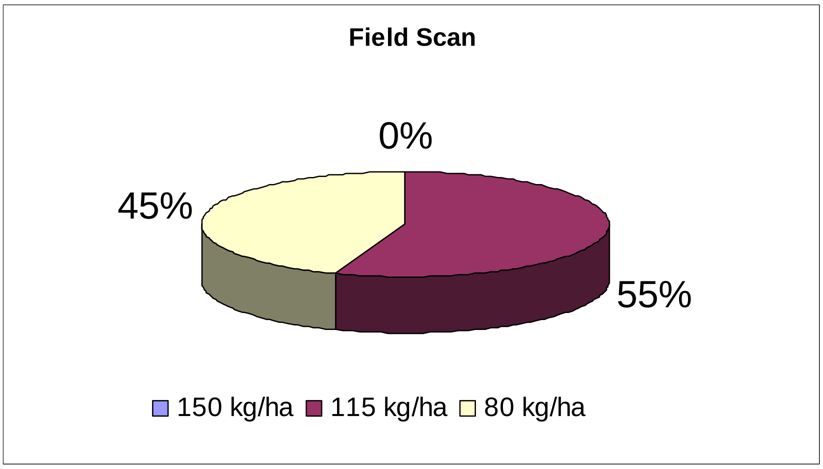


Figure 4-6 Analyses of nitrogen dose applied based on FS NDVI data

Resulting from the analyses, it could be concluded that variable application of nitrogen brought more precise targeting of nitrogen application, using the sensor approach lower nitrogen rates were applied at almost half of the field area.

Comparing the maps of NDVI (Figures 4-2 and 4-3), where the values are divided with respect to their equivalent threshold tiller density values, the CC sensor determined a larger zone of below-target crop (< 600 tillers/m^2) shown in red than that found using FS.

4.3.2 Yield analyses

The field was harvested using a Massey Ferguson 7276 (Figure 4-7) combine equipped with a grain flow monitoring system. The parameters of the monitoring system were set up as following:

- „Lead time“ –minimum - 5 seconds,
- „Lag time“– maximum.

The yield map of the field is given in Figure 4-8. The crop was harvested in 7.5 m strips, where two were taken from each side of tramline. This technique enabled to use the full width of the cutter bar. Data were recorded with a frequency of 1 second; the forward speed of the combine harvester was 3.5 km/h. Data obtained were used for further analyses given in next sections.

Figure 4-7 Harvesting of the experimental field by Massey Ferguson 7276 equipped with a yield monitor

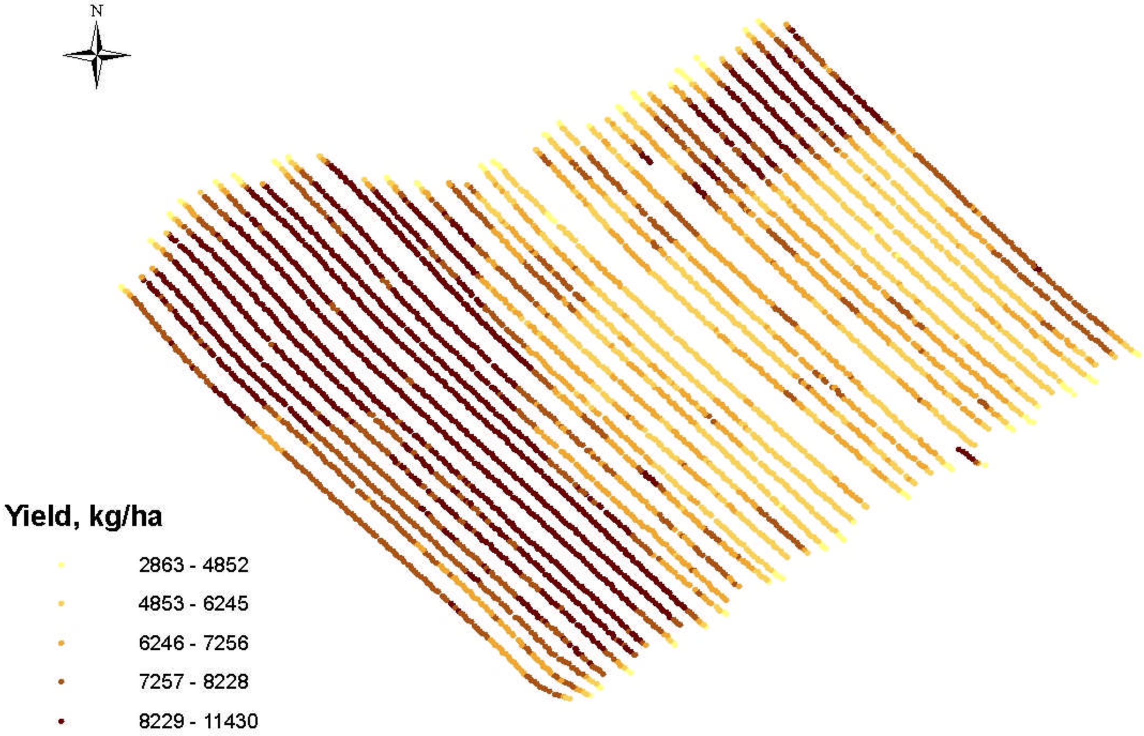


Figure 4-8Yield map of the experimental field

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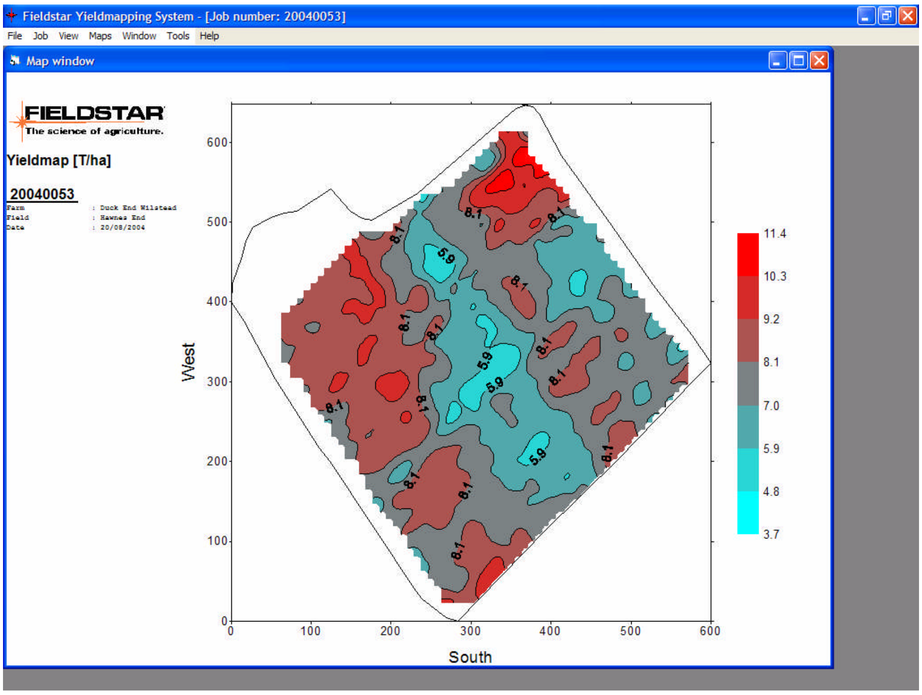
Comparing the yield map from the 2004 (Figure 4-9) with the yield map from 2006 (Figure 4-10), two zones were created (higher yield and lower yield). The higher yielding zone is the zone, where the yield reached above the value of 8 t.ha^{-1} in the years 2004 and 2006. Lower yielding zone is a zone below 8 t.ha^{-1} in the two growing seasons.Therefore the data were analysed in respect of the zones and of the sensors.



20040053

Farm : Duck End Wilstead
Field : Hawnes End
Date : 20/08/2004

Figure 4-9 Yield map from 2004

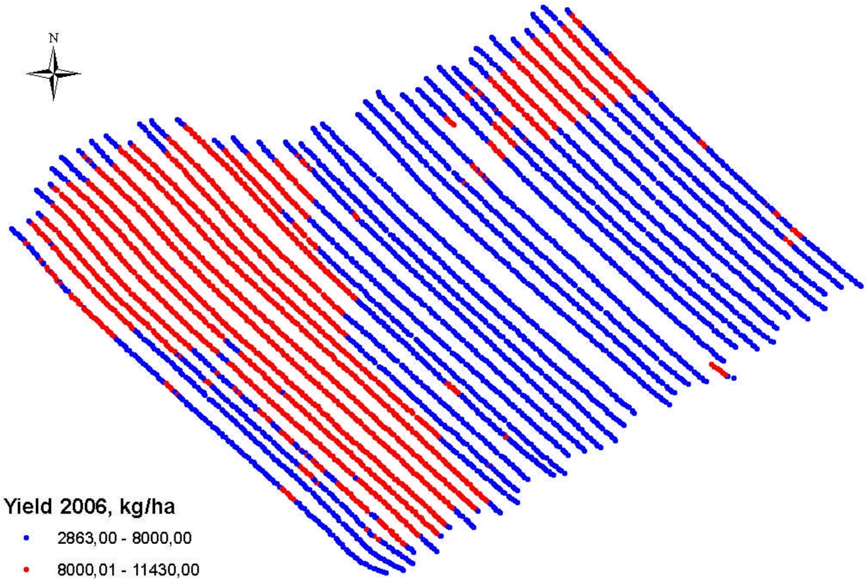


Figure 4-10 Yield map from 2006, where the yield is divided to categories above and under the value of 8 t/ha

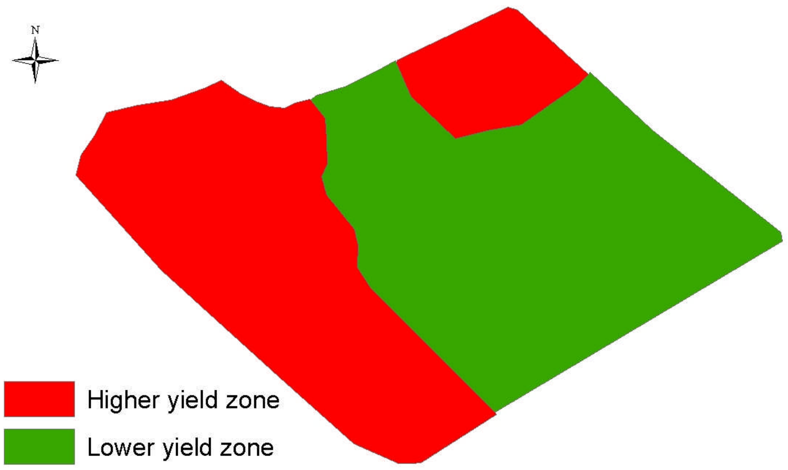


Figure 4-11 Determination of higher and lower yield zones based on two years yield maps

4.3.2.1 Total yield per field

The total yield for each alternative was determined and statistically compared. The basic statistics of overall yield are summarized in Table 4-5.

Table 4-5 Basic statistics for yield

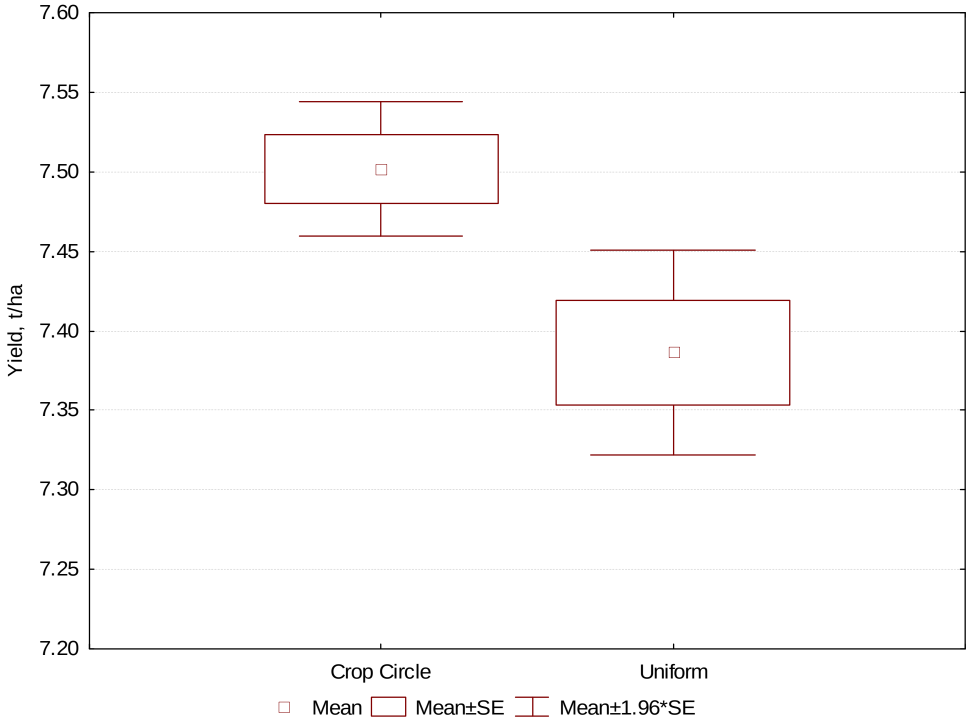
Parameter	Yield , $t.ha^{-1}$		
	CC	Uniform	FS
Mean, $t.ha^{-1}$	7.50	7.39	7.28
Standard error of the mean, $t.ha^{-1}$	0.02	0.03	0.03
Standard deviation, $t.ha^{-1}$	1.07	1.35	1.13
Minimum, $t.ha^{-1}$	4.72	4.67	4.51
Maximum, $t.ha^{-1}$	9.64	9.47	9.27
Number of samples	2453	1714	1975
Coefficient of variability, %	14.31	18.31	15.47

By the very nature of the problem, the treatments could not be replicated and hence the most useful comparison would be between each variable treatment and the

Uniform “control” treatment. The actual zones compared were not the same but near neighbours. The other unusual feature of this data set is that it is virtually a collection of whole population of samples because of the all of the crop passes through the combine and the flow rate is recorded at approximately 1m intervals. This resulted in 1714 to 2453 samples per treatment. Using this information, the mean was calculated with a very small standard error of the mean (Table 4-5). As a result of this there is a statistically significant difference between mean yields of the two variable treatments and the Uniform treatment (Figure 4-12). However, the box and whiskers graphs for the standard deviation of the treatments (Figure 4-13) show no significant difference between the yields from an agronomic point of view. This was caused by the overall variability of the field.

Comparing the means of yield, there was an overall yield increase of 1.6% for the strips managed by the active sensor (CC) and a decrease of 1.5% for the strips managed by the passive sensors (FS). However, the strips were not on absolutely identical soil zones so a small variation might be expected on either side of the uniform treatment. Moreover, the absolute yield was strongly influenced by soil conditions as it reflects the higher and lower yielding zones from the historical information.

The results in Table 4-5 also show that the coefficient of variability for the CC and FS treatments respectively, are 16% and *22*% lower than in the uniform approach.



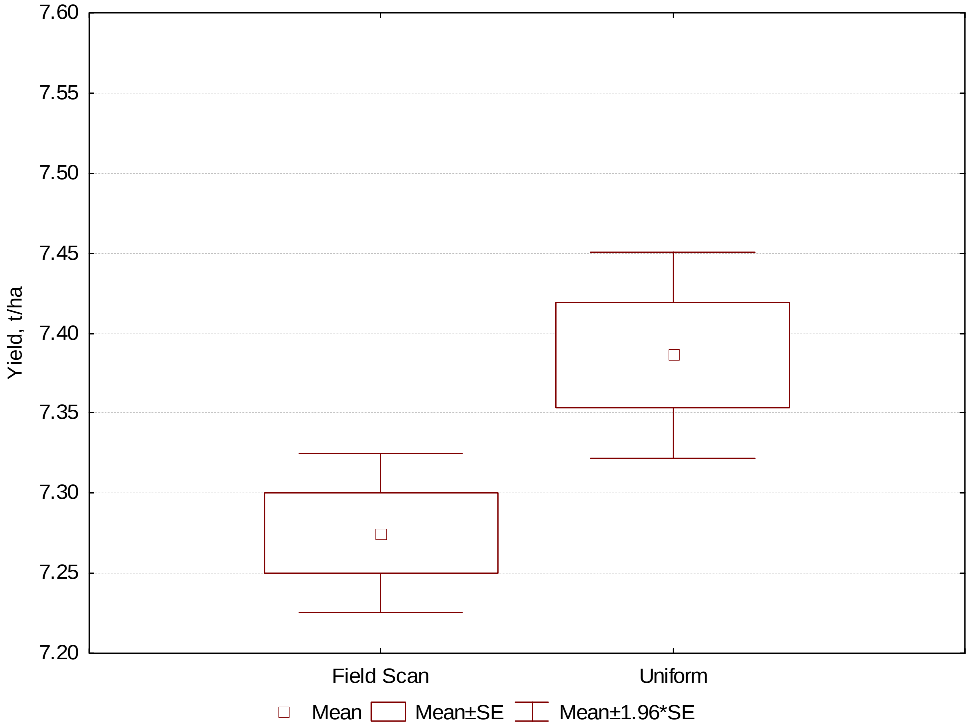
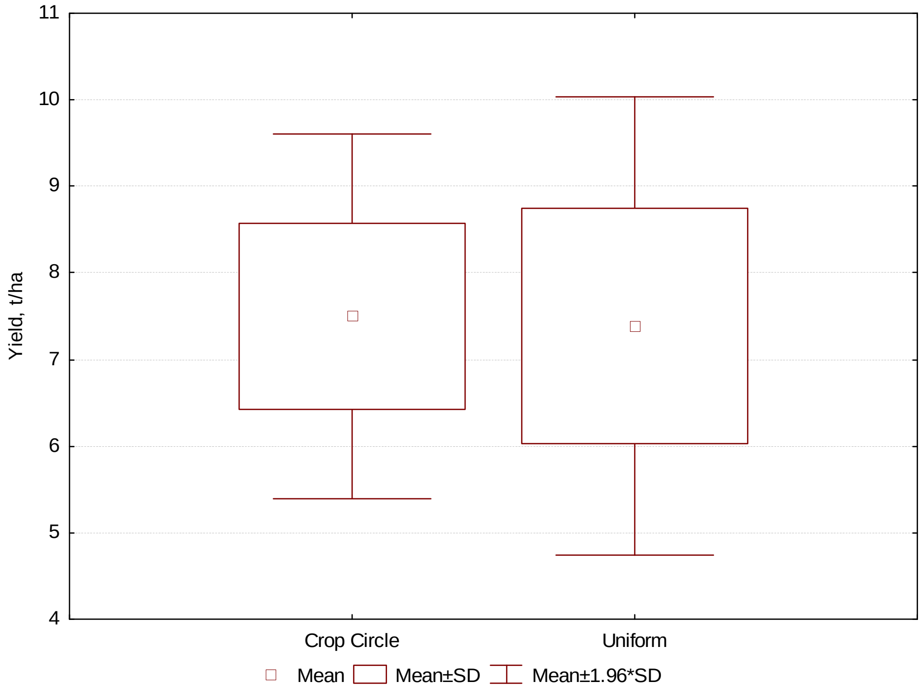


Figure 4-12 Box and whiskers graphs for the mean and the standard error (above – Crop Circle vs. Uniform, below- Field Scan vs. Uniform)



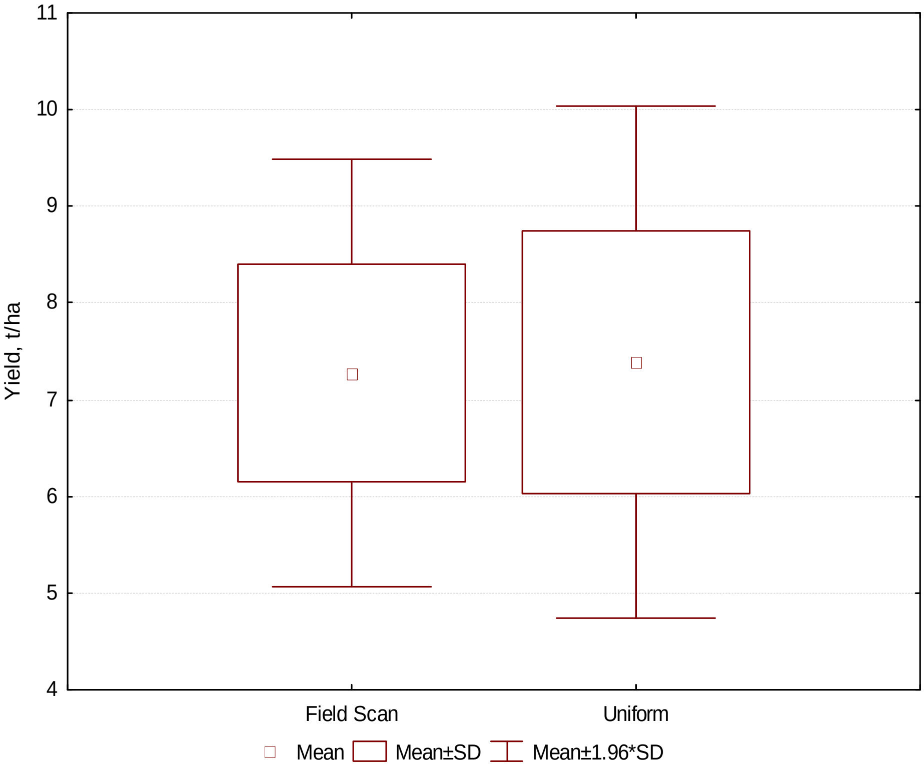


Figure 4-13 Box and whiskers graphs for the mean and the standard deviation (above –Crop Circle vs. Uniform, below – Field Scan vs. Uniform)

4.3.2.2 Total yield per strip

The total yield per each strip is given in Figure 4-14 together with coefficient of variability. From the figure is obvious that the higher yielding zone is allocated from tramlines no 1 to tramline no 7.

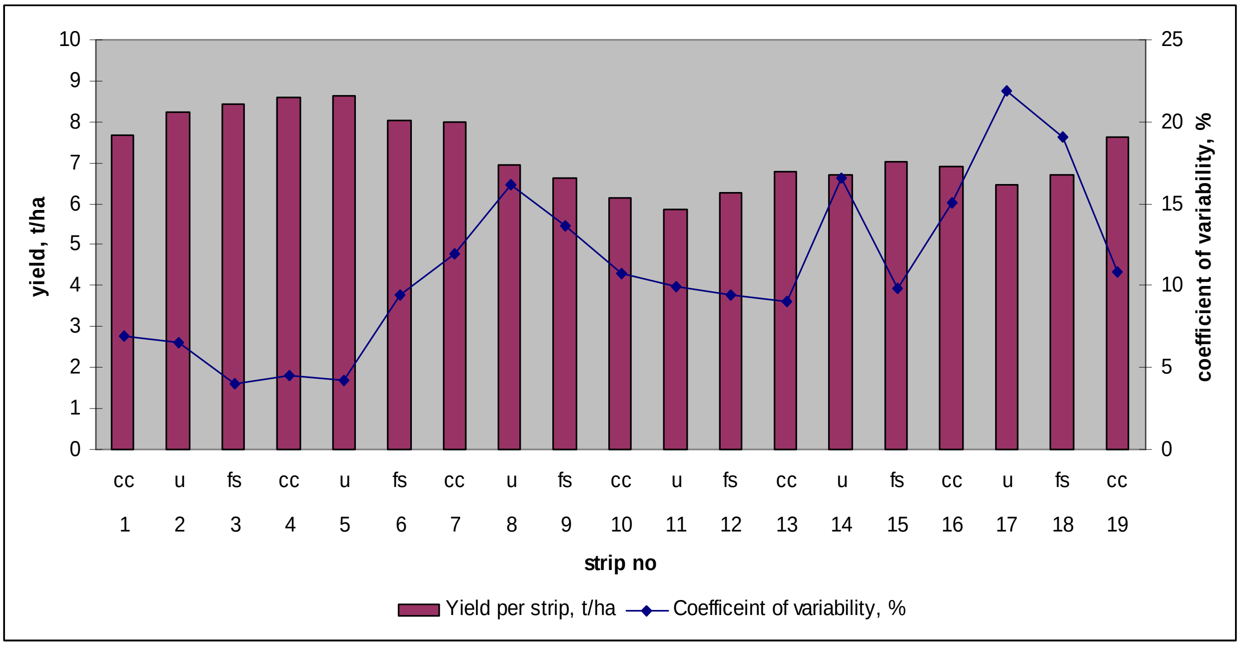


Figure 4-14 Total yield per strip

The coefficient of variability reflects the variability of the yield within the strip. Analysing each strip separately, there are three strips with high value of coefficient of variability (Figure 4-14). The harvested yield along tramlines no 8, 14 and 18 have higher variability compared to their neighbouring tramlines. All three tramlines were treated uniformly. Moreover, all three tramlines are located across both yield zones of the field (Figure 4-15). Compared to their neighbour tramlines (Table 4-6), which were treated variably, the coefficient of variability is from 18% to 84 % higher. According to these results, it can be concluded that the variable application brought benefit through reduction of the yield variability. This is apparent mainly in the parts of the field where both higher and lower yielding zones are present.

Table 4-6 Basic statistics of yield for selected tramlines

Strip / Treatment	7/CC	8/U	9/FS	13/CC	14/U	15/FS	16/CC	17/U	18/FS
Mean, t/ha	8.00	6.96	6.65	6.77	6.72	7.04	6.91	6.46	6.73
Median, t/ha	8.30	6.65	6.56	6.74	6.49	6.98	6.61	5.84	6.16
Modus, t/ha	7.33	5.46	7.50	6.17	5.86	6.75	5.52	5.52	5.78
Standard deviation, t/ha	0.96	1.12	0.91	0.61	1.12	0.69	1.04	1.41	1.28
Minimum, t/ha	5.32	4.79	4.78	5.20	2.99	4.51	4.72	4.67	5.02
Maximum, t/ha	9.65	9.47	8.81	8.11	11.43	8.62	9.36	9.39	9.27
Coefficient of variability, %	11.97	16.12	13.65	9.01	16.60	9.85	15.03	21.88	19.09

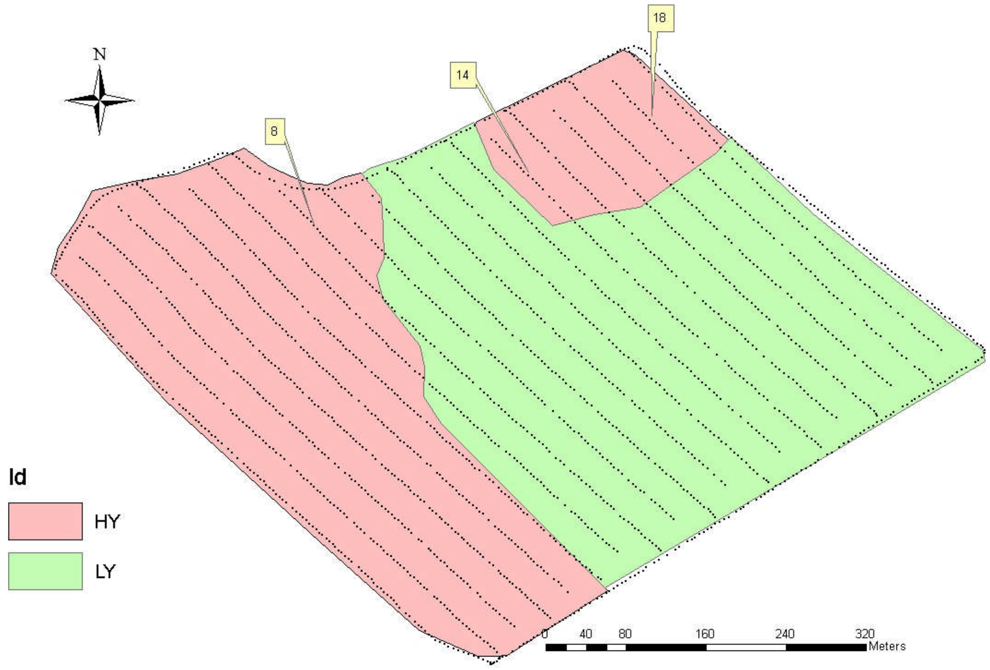


Figure 4-15 Location of the selected tramlines in respect to the High and Low yielding zones

4.3.2.3 Variability of yield per strip

Variability of each strip was further analysed. Factorial analysis was conducted on the yield picked from along the tramline transects (Appendix 4-1) and the higher and lower yield zone factor was separated along with the three treatment factors (Crop Circle, Uniform, Field Scan).The statistical results in Appendix 4-1 show that the zone factor has a significant influence on yield and the treatment factor does not.

Variability within a strip was analysed based on the yield mapping data of the recorded yield. The yield along strips is shown in Figures 4- 16 to 4 – 18.

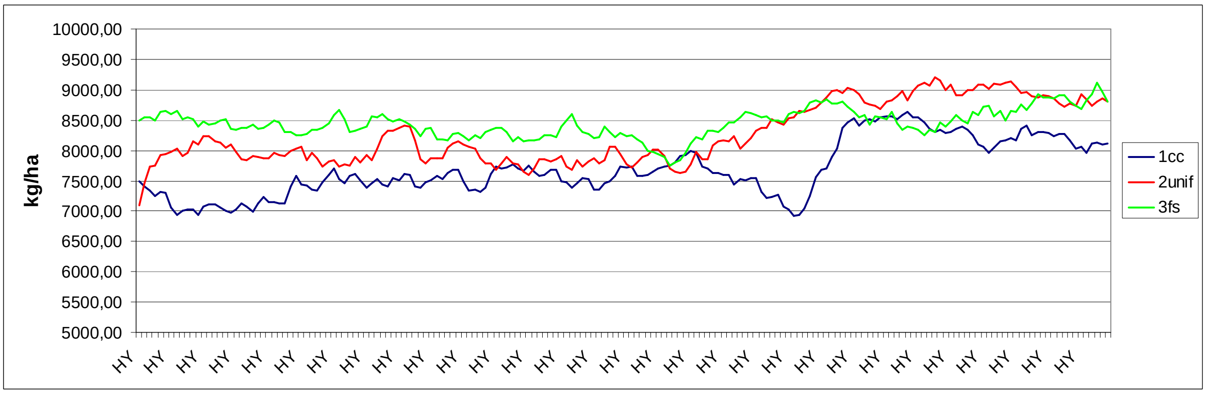


Figure 4-16 Yield data along the strips 1, 2 and 3 belonging to the higher yielding zone (HY)

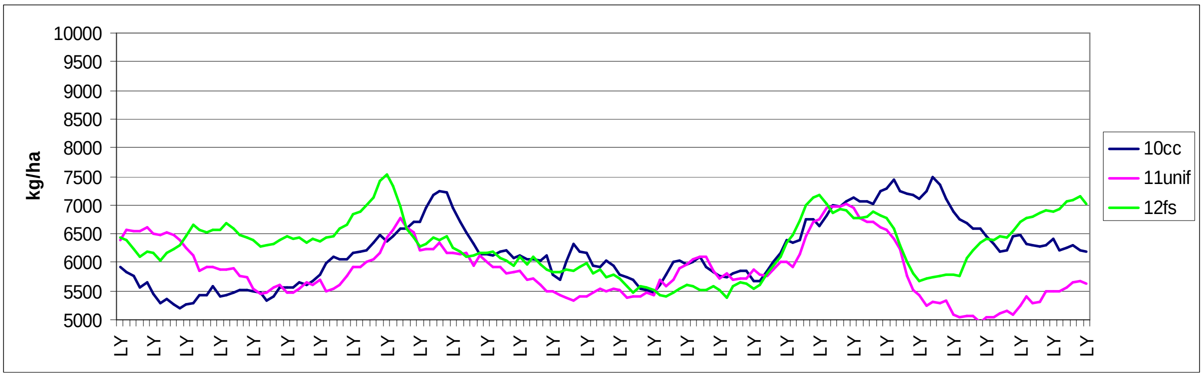


Figure 4-17 Yield data along the strips 10, 11 and 12 belonging to the lower yielding zone(LY)

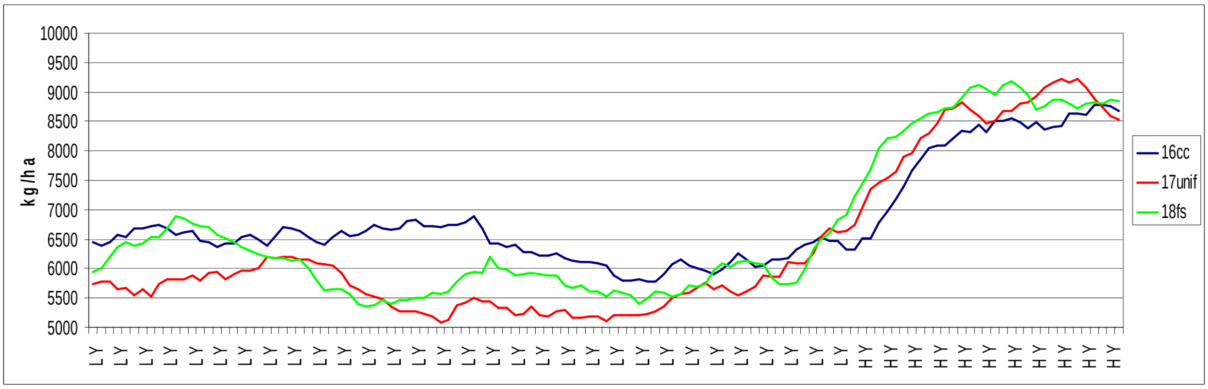


Figure 4-18 Yield data along the strips 16, 17 and 18 belonging to the lower and higher yielding zone

From these figures it is evident that the yield along the strips tends to change in similar manner for all treatments. This may be a result of the fact that each strip is offset from its neighbour by 24m. The average difference between yield of uniform treatments and yield of variable treatments for all three cases (Figure 4 – 16 to 4-18) is given in Table 4-7. In average the difference between uniform and variable strips as from 2.26% to 6.85% in favour of variable strips. However, the yield of the strip number one (CC) was lower by 7.07% compared to the next uniform strip. The crop along this strip was below target crop before the application (see Figure 4-2).

Table 4-7 Yield difference between UNIFORM and variable treatments (%)

Selected tramlines and zones where they belong	Yield difference between UNIFORM and variable treatments (%) for selected tramlines	
	CC	FS
HY zone (tramlines 1-3)	-7.07	2.26
LY (tramlines 10 – 12)	5.30	6.85
HY and LY (tramlines 16-18)	6.59	4.27

The influence of type of zone on the yield could be seen from Figure 4-19, where all three treatments go through Higher as well as Lower yield zones. The limiting factor of yield was therefore probably soil conditions. The soil conditions were not analysed in detail. Information about soil variability is evident from Figure 3-3 and the map given in Appendix 4-2, where two soil types have been identified in the field (Evesham and Efford), the former is a clay loam soil and the later a well gravely loam soil (Mackney et al., 1983). The resolution of the field survey was not sufficiently precise to allocate the boundaries found in this study. It could be concluded that the absolute yield obtained was not influenced by the dose of Nitrogen but the soil conditions of the zones of the field. However, this information showed also, that use of sensors enabled the reduction in the nitrogen dose without any significant influence to yield.

4.3.2.4 N utilisation

The yield obtained at a particular location was divided by the amount of Nitrogen applied to obtain an N utilisation value – *i.e*. kilogram of yield per kilogram of N (Figure 4-19).

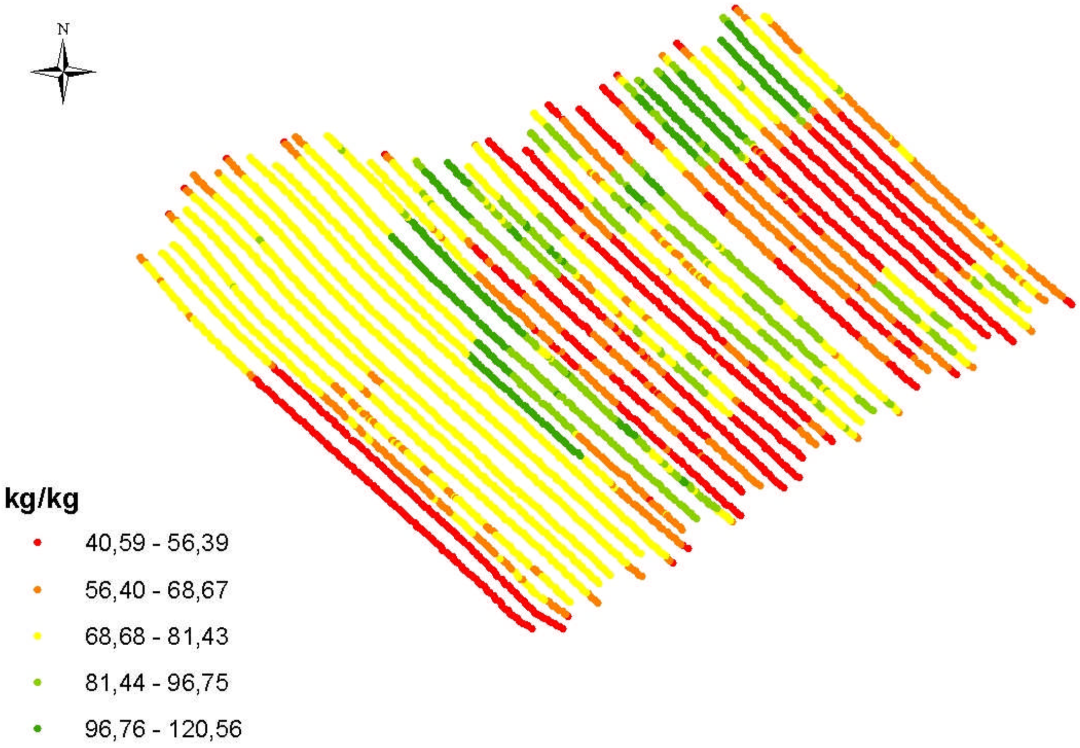


Figure 4-19 Map of Nitrogen utilisation

Nitrogen utilisation was also assessed along the strips. The first tramline, managed by CC was along the western headland; because of the poor crop stage it required an increased amount of nitrogen. The effect of this was reflected in the reduced nitrogen efficiency (Figure 4-19).

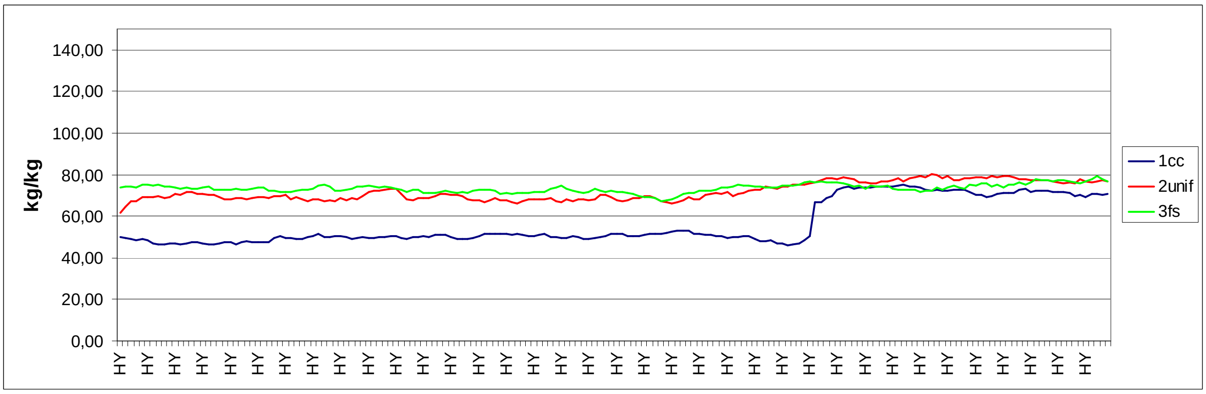


Figure 4-20 Nitrogen utilisation along tramlines number 1, 2 and 3 in higher yielding zone

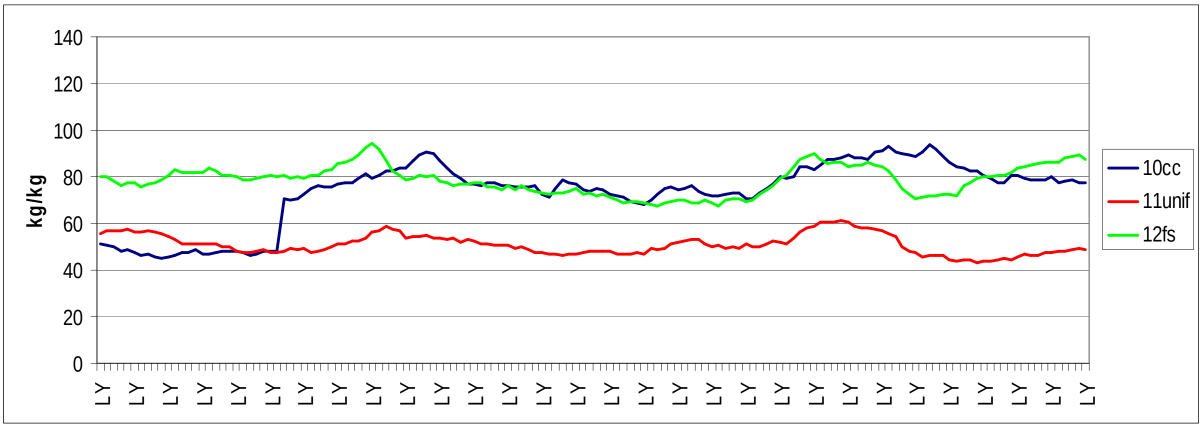


Figure 4-21 Nitrogen utilisation along tramlines number 10, 11 and 12 in lower yielding zone

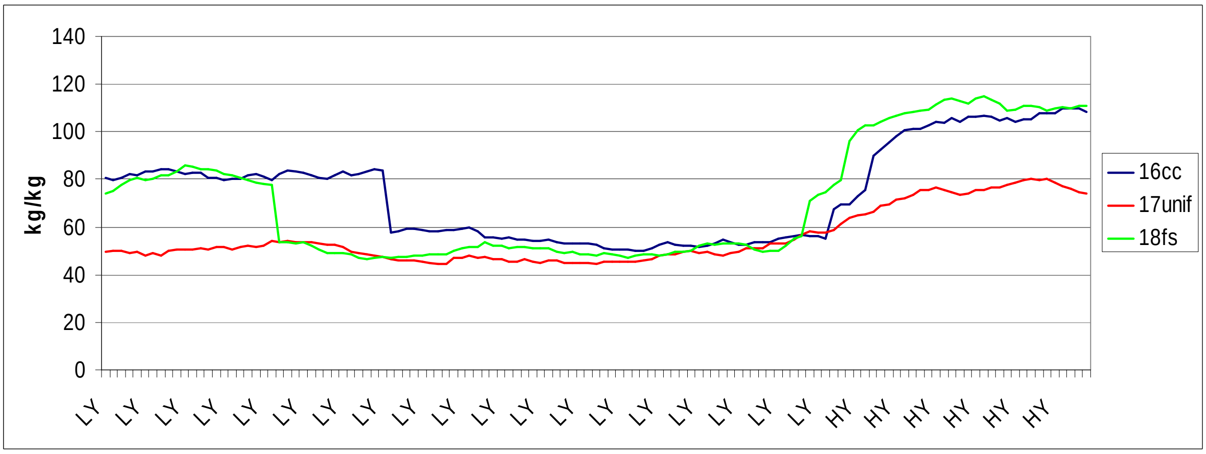


Figure 4-22 Nitrogen utilisation along tramlines number 16, 17 and 18 in higher and lower yielding zone

The spatial pattern of N utilisation corresponds closely to the historical yield information. The poorest utilisation of N is in the area with low yield. Apparently from Figure 4-21, the lower dose of nitrogen managed by CC and FS enabled an increase in Nitrogen efficiency. This shows that especially in this zone it is essential that the dose of nitrogen has to be applied with care, to reduce any over-application.

Tramlines 17, 18, 19 (Figure 4-22) represent a change from the lower yielding zone, from which it is obvious that reducing the dose based on the ground based remote sensing system brought a benefit in Nitrogen use efficiency at the beginning and the end of the tramline. The mid tramline zone has a poorer utilisation as for the CC and FS an extra nitrogen has been applied to stimulate the crop development which failed to be utilised. This suggests that the problems with the soil in this zone are not due to nitrogen but other fertility issues, which the lack of time prevented from the detailed investigation. From which it could be concluded that the yield overall was influenced by soil conditions (belonging to production zones). However, the efficiency of Nitrogen use is increased using the precision farming methods.

4.3.2.5 Residual N analyses

From the environmental point of view it is essential to apply nitrogen in the way that it does not negatively impact on ground water quality through leaching of excess, unused fertiliser. Therefore, the amount of residual nitrogen is important. To understand the N balance, five soil samples were taken at the beginning of the season

The soil samples were taken at the field in order to estimate the level of Nitrogen available form soil. The laboratory analyses showed the average nitrogen level available for the field was 6 kg/ha. This amount did not influence the amount of nitrogen applied. The average amounts of applied Nitrogen are given in Table 4-8. The uniform treatment resulted in nitrogen residuals of 36.15 kg/ha whereas the variable applications CC and FS only 17.5 and 23.5 kg/ha assuming that each tonne of winter wheat grain together with equivalent of straw will take off 25 kg of N (Fecenko & Ložek, 2000).

On the basis of these analyses it can be concluded that the variable application of nitrogen, which is based on the crop status, enables a reduction of nitrogen residuals comparing to uniform treatment of 36 – 52%, which is a potentially significant environmental benefit.

Table 4-8 Nitrogen residual analyses

Treatment	N in soil, kg/ha	Other applications, kg/ha	Experiment application, kg/ha	Sum of applied nitrogen, kg/ha	Average yield, t/ha	Take off, kg/ha	N residuals, kg/ha	N residuals, %
Uniform	6	100	115	221	7.39	184.85	36.15	100
CC	6	100	99	205	7.5	187.5	17.5	48.4
FS	6	100	99	205	7.27	181.75	23.25	64.31

4.4 Economical analyses

The use of the two sensors was analysed from an economical point of view. The use of ground based sensors influences the overall costs of nitrogen management in the following aspects:

- the cost resulting from the sensor price (cost of sensor and tractor),
- costs of data processing and analysing, calibration of data and design of fertiliser application protocols,
- costs of equipment needed for variable application,
- the amount of fertiliser applied may be changed due to variable application.

Regarding the returns, the influence can be seen in resulting crop yield and so the returns from production. However, it was not possible to calculate the economic values of the environmental benefits. Assumptions:

- Depreciation is estimated to 13.5% (Nix, 2005) – 6 years retained and the trade-in value at the end would be 20%.
- Repairs and maintenance costs – 4% (Nix, 2005),
- Radiometry calibration was estimated as £4.85 per hectare (Godwin et al., 2003b)
- Costs of sensor use were calculated based on Godwin et al. 2003b.

Purchasing costs of sensors used in the calculations were as following:

- Field Scan (sensor & terminal) – £13000,
- Crop Circle (£2500), iPAQ & FarmWorks software (£2000) - £4500 (Morris, 2006).

The annual costs of Field Scan and single CC sensor per unit area for a range of arable areas given in Figures 4-23 and 4-24. The costs initially decrease rapidly with increasing the area over which they are used. They start to approach steady state at area above 600 ha.

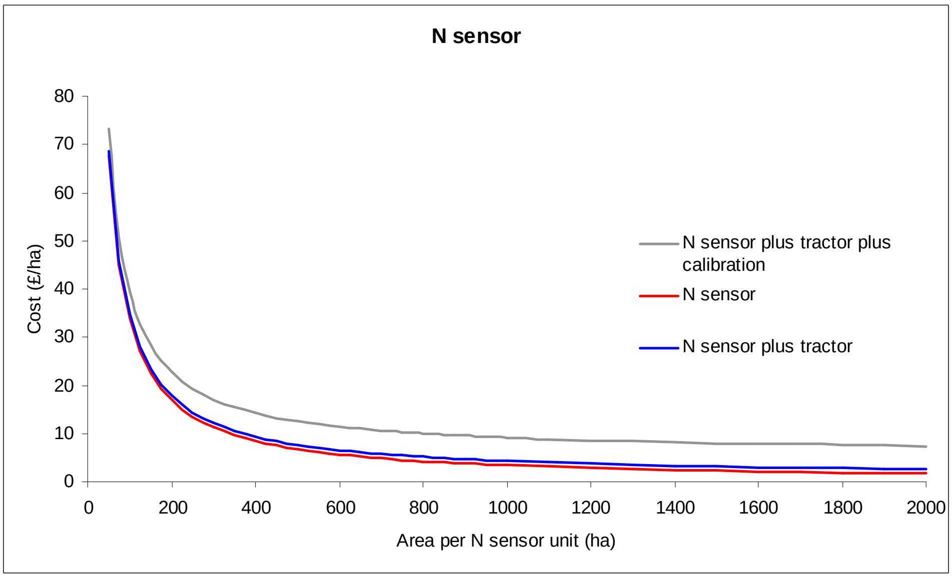


Figure 4-23 Costs of N sensor (Field Scan) sensor per area

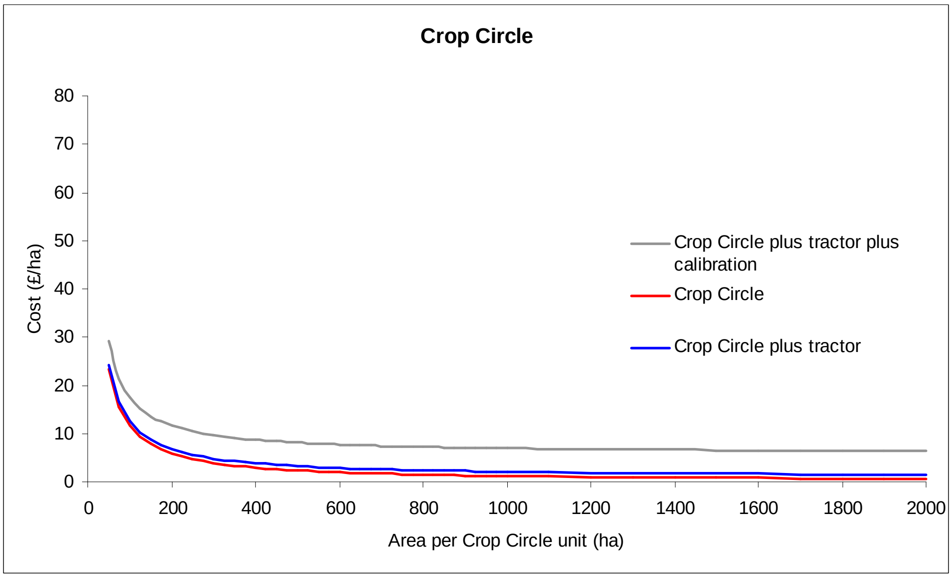


Figure 4-24 Costs of Crop Circle sensor per are

Cost of nitrogen application for all three treatments was calculated with assumption of area of 600 ha, which is modest but could be practically achieved. The analysis assumes that the conventional farm machinery will be used. New cost item is cost of scanning (using the scanned to asses the variability in crop) and cost of ground calibration of sensor values. After Morris (2007) one Crop Circle sensor has to be used on each side of the sprayer, therefore two Crop Circle sensors are included in the analysis (Table 4-9). The costs of sensors, including the ground calibration of the sensors of £4.85 /ha (Godwin, 2003), is £9.65/ha for Crop Circle and £11.38/ha for Field Scan. However, cost of data processing and analysing should be included as well.

Table 4-9 Costs of sensors for scanning of the crop

	Crop Circle + iPAQ	Field Scan
Sensor price, £	4500	13000
Cost of sensor use, £/ha	1.95	5.63
Sensor + tractor use per hectare, £/ha	2.85	6.53
Sensor + tractor + calibration use per hectare, £/ha	7.7 (one sensor)	11.38
	9.65 (Two sensors)	

Considering the average saving on Nitrogen per hectare at 15 kg at £0.43/ kg brings benefit of almost £6 per hectare. The difference which should be covered by benefit (yield increase or environmental benefit) is for Crop Circle £3.65/ha and for Field Scan £5.38 / ha. At the price level of £80 (Bullen, 2007) per tonne of winter wheat, it means increasing the yield by 0.05 to 0.07 t. Having the average yield 8 t/ha it gives the increase by 0.5% - 1%.

Considering the overall costs of nitrogen fertilisation, based on Nix (2005), the cost items of traditional UNIFORM application could be estimated as following:

➢ Fertiliser	220kg* £0.43 /kg= £94.6/kg
➢ Machinery (sprayer) (usually 3 application)	£8.25/ha *3 = £24.75/ha
➢ Overall cost of nitrogen application	£119.35/ha

Considering the overall costs of nitrogen fertilisation, based on Nix (2005), the cost items of variable application based on FIELD SCAN could be estimated as following:

➢ Fertiliser	220kg* £0.43/kg= £94.6/kg
➢ machinery (sprayer) (usually 3 application)	£8.25/ha *3 = £24.75 /ha
➢ Use of sensor (for three application)	£11.3/ha * 3 = £33.9/ha
➢ Overall cost of nitrogen application	£153.27 /ha

Costs of nitrogen application using the CROP CIRCLE approach would consist of following (with assumption of no changes of nitrogen amount):

➢ Fertiliser	220kg* £0.43/kg= 94.6£/kg
➢ Machinery(sprayer) (usually 3 application)	£8.25/ha *3 = £24.75 /ha
➢ Use of sensor (for three application)	£9.65/ha * 3 = £28.95/ha
➢ Overall costs	£148.3/ha

However, using the commercial application of N sensor (for the real time application) would result in a 10% decrease in the cost of nitrogen application from £153.27/ha to £137.35/ha. From which, it can be concluded that the Crop Circle system would be more economically effective if it was be integrated into a real time application system. This would reduce the number of operations because the scanning and the application would be conducted in one pass of the machine.

Table 4-10 Costs of N sensor when using integrated real time application systems

	N sensor
Sensor price, £	13000
Sensor, £/ha	5.63
+calibration by (N tester @£1000)	0.43
Use of sensor for real time application	6.06

Costs of nitrogen application using the N sensor commercial approach would consist of following (with assumption of no changes of nitrogen amount):

➢ Fertiliser	220kg* £0.43/kg= £94. 6/kg
➢ Use of sensor (for three application)	£6 /ha * 3 = £18/ha
➢ Machinery(sprayer) (usually 3 application)	£8.25/ha *3 = £24.75 /ha
➢ Overall costs	£137.35/ha

4.5 Conclusions

1. Real time application with ground based remote sensing systems brings benefits. However, the yield was marginally sensitive to the technique +/- 1.5%.

2. Estimation of threshold values of biomass is critical and can influence the overall economical performance of the system.

3. Both ground based systems brought benefits in terms of nitrogen saving, up to 15kg N/ha (£6/ha) at Wilstead and the use of Nitrogen was improved in terms of its utilisation per tonne of yield without negative influence to yield.

4. Variable application of Nitrogen brings potential environmental benefits. The variable application reduced the residual Nitrogen in the soil by 36% - 52% for the Crop Circle and the Field Scan strips respectively.

5. The yield increase could be expected, however the yield is significantly influenced by soil conditions. Therefore it could be recommended to include the yield zones factor into the analyses and manage the Nitrogen accordingly.

6. Application machinery with the integrated real time application system is critical to be able to use the economic advantage from Crop Circle.

7. In addition to the potential economic and environmental benefits, real time application can also provide data for the traceability of Nitrogen fertilizer application levels.

5 Field comparison of Nitrogen Management Strategies - Oponice

5.1 Introduction

The use of remote sensing sensors in practical farming conditions requires further information on the operational conditions, required time to use the information and the costs/benefits of the operation. Currently, three strategies for nitrogen management are available:

- Real-time nitrogen management – where the information is gathered, process and immediately nitrogen is variably applied based on this. Such a system is e.g. N sensor and Greenseeker.
- Farmer's best practice using information only in terms of determining the dose of nitrogen for the field – application is uniform.
- Near real time application of nitrogen, information is gathered, processed, application map is created and then used to apply nitrogen variable, usually in zones.

The upper two are used within the technology of precision farming; the later is traditional uniform nitrogen management.

The difference between these three alternatives is a function of time, skills, technology and equipment. Whereas for the uniform nitrogen management the traditional farm machinery is used, the variable application requires additional hardware and special machinery to be used.

The relationship between the value of information, benefit from its use and the time, special knowledge and costs increasing needs to be assessed. This chapter overviews an experiment conducted in a winter wheat field in Oponice (Slovakia), where three different levels of input information were assessed in terms of nitrogen efficiency, yield and economics. The impact on overall economics of winter wheat production was assessed too.

5.2 Methodology

The experiment was conducted at a winter wheat field in Oponice (38 ha) (lat 48.475697; long 18.155478) Slovakia. Strip design was used in these experiments to apply nitrogen; all other procedures at these fields were completely controlled by farmers. 18 m wide strips were treated based on the following pattern throughout the whole field (Figure 5-1):

a) Using passive sensor with real time variable application (SENSOR)

b) Farmer's best practice - uniform treatment – (UNIFORM)

c) NDVI obtained from passive sensor and N applied with standard machinery in zones – near real time application (ZONAL)

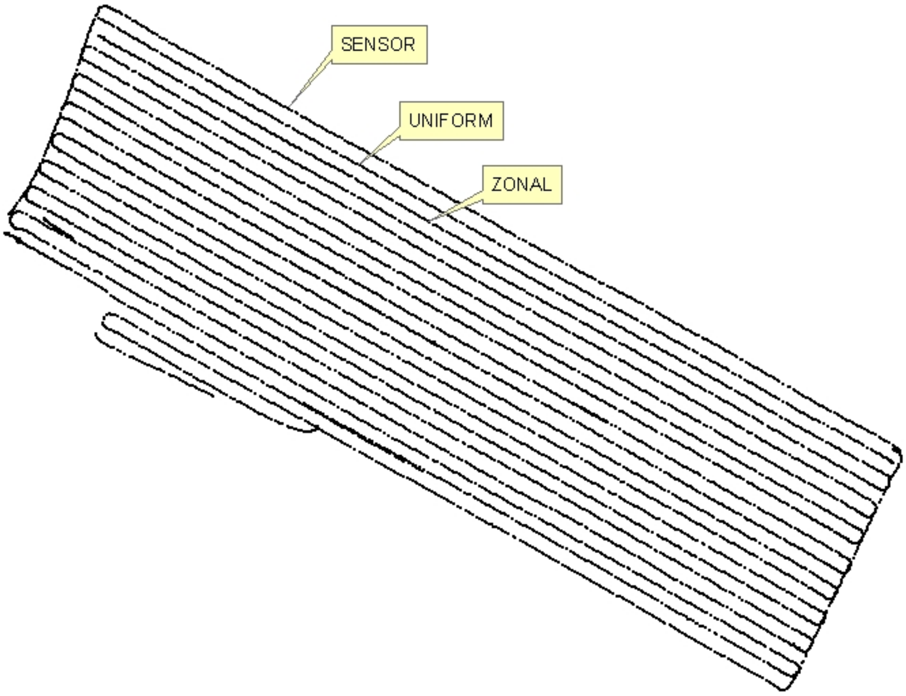


Figure 5-1 The experimental design in Oponice 2006

In this situation following steps were conducted to apply nitrogen based on the above mentioned design:

- to scan the all field with the passive sensor,
- to do the calibration of the values of "index biomass" obtained (see section 3.2.1) following the methodology after Wood et al. (2003a)

- to divide the field into strips based on the principle above – SENSOR, UNIFORM, ZONAL,
- to divide the ZONAL strips into zones on the same principle as in the experiment in Section 4
- to apply nitrogen.

Nitrogen application was conducted twice – for main dose (April) and for late application (June). The equipment is illustrated in Figure 5-2 which comprised N sensor, the control computer of the N sensor, GPS receiver, sprayer equipped with control computer.

Figure 5-2 Devices used to control the experiment in Oponice

The information about biomass was obtained as a first step, the “index biomass” from N sensor was used (Figure 5-3 left). Afterwards, calibration of these numbers was conducted. The crop characteristics (shoot number, nitrogen content) (Figure 5-3 right) were determined and the linear regression was used following the protocol in Section 3.

Figure 5-3 Scanning of the crop in April (left) and sampling for calibration (right)

Application rates were estimated based on the farmer's best practice used in Slovakia, which were supported by the information from plant analyses, and the dose was estimated based on a methodology used in Slovakia after Ložek (1998). The dose was limited by legislative restrictions a maximum limit of 60 kg N.ha^{-1} for one application (Bielek, 2005).

Technically the application was conducted as follows. For the SENSOR treatment strips the N sensor was operated as in commercial use. The control computer automatically changed the application rate based on the sensor's recommendation. This required an agronomical calibration of the N sensor values, which was achieved by an average representative area of the field before the application, to which the mean recommended nitrogen application rate was referred. Minimum and maximum nitrogen rates were also set up. Based on Yara's methodology the rate should be determined from the N tester device and their calibration tables. However, this is not possible to use in Slovakian conditions as the rates given in the above mentioned tables are too high. As a result, the reference rate of nitrogen was determined on either the basis of farmer's best practice or the plant analysis. For the experiment the reference rate of nitrogen was determined based on the plant analyses and methodology after Ložek (1998).

For the UNIFORM application, the control computer of the sprayer was set up for Uniform rate. ZONAL fertilising was controlled with control computer of the sprayer manually. Nitrogen rates for ZONAL application were designed based on methodology proposed by Godwin et al. (2002b). The fertiliser Nitrohum (30% of N) was used.

As there was no yield monitoring system available for the combine harvesters on the farm, the yield was estimated on the base of yield hand samples taken from 152 x $1m^2$ quadrates. Sampling locations were targeted at the centre of each application rate zone along the variable strips. Where uniform rates were applied, the sampling location was at the centre of each zone of similar biomass.

Economic analyses were conducted to determine the detailed cost of applying fertiliser. Moreover the effect on the overall production efficiency was assessed. At first the costs of nitrogen fertilisation were analysed. Costs were divided into three: costs of fertiliser, cost of machinery and “cost of information”. Cost of information included additional costs needed to get the information about the crop, to process the information and to use the information in nitrogen management (Havránková, 2007). These were calculated with assumption, that the technology is used for 500 ha area based on methodology after Rataj & Havránková (2006). The costs of machinery were calculated after Rataj (2005). Costs of fertiliser were calculated base on application maps, where the total applied amount of nitrogen can be derived.

5.3 Results and discussion

April 2006

The map of “biomass index” is given in Figure 5-4, where the variability of the crop within the field is very obvious.

The application was performed in April, where:

- Reference rate for the N sensor was 42 kg $N.ha^{-1}$, the minimum dose for N sensor was set up as 37 and maximum 46 kg $N.ha^{-1}$. The difference between the minimum and the uniform rate was low because of very poor status of the crop, caused by poor climate conditions in the spring of 2006.
- UNIFORM application – farmers’ best practice for main dose application was 42 kg $N.ha^{-1}$.
- The nitrogen rates for ZONAL application were 37, 42 and 46 kg $N.ha^{-1}$.

The final application map is given in Figure 5-5. Because there were problems with fertiliser during the application of Nitrogen at the bottom tramlines, the last two tramlines were excluded from this experiment. This gives the number of 17 tramlines used for analyses (Figure 5-4). The headlands were not considered as well.

Based on the analyses conducted after the application the average rate applied with passive sensor was 44 kgN. ha^{-1} and for ZONAL application 42 kg N.ha^{-1}.

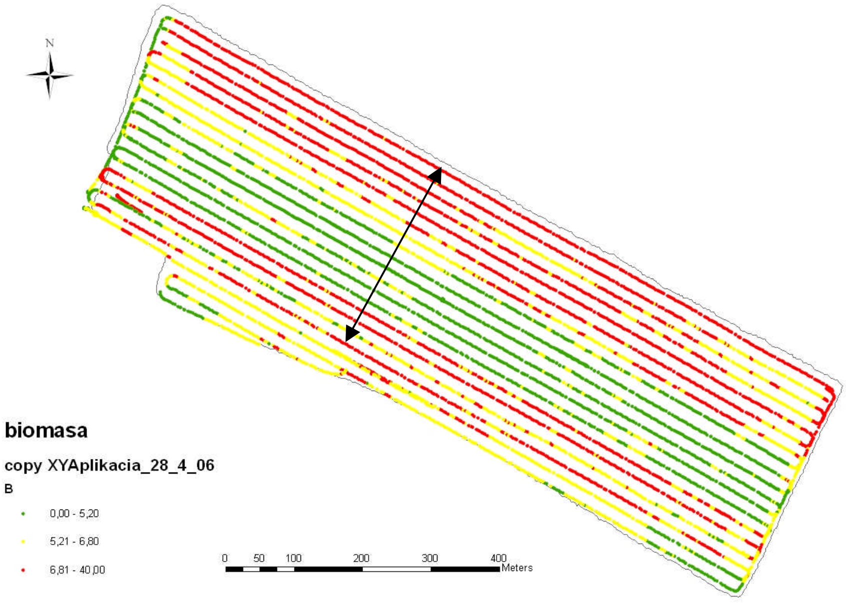


Figure 5-4 Map of biomass used as input data for April fertilising and the range of tramlines used for April experiment

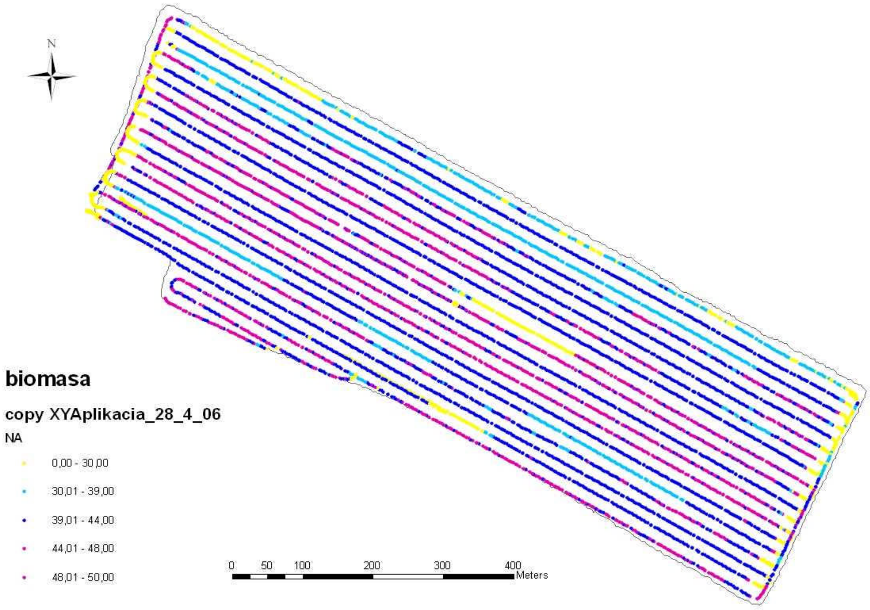


Figure 5-5 Application map of Aril fertilising

The results in Table 5-1 show that in April the SENSOR applied more nitrogen to 63% of area and less nitrogen to 19% of area in comparison to the Uniform application. The same rates were applied at 18% of area (Figure 5-6).

Table 5-1 Summary of application of nitrogen in April

Total area per treatment, ha	Treatment	Nitrogen rate					
		Less		UNIFORM (42 kg N. ha^{-1})		More	
		Area		Area		Area	
		%	ha	%	ha	%	ha
11.96	Sensor	19	2.23	18	2.12	63	7.61
11.97	Uniform	-	-	100	11.97	-	-
9.97	Zonal	30	2.98	23	2.31	47	4.68

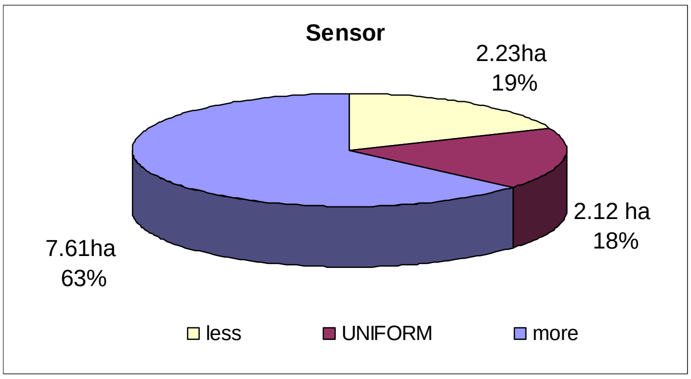


Figure 5-6 Analyses of nitrogen dose applied compared to UNIFORM for N sensor

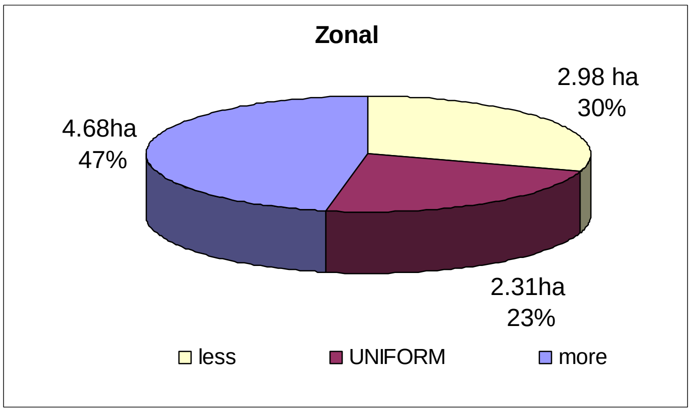


Figure 5-7 Analyses of nitrogen dose applied compared to UNIFORM for ZONAL application

More nitrogen was applied over 47% of the area, less nitrogen was applied over 30% of the area and 23% of the area received the UNIFORM nitrogen rate using ZONAL application (Figure 5-7). It has to be stressed that the crop was very poor after winter and that laboratory analyses showed that there was need for a maximum rate across almost all over the field. From these results it is evident that almost approximately 80% of the field required different nitrogen rate compared to the UNIFORM rate.

June 2006

The map of biomass in June is given in Figure 5-8. For this experiment all tramlines given in the Figure were used, however, the headlands were excluded again. Nitrogen application rates were determined as following:

- the reference rate for N sensor was estimated as 11 kgN.ha^{-1} following the same methodology as for April. The maximum rate, set up for the SENSOR strips, was 15 kgN.ha-1 and minimum 5 kg N .ha^{-1},
- the UNIFORM rate was determined as 11 kg N.ha^{-1} ,
- for ZONAL application rates of 7, 11, and 15 kg N.ha^{-1} were used.

The application map of the fertilising in June is given in Figure 5-9. The average applied rate for SENSOR was 10 kg N. ha^{-1} and for ZONAL application 14 kg N. ha^{-1}. The experiment in June was analysed from the dose distribution point of view as well. The saving in fertiliser in June was at 56% of area using the SENSOR and 14 % using ZONAL application as given in Table 5-2.

Table 5-2 Summary of application of nitrogen in June

Total area per treatment, ha	Treatment	Nitrogen rate					
		Less		UNIFORM (11 kg N. ha^{-1})		More	
		Area		Area		Area	
		%	ha	%	ha	%	ha
13.17	Sensor	56	7.37	14	1.83	30	3.97
11.69	Uniform	-	-	100	11.69	-	-
11.74	Zonal	14	1.68	23	2.65	63	7.40

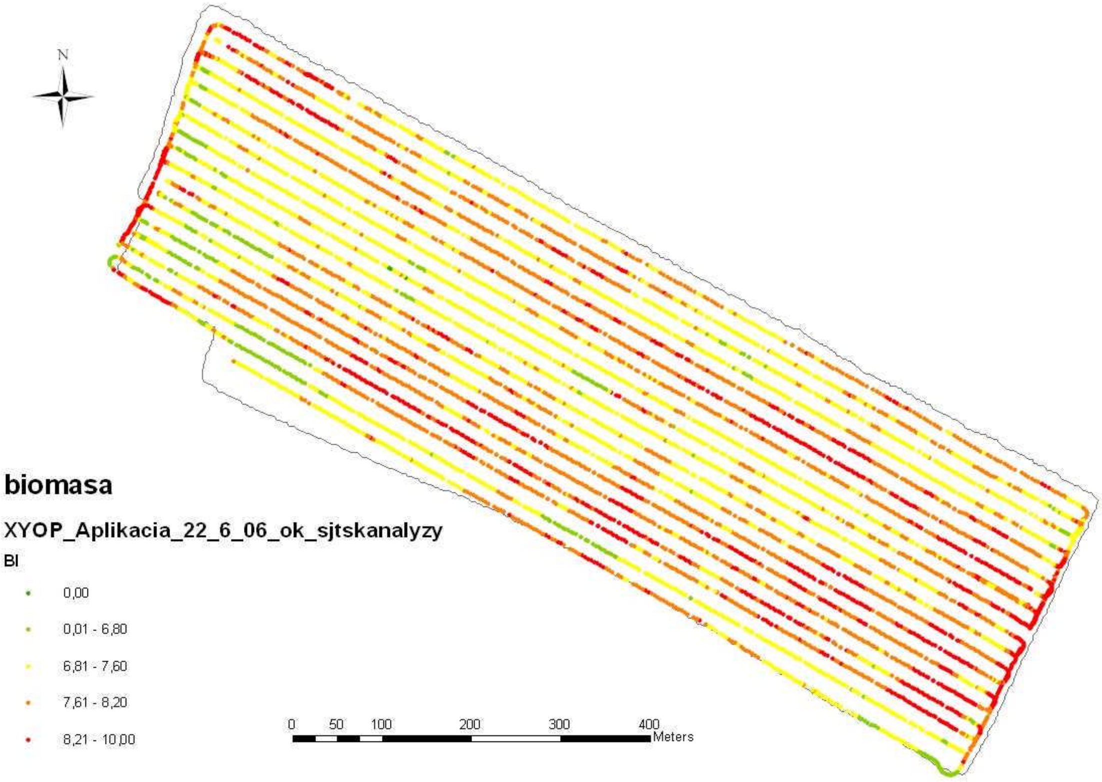


Figure 5-8 Map of biomass used as input data for experiment in June

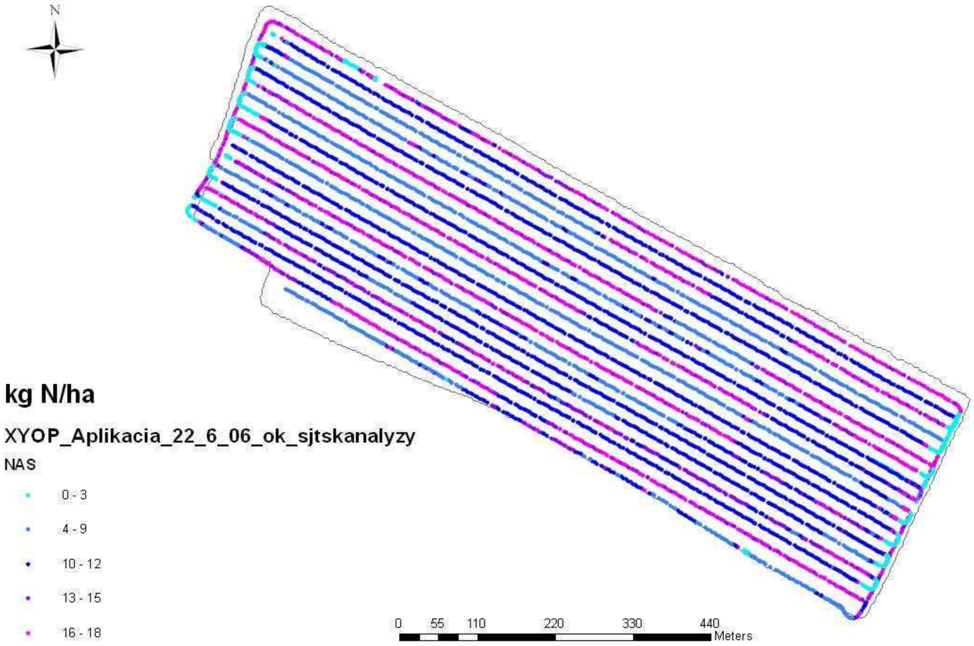


Figure 5-9 Application map in June

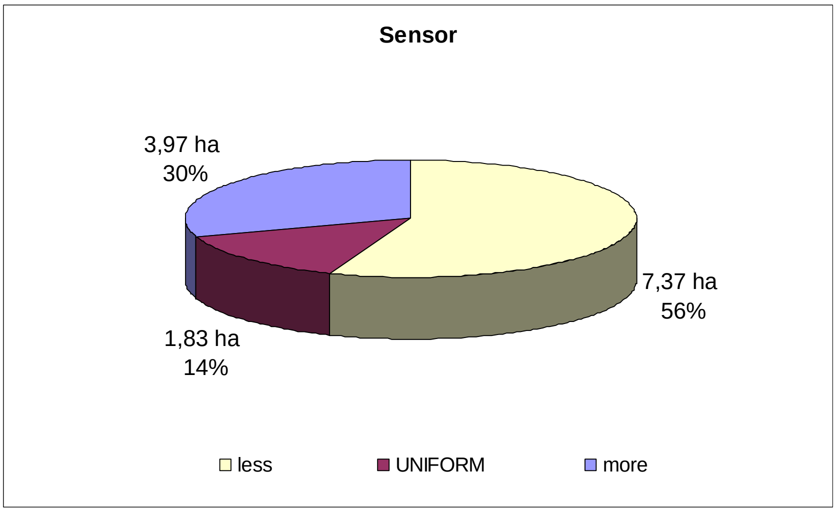


Figure 5-10 Analyses of nitrogen dose applied compared to UNIFORM for SENSOR application

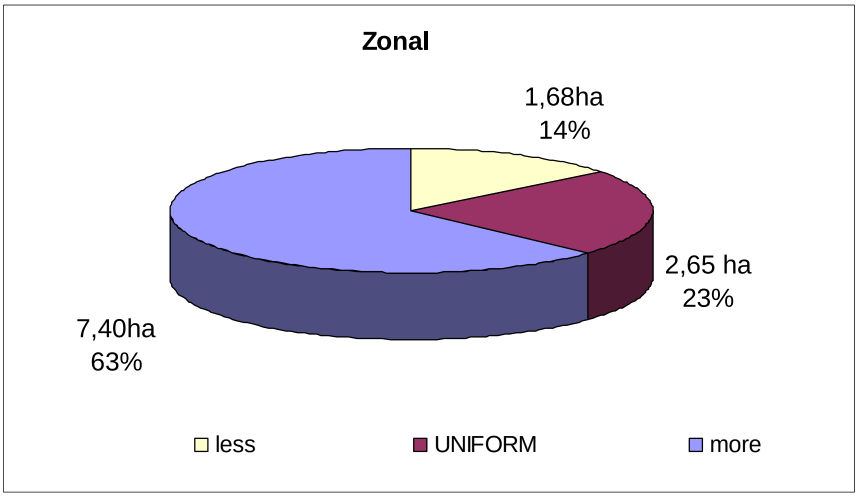


Figure 5-11 Analyses of nitrogen dose applied compared to FBP for ZONAL application

Lower nitrogen rate was applied at 56% of the area using the N sensor and at 14% of area using ZONAL approach (Figure 5-10 and 5-11). The same dose as the UNIFORM dose was applied only at 14% and 23 % of the field for SENSOR and ZONAL approach. So almost 80% of the field required different nitrogen levels compared with the Uniform dose. The saving of total Nitrogen applied at that field was 1.5 kg/ha, however, this was trivial. Also, it has to be stressed that the calibration of the NDVI data for the ZONAL application as well as the determination of reference rate of Nitrogen for the SENSOR data is very important, and it may influence the total nitrogen applied.

Yield analyses

Hand samples were taken at 152 sites to assess the effects of variable application on crop yield. The locations are shown in Figure 5-12 together with their respective yields (t/ha). From this figure it is evident that the difference in crop conditions visible in earlier grow stages (Figure 5-4) was not present at the time of harvesting. The satellite image of the field (Figure 5-13), which was taken a few days before the harvest, indicates relatively low variability in crop conditions. The strip 1/3 from the North-East boundary shows a zone of bare soil.

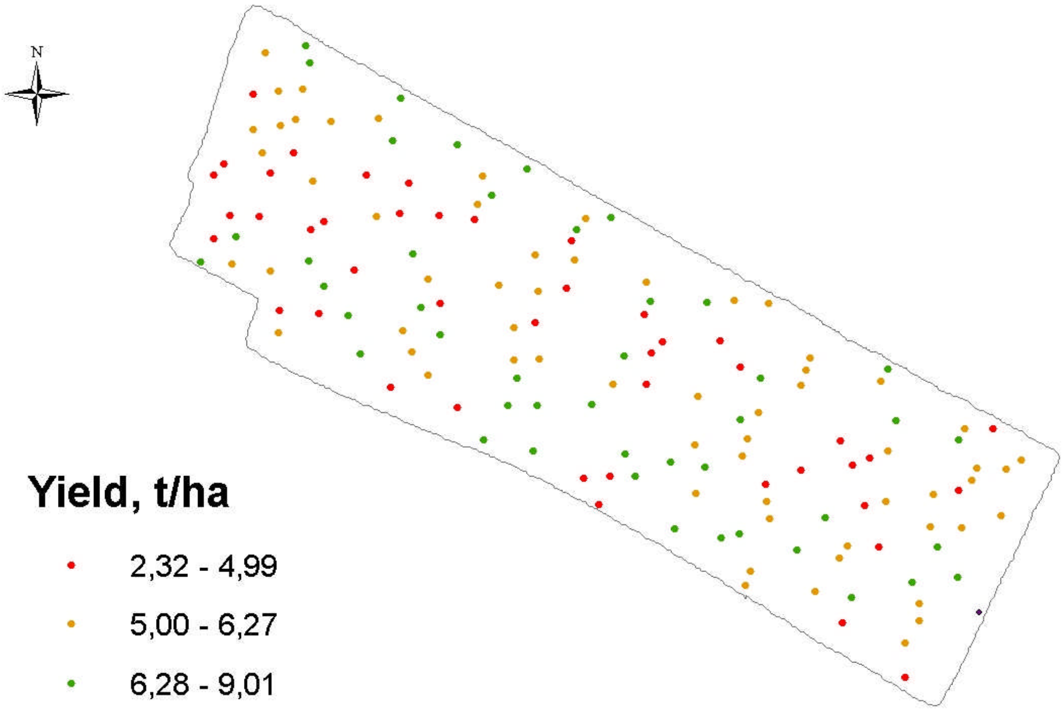


Figure 5-12 Location of hand samples taken in order to get yield

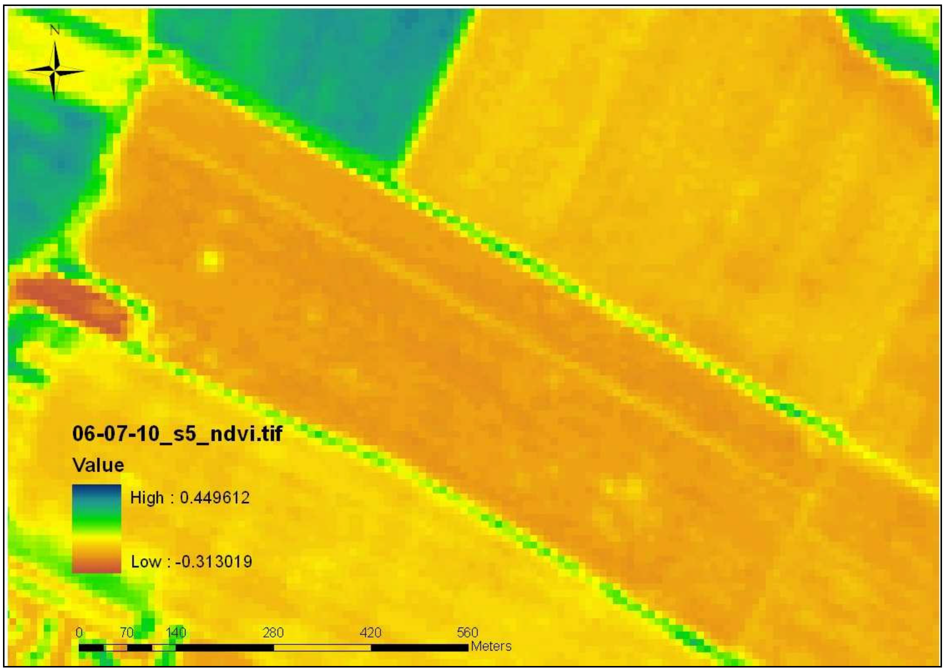


Figure 5-13 Satellite image of the field in Oponice in June, shortly before taking samples

Table 5-3 Basic statistics for yield data of experiment in Oponice

Parameter	SENSOR	UNIFORM	ZONAL
Mean, t.ha^{-1}	5.67	5.59	5.69
Standard error of the mean, t.ha^{-1}	0.16	0.16	0.15
Median, t.ha^{-1}	5.64	5.55	5.81
Minimum, t.ha^{-1}	3.46	2.32	3.58
Maximum, t.ha^{-1}	9.01	8.07	7.99
Standard deviation, t.ha^{-1}	1.20	1.04	1.06
Number of samples	54	45	53
Coefficient of variability, %	21.22	18.68	18.59

The yield samples were analysed in the laboratory to obtain the yield per hectare for targeted sites. Basic statistics for the treatments are given in Table 5-3. The data was analysed in the same way as the one from Wilstead. The lower number of samples, compared to those recorded with the yield monitoring system, resulted into higher standard error of the mean (Table 5-3) . The “t” - test statistics showed that the mean values of yield are not significantly different (Figure 5-14). However, there is an increase by 1.43% for the SENSOR and by 1.79% for the ZONAL application. This difference is not significant form agronomical point of view either (Figure 5-15). The small differences in the yield may be due to the lack of variability in soil what are evident from Figures in Appendix 5-1.

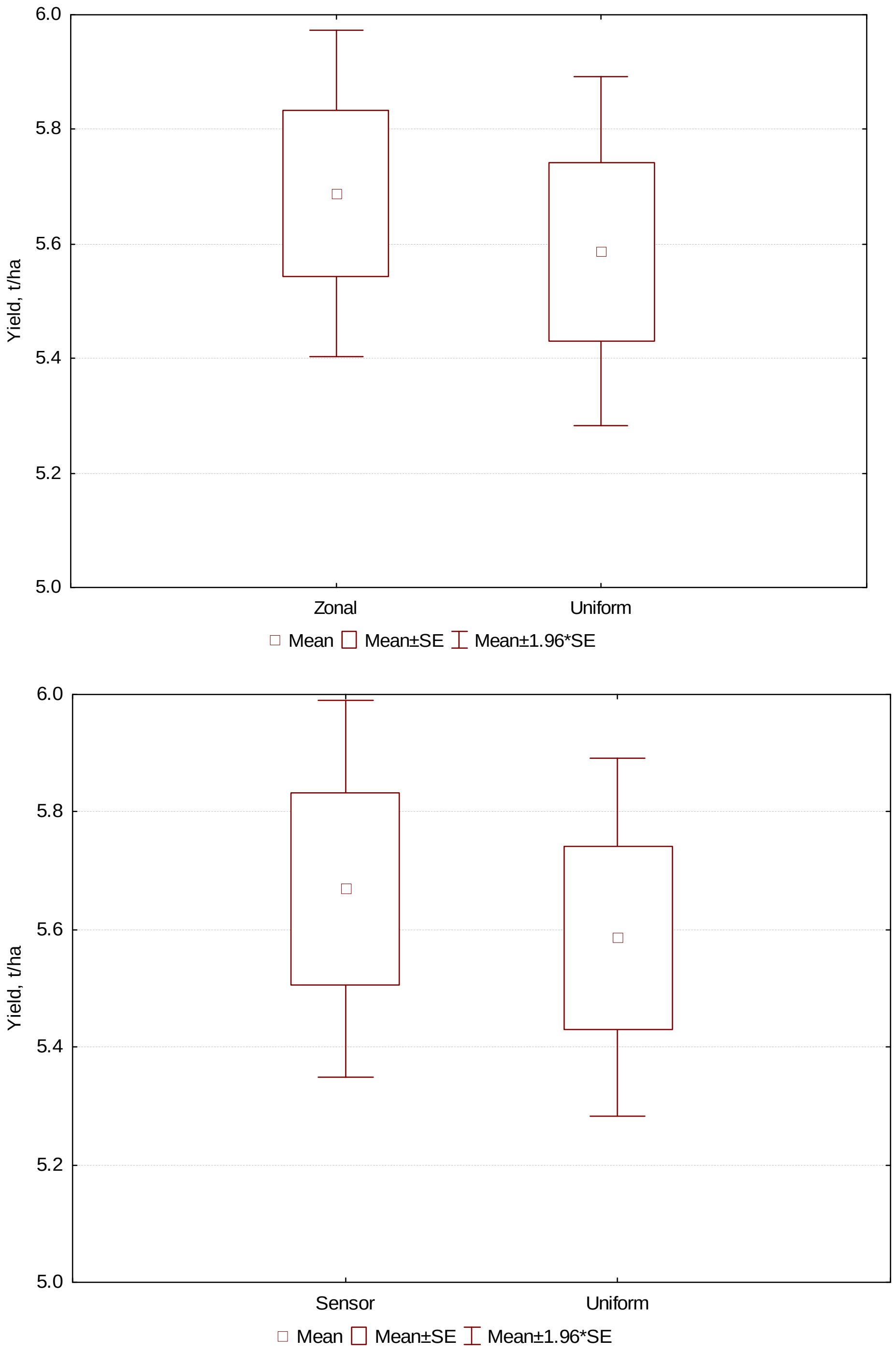


Figure 5-14 Box and whiskers graphs of Mean and Standard errors for yield comparison in Oponice

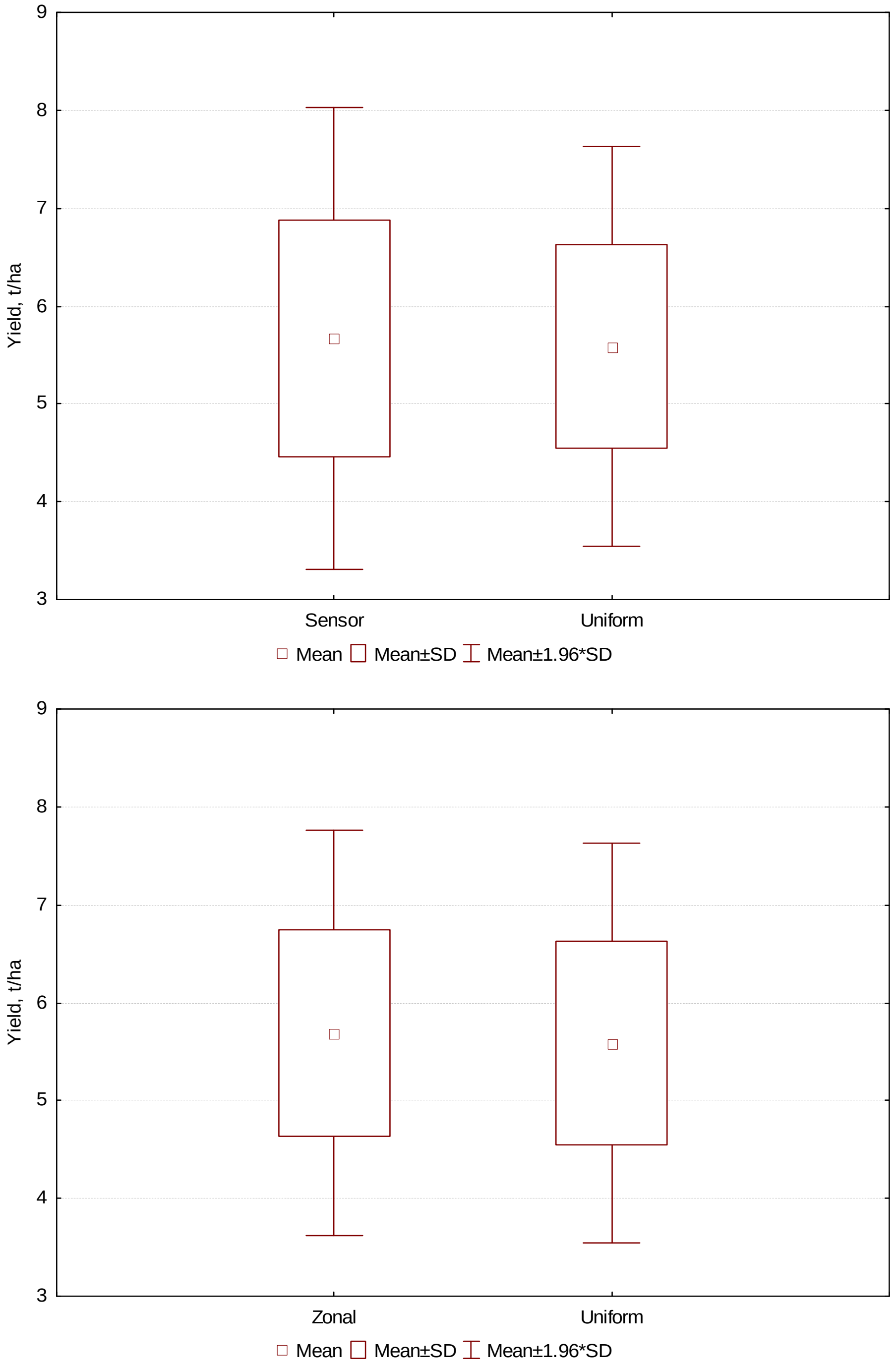


Figure 5-15 Box and whiskers graphs of Mean and Standard deviation for yield comparison in Oponice

The average values of the yield (about 5.6 t/ha) obtained for all three treatments were at the same level. The average winter wheat yield for that region (Southern Slovakia) ranges from 5.3 – 7.0 t/ha (Kubalová, 2006). As the growing conditions differ from very dry to very wet seasons with long winters, the yield obtained in the growing season is corresponding to these values. Figure 5-16 shows the variability in the average yield due to seasonal effects, whilst is typically less then 5 t/ha (Blaas, 2005).

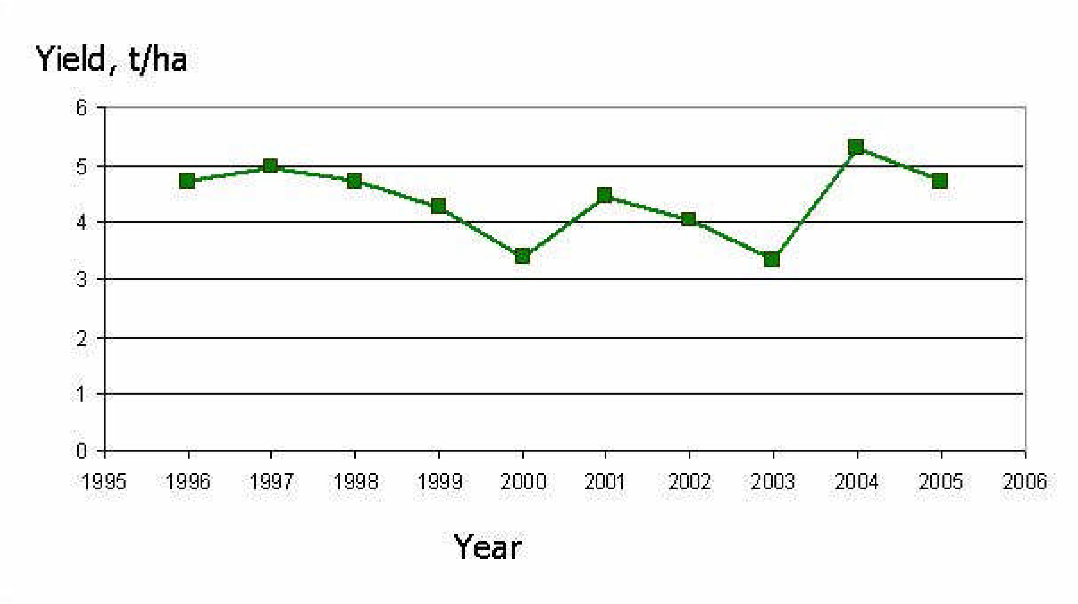


Figure 5-16 Variability in the average yield in Slovakia (Blaas, 2005)

Economic analysis

The costs of nitrogen fertilisation in April and June are summarized in Table 5-4, where the red colour represents costs of information and the green costs of machinery. The assumption purchasing cost of N sensor was 650000SKK (£13000). The costs of machinery and costs associated with precision agriculture were calculated based on methodology published by Rataj (2005) and Rataj &Havránková (2006).

The percentage of these values is given in Figure 5-17, 5-18 and 5-19. The proportion of costs of the information from the total costs of fertilising was 19% for SENSOR and 30 % for ZONAL application. However, the total cost of Nitrogen application was increased by 7.9% for the SENSOR and by 28.62% for the ZONAL application.

Table 5-4 Costs connected with nitrogen application in April and June

Date	**Operation**	**Costs, SKK. ha^{-1} (£1 = 50 SKK)**		
		SENSOR	**Uniform**	**ZONAL**
Short before application	**Scanning of crop (sensor and data processing)**	-	-	(149,6+28+10) x 2 ∆ see below the table
	Sampling and laboratorial analyses	117,5 x 2	117,5 x 2	117,5 x 2
	Creating application map	-	-	7 x 2
Application	**Application machinery**	199,7 x 2	199,7 x 2	199,7 x 2
	Cost of variable application equipment	28 x 2 N sensor	-	10 x 2 LH control computer and GPS
After application	**Processing of “as applied map” (price of contractor)**	30 x 2	-	-
Fertiliser 1kgN ā 19,5SKK (£0.39)		1050.34 (£21)	1033.5 (£20.7)	1101.61 (£23)
Sum		**1800.40 (£36)**	**1667.4 (£33.35)**	**2144.6 (£42.9)**

$^{\Delta}$ Obtaining the information about crop variability (Scanning)

Tractor costs...149 SKK.ha^{-1}

N sensor costs...28 SKK.ha^{-1}

Information processing (costs of software, hardware and labour)…………..10 SKK.ha^{-1}

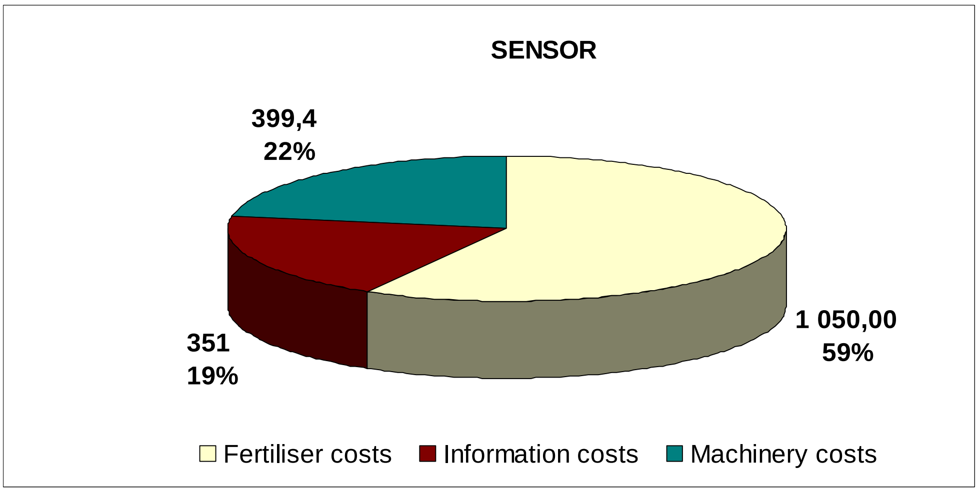


Figure 5-17 Costs of nitrogen application in April and June for SENSOR alternative

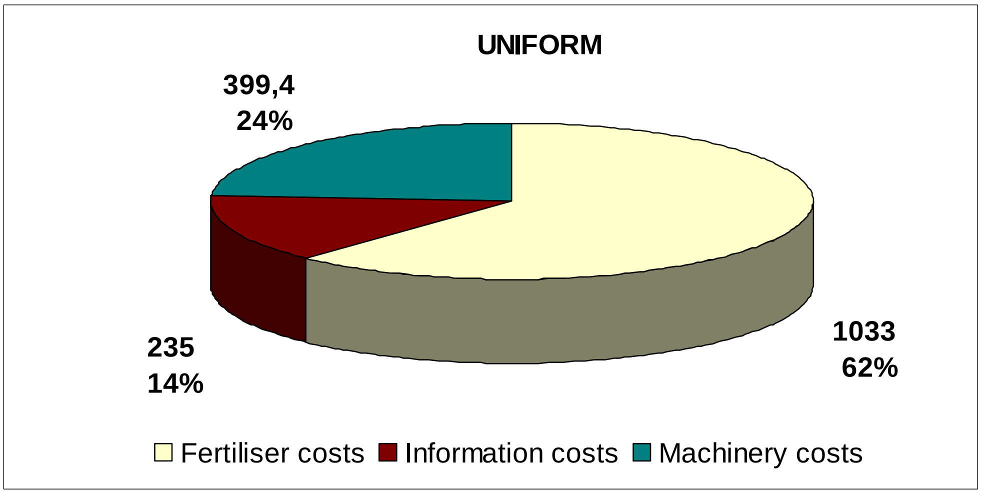


Figure 5-18 Costs of Nitrogen application in April and June for UNIFORM alternative

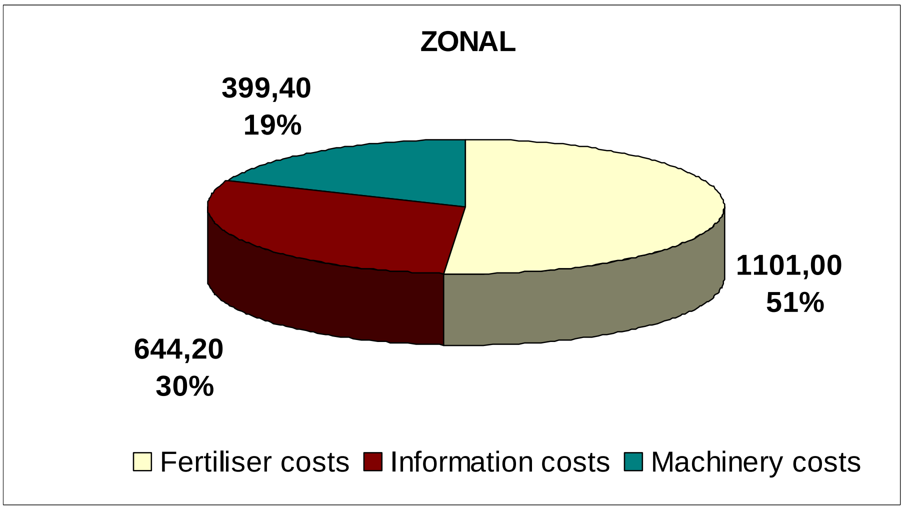


Figure 5-19 Costs of Nitrogen application in April and June for ZONAL alternative

The total costs of winter wheat production were calculated in order to express the overall economical efficiency of the three treatments. The three treatments differ only in costs of fertilising and harvesting, the remainder of operations during the growing season were identical. The cost of fertilising in April and June is given in Table 5-4. In terms of harvesting cost, a yield monitoring system was included for the SENSOR and ZONAL alternatives as these are linked to precision farming technology. This added a value of 200 SKK.ha^{-1} (£4) to the cost of the combine harvester. All operations during the growing season are summarized in Table 5-5. The increasing of the overall costs of production (Table 5-6) was 2.67% for the SENSOR and 5.21% for the ZONAL application.

Table 5-5 Summary of operations, machinery and costs connected with growing the winter wheat

Operation	Date	Machinery used	Machinery costs, SKK.ha-1	Material	Material costs SKK.ha-1
Soil preparation	15. – 16. 9.	Tractor JD 8100 Disk harrow “Ostroj Opava “	346,10	-	-
Seeding	12. – 13. 10.	Fendt 926 “Kompaktor” Lemken 6m Drilling machine Lemken Soliter	502,60	Petrana	2320,00
First Fertilising	3. 3. 2006	Zetor 120 11 Fertiliser spreader Kverneland	311,40	DASA	1048,00
Spraying	24. 4. 2006	Zetor 120 11 Sprayer Hardi TWIN	199,70	Mustang	575,40
Harvesting	13. 7. 2006	Contract harvesting	1970,00* 2170,00**	-	-
Baling	20. 7. 2006	Contract harvesting	1200,00	-	-

* UNIFORM, ** SENSOR and ZONAL

Table 5-6 Average values of economical indicators of production

Costs/Returns SKK.ha^{-1}	**Alternative**		
	SENSOR	**UNIFORM**	**ZONAL**
Costs of production	10325.07 (*£206.50)*	10056.35 *(£ 201.13)*	10580.72 (*£ 211.61)*
Returns (3900 SKK/t or £ *78/t* of wheat)	22 111,96 *(£ 442)*	21 757,83 (*£435)*	22 186.35 *(£ 443.73)*
Gross profit	11786.89 (*£235.74)*	11701.47 (*£234.03)*	11605.63 *(£232.11)*
Gross Profit / costs	1.14	1.16	1.10

The returns increased by up to 2% (Table 5-6), assuming the price of wheat at 3900 SKK/t (£78/t). However, because of the cost increase, the Gross profit increase only by 0.73% for the SENSOR and decreased by 0.82% for ZONAL treatment. From these results it can be concluded that the variable application (at this field and for this growing season) did not bring any economic benefit. The most profitable alternative appears to be the UNIFORM and then the SENSOR. The economic indicators, however, are influenced by the economical environment of the country. These values are influenced by climate and growing conditions of the particular year, which were for 2006 year extremely bad because of the long winter. The poor stage of the crop in Oponice after winter in March could be seen in Figure 5-20 compared to the stage of crop at Hawnes end (UK) (Figure 5-21). However, considering the average range of yield for that region (5.3 t/ha – 7 t/ha), a yield increase may be possible. According to data from Czech Republic, where the yield increased by 5%, there is a yield increase potential in central Europe especially in fields with greater variability in soil conditions.

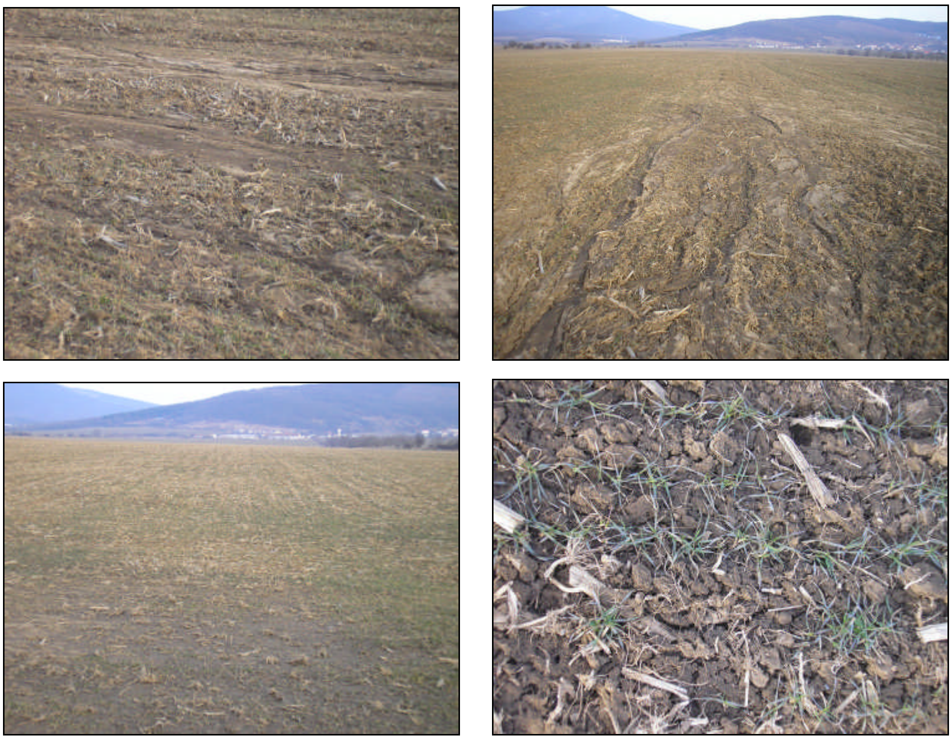


Figure 5-20 The stage of the winter wheat crop after winter at experimental field in Oponice 23th March 2006

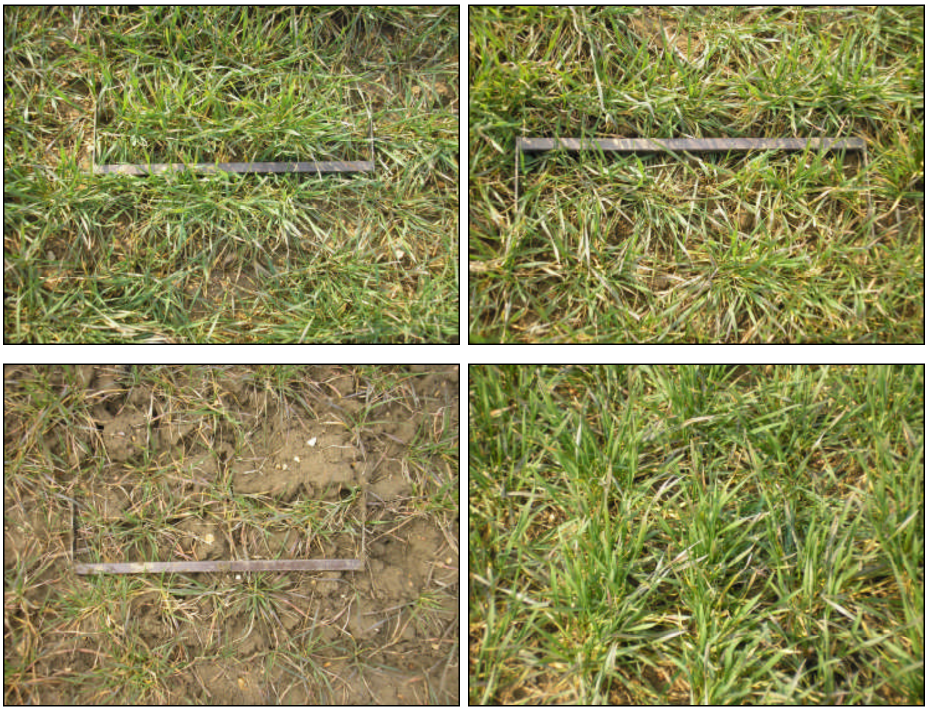


Figure 5-21 Stage of the winter wheat crop at Hawnes end field on 15th March 2006

5.4 Conclusions

From this experiment it can be concluded that:

- real time application with ground based remote sensing systems brings potential benefits mainly in terms of environmental efficiency, the use of the sensor allows matching of the spatially different requirements of crop,
- the sensor brought benefits in terms of nitrogen saving of 1.5 kg N/ha (3.5%), this could be due to the long winter and therefore bad crop conditions in spring and little variation in nitrogen application rates,
- Slovakia experiment also demonstrated no significant yield and economic benefit in this particular field and growing season, possibly due to of the lack of variability,
- the use of sensors does influence the costs of fertilising by 7.9% for SENSOR and 28.62 % for ZONAL, whilst the overall production costs were increased by 2.67% and 5.21% for SENSOR and ZONAL respectively (the costs of training and developing the overall skills of the manager were not included),
- more research work should be done in fields of greater variability and over a larger period of time.

6 Discussion and Recommendations

The results from assessing the performance of the active and passive ground based remote sensing systems showed that both sensors determined the crop characterises such as shoots number and total canopy nitrogen with similar results. The relationship was the most significant during the earlier growth stages. This confirms results introduced by other researcher e.g. Boegh et al. (2002) and Scotford & Miller (2005), for the typical remote sensing system. There is a difference between the NDVI data obtained by the two sensors; however the slope of the best fitting line is similar at given time. The active sensor has potential advantages in terms of longer possible working hours a day, as the sensing is not dependent on ambient light conditions (Morris, 2006).

Similar results for the Crop Circle sensor were obtained by Morris (2006) in Northern Ireland. Otherwise, its performance has been investigated only by Schepers (2005) for corn and sport surfaces. Morris (2006) investigated mainly the operational considerations of the Crop Circle, with the main results, that the max distance of the sensors should not exceed 12m.

The performance of the two sensors in field conditions of winter wheat nitrogen management was assessed in the growing season of 2006. The NDVI data were calibrated by number of shoots; afterwards the threshold values were estimated based on Godwin et al. (2002b) and personal communication with the agronomist. After this the field was divided into strips where the application based on Crop Circle, UNIFORM application and application based on Field Scan was repeated across the field. This point of using the sensors may be considered as critical as different threshold values may change the area of particular dose applied and so the overall efficiency. Using the two sensors brought benefits, the lower nitrogen rate was applied over almost half of the field and the savings on Nitrogen were up to 15 kg/ha. The performance of the sensors was assessed also through the yield achieved. There was statistically significant difference in the mean yield of the treatments; however, the increase of 1.5 % for CropCircle and decrease of 1.5 % for the FieldScan is not significant from the agronomical point of view. This relative performance of the sensors on yield was not due to the type of sensor, but mostly likely because of the exact allocation of each strip where some local variability may appear. However, the benefit introduced by SOYL (2007) and the SOYL sense system, which uses a satellite platform but works on a similar base in terms of calibration and determining of the dose, reached up to £25. Also, Welsh et al. (2003) reported the £20/ha benefit from variable application. The use of aerial digital photography compared to standard uniform rate provided an average improvement of £22/ha (Godwin et al., 2003b).

The use of the sensors allows the nitrogen amounts to be decreased without any negative influence on yield; this increased the nitrogen efficiency of the application. Because the absolute yield values were probably influenced by soil conditions and the fertility of the soil, the absolute values of nitrogen were not the most influencing factor in terms of the yield achieved. According to the coefficient of variability, the yield was less variable along the strips where nitrogen was applied variably, compared to the uniform strips. Similar results were obtained by Feiffer et al. (2003).

The nitrogen residuals in the area where Nitrogen was applied uniformly were 36.15 kg/ha, whereas in areas treated variable were the values of N in soil estimated to 17.5 and 23.5 kg/h. The variable application of nitrogen, which is based on the crop status, enables a reduction of nitrogen residuals comparing to the uniform treatment of 36 – 52%, which is a significant environmental benefit. The economical values of the benefit in the spatial redistribution of the nitrogen dose together with the benefit from reduction of nitrogen residuals in soil are however, difficult to calculate at current time. However, future work should consider the impacts of Nitrogen leaching through the de-nitrification of surface and ground water with the impact of nitrogen on soil fauna and flora as well as Nitrous oxide in the atmosphere. These would vary depending upon the soil and climatic conditions.

The economical performance of the sensors was assessed. The active sensor has an advantage of the lower price, however it is recommended by Morris (2006) to use the sensors maximally 12m apart each other, which results in using two sensors at the same time. In addition, the price of calibration and variable application has to be included. Therefore the integrated systems of scanning and real time application have an advantage. The added values resulting from initial costs of sensors can be offset by the nitrogen saved and the required yield increase by 1%, considering the area managed of 600 ha.

The different nitrogen strategies in terms of level of machinery and PA equipment needed and in terms of levels of input information were assessed in Oponice (Slovakia) in 2006. The experiment was designed to include all possibilities in central European countries in terms of sensors and strategies used for nitrogen management in winter wheat. These were (a) the sensor based (real time application), (b) the uniform application and (c) the zonal application, based on scanning with the sensor and application in zones based on the scanned and calibrated data. The most significant benefit was introduced by the spatial redistribution of nitrogen using the remote sensing approach. Because of the very poor stage of the crop after long winter in the 2006, the increase and decrease in application rates for different zones in the field were almost in balance; hence the amount of nitrogen saved was trivial. The yield was not affected by any of the techniques significantly; what may be due to the low variability of the field. However Company Leading Farmers reported that in the Czech Republic of using the N sensor brought a yield increase of 5 % (Leading Farmers, 2006). The company reports that variable application in Germany increased the yield from 0.2 to 0.39t.ha^{-1}, while the savings in Nitrogen ranged from 2 to 52 kgN.ha^{-1} annually (Schmerler, 1999).

The costs of fertilising were analysed in detail. The cost of information, introduced by using the variable application with remote sensing systems was 19% for N sensor and 30% for ZONAL application of the total cost of fertilising in April and June. The overall costs of production were increased by 2.67% and 5.21 % compared to uniform application. Returns increased by up to 2%. However, the variable application at this field and for this growing season did not bring significant benefits because the gross profit of the production was increased by 0.73% for the SENSOR and decreased by 0.82% for the ZONAL application. These economics indicators are, however, influenced by the economical environment of the country and by the climate and growing conditions of the particular year, which were in this case extremely bad. However, considering other published results (Leading Farmers, 2006), there is a yield increase potential in the central Europe especially at fields with greater variability in soil conditions. Therefore more research work should be done in fields of greater variability and over a larger period of time

7 Conclusion

1. The assessed sensors could be used as an indicator of the crop variability for nitrogen management as there are strong relationships between the NDVI values and crop characteristics. The strongest relationships were reached for both the shoot numbers and total N in plants, which are the indicators for dose determination in agronomical methodologies. The strongest relationship was obtained particularly in April and May, with a reduction in June when canopy size is a maximum and the NDVI saturates.

2. The active sensor (CC) has advantages resulting from a smaller footprint size and possible longer working day length as it is possible to scan under poor light conditions (Morris, 2006); however the relative performance of the two sensors was not significantly different when determining the variation in the winter wheat canopy.

3. Application of Nitrogen using ground based remote sensing systems is beneficial. However, the correct calibration of the sensors values is critical. In the UK conditions both ground based systems brought benefits in terms of nitrogen saving of 15kg N/ha, whilst the amount of nitrogen saved in Slovakia was small (1.5 kg/ha) in the 2006 season.

4. Variable application of Nitrogen brings potential environmental benefits. The variable application in the UK reduced the residual Nitrogen in the soil by between 36 and 52%.

5. The nitrogen use efficiency can be increased using the sensors. Despite the fact that the yield may be influenced by soil conditions, the sensors enabled the reduction in nitrogen without a negative influence on yield.

6. The use of sensors enabled the spatially redistribution of nitrogen to 80 % of the field area in Slovakia. This required a different application rate compared to that of the uniform farmer’s best practice. The above mentioned small savings were due to the fact, that the increase and decrease in application rates were almost equal.

7. The increase in both returns and costs in Slovakia 2006 did not bring any economical benefit from the spatially variable application of nitrogen. It is recommended that due to the limited scale of this work more research is conducted over a wider number of fields and more growing seasons.

8. In addition to the potential economic and environmental benefits, real time application can also provide data for the traceability of Nitrogen fertilizer application levels.

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Appendix 3-1

Crop Characteristics in March 2005

	shoot per 1m sq	shoot per 1m sq	dry matter in 1 m sq(g)	dry matter in 1 m sq(g)	% N	% N	N in 1 m sq	N in 1 m sq	weight of moisture	weight of moisture	moisture content	moisture content
1A	569,60		167,84		3,16		531,03		18,03		80,31	
1B	579,20		238,30		3,41		813,71		33,72		79,60	
1C	534,40		187,31		2,57		480,64		25,51		78,44	
1D	566,40	562,40	205,12	199,64	2,48	2,91	508,65	583,51	17,18	23,61	77,21	78,89
2A	748,00		276,76		3,53		975,69		31,07		79,99	
2B	686,80		222,42		3,81		846,31		35,93		81,01	
2C	608,00		198,69		3,56		708,00		35,93		79,70	
2D	592,00	658,70	198,20	224,02	3,59	3,62	710,95	810,24	32,98	33,98	79,76	80,12
3A	470,40		219,35		4,39		963,78		30,86		77,69	
3B	624,00		251,16		3,95		991,73		37,55		79,54	
3C	467,20		198,68		3,66		726,89		28,23		77,75	
3D	563,20	531,20	319,29	247,12	3,39	3,85	1083,36	941,44	47,95	36,15	76,49	77,87
4A	717,40		291,13		4,03		1174,48		47,30		78,99	
4B	690,20		302,36		3,87		1171,43		41,44		78,44	
4C	659,60		313,78		4,05		1269,68		38,03		79,20	
4D	659,60	681,70	295,81	300,77	3,77	3,93	1113,93	1182,38	43,90	42,67	79,01	78,91
5A	850,00		338,74		3,44		1165,06		43,95		80,33	
5B	778,60		292,85		3,95		1155,85		48,55		80,63	
5C	691,20		248,10		3,36		834,42		28,11		80,48	
5D	822,40	785,55	298,21	294,48	3,50	3,56	1043,05	1049,60	34,57	38,80	80,56	80,50
6A	560,00		245,75		2,66		652,99		41,29		78,35	
6B	620,80		225,84		2,79		629,98		40,45		79,31	
6C	611,20		277,33		2,82		781,67		39,41		78,35	
6D	643,20	608,80	249,78	249,68	3,40	2,92	850,17	728,70	37,60	39,69	80,14	79,04
7A	816,00		398,36		3,70		1472,56		64,19		79,94	
7B	856,80		420,15		4,21		1769,13		49,94		79,04	
7C	752,00		311,03		3,59		1115,13		38,96		79,03	
7D	707,20	783,00	339,96	367,37	3,32	3,70	1127,17	1371,00	51,00	51,02	79,12	79,28
8A	764,80		393,36		3,31		1301,91		59,22		79,33	
8B	774,40		362,31		3,45		1249,92		49,87		79,20	
8C	614,40		364,03		2,96		1079,20		47,27		76,87	
8D	707,20	715,20	320,36	360,02	3,19	3,23	1022,55	1163,39	53,84	52,55	79,85	78,81
9A	816,00		347,38		4,26		1478,86		50,63		80,94	
9B	668,80		362,55		3,52		1277,92		52,67		80,19	
9C	876,80		472,33		3,93		1856,30		50,76		80,38	
9D	806,40	792,00	401,05	395,83	3,38	3,77	1354,63	1491,93	59,47	53,38	79,94	80,36
10A	768,40		448,52		3,68		1652,13		56,31		78,13	
10B	826,20		479,95		3,22		1543,32		48,88		79,27	
10C	822,40		462,60		3,72		1722,05		40,83		78,40	
10D	886,40	825,85	493,02	471,02	3,70	3,58	1825,07	1685,64	61,25	51,82	79,15	78,74

Crop characteristics in May 2005

site	shoot per 1m sq		dry matter in 1 m sq(g)		% N		N in 1 m sq		height of crop		moisture content	
1A	460,80		316,70		2,87		910,40		35,00		80,71	
1B	585,60		349,41		3,05		1064,96		30,00		79,95	
1C	454,40		369,26		2,91		1072,94		33,00		78,50	
1D	505,60	501,60	365,80	350,29	3,04	2,97	1111,24	1039,88	32,00	32,50	78,43	79,40
2A	680,00		328,67		3,25		1067,62		34,00		79,66	
2B	639,20		421,02		3,93		1655,70		38,00		79,51	
2C	579,20		319,47		3,16		1009,67		35,00		78,98	
2D	560,00	614,60	342,91	353,02	3,96	3,58	1359,48	1273,12	36,00	35,75	79,46	79,40
3A	502,40		556,89		3,39		1887,36		47,00		77,97	
3B	518,40		424,54		2,91		1236,89		40,00		77,69	
3C	473,60		587,26		3,08		1806,31		42,00		70,31	
3D	428,80	480,80	389,96	489,66	2,98	3,09	1160,79	1522,84	39,00	42,00	73,96	74,98
4A	629,00		543,82		2,62		1425,41		42,00		77,75	
4B	557,60		420,37		2,83		1188,01		41,00		77,77	
4C	598,40		592,75		3,08		1823,26		41,00		76,81	
4D	632,40	604,35	632,72	547,41	3,03	2,89	1915,51	1588,05	43,00	41,75	76,40	77,18
5A	700,40		470,60		3,48		1639,77		38,00		79,62	
5B	690,20		486,43		3,88		1888,19		36,00		79,50	
5C	710,40		596,29		3,21		1913,95		44,00		78,77	
5D	598,40	674,85	488,78	510,53	3,32	3,47	1622,05	1765,99	42,00	40,00	78,27	79,04
6A	419,20		288,78		2,85		823,95		38,00		80,04	
6B	457,60		332,90		3,40		1131,36		38,00		80,06	
6C	528,00		400,02		3,04		1214,57		37,00		79,12	
6D	553,60	489,60	409,41	357,78	2,49	2,95	1021,08	1047,74	38,00	37,75	79,04	79,56
7A	601,80		618,99		3,32		2052,00		45,00		76,63	
7B	629,00		465,11		3,17		1474,76		42,00		78,44	
7C	521,60		547,68		2,97		1628,42		44,00		75,50	
7D	572,80	581,30	529,22	540,25	2,74	3,05	1448,35	1650,88	46,00	44,25	80,49	77,76
8A	675,20		518,22		3,08		1596,66		42,00		79,52	
8B	627,20		523,14		2,92		1526,03		47,00		79,83	
8C	556,80		392,36		3,43		1345,17		36,00		78,69	
8D	665,60	631,20	532,48	491,55	3,32	3,19	1766,12	1558,50	44,00	42,25	79,82	79,46
9A	784,00		563,70		3,12		1758,14		45,00		79,32	
9B	601,60		436,83		2,79		1219,56		45,00		79,34	
9C	697,60		586,33		3,24		1898,73		44,00		79,66	
9D	652,80	684,00	461,93	512,20	3,13	3,07	1443,99	1580,10	50,00	46,00	78,96	79,32
10A	686,80		796,94		3,19		2540,96		50,00		76,88	
10B	642,60		640,91		2,88		1848,53		52,00		77,52	
10C	617,60		746,93		3,29		2455,66		50,00		77,53	
10D	531,20	619,55	612,33	699,28	3,11	3,12	1905,89	2187,76	49,00	50,25	77,97	77,48

Crop Characteristics in June 2005

site	shoot per 1m sq		dry matter in 1 m sq(g)		% N		N in 1 m sq		height of crop		moisture content	
1A	617,6		939,01		2,36		2211,37		63,00		75,84	
1B	521,60		909,82		2,13		1938,30		64,00		73,83	
1C	422,40		869,18		1,89		1639,90		62,00		73,28	
1D	553,60	528,80	979,13	924,29	2,40	2,19	2351,50	2035,27	60,00	62,25	74,62	74,39
2A	571,20		1019,93		2,12		2162,91		62		72,17	
2B	625,60		1201,85		2,14		2566,21		66,00		73,76	
2C	601,60		1067,19		2,09		2230,04		60,00		73,45	
2D	592,00	597,60	1004,12	1073,27	2,82	2,29	2836,56	2448,93	64,00	63,00	73,32	73,17
3A	617,60		1181,04		1,84		2168,70		66,00		73,12	
3B	521,60		996,91		2,15		2141,69		64,00		72,41	
3C	422,40		932,90		2,36		2200,73		65,00		71,16	
3D	553,60	528,80	1158,41	1067,31	2,04	2,10	2365,83	2219,24	65,00	65,00	71,28	71,99
4A	564,40		1139,11		1,80		2045,03		63,00		73,07	
4B	673,20		1591,00		2,25		3583,39		65,00		70,19	
4C	656,20		1248,42		1,87		2332,29		62,00		69,08	
4D	571,20	616,25	1045,30	1255,95	2,10	2,00	2191,30	2538,00	62,00	63,00	69,59	70,48
5A	697,00		1005,62		2,24		2249,80		62,00		75,99	
5B	686,80		1261,62		2,60		3286,51		65,00		74,32	
5C	646,40		1242,70		1,72		2142,05		64,00		72,55	
5D	700,80	682,75	1197,49	1176,86	2,83	2,35	3386,63	2766,25	62,00	63,25	74,40	74,32
6A	550,40		1268,67		2,20		2784,81		57,00		71,05	
6B	534,40		1164,99		1,98		2301,89		63,00		71,50	
6C	556,80		1177,01		2,11		2484,04		60,00		72,77	
6D	617,60	564,80	1390,41	1250,27	2,01	2,07	2796,95	2591,92	65,00	61,25	73,00	72,08
7A	516,80		1406,21		2,12		2984,66		60,00		65,11	
7B	612,00		1213,22		1,75		2127,45		62,00		69,25	
7C	617,60		1176,53		1,77		2080,95		60,00		68,15	
7D	595,20	585,40	1144,33	1235,07	2,17	1,95	2487,21	2420,07	63,00	61,25	65,50	67,00
8A	592,00		1209,79		2,71		3273,52		70,00		75,35	
8B	614,40		1284,65		2,62		3370,41		76,00		75,30	
8C	470,40		842,02		2,44		2054,35		68,00		72,51	
8D	560,00	559,20	1141,00	1119,37	1,91	2,42	2182,53	2720,20	75,00	72,25	72,54	73,93
9A	764,80		1549,76		2,56		3971,42		75,00		73,91	
9B	656,00		1214,54		2,13		2592,82		80,00		72,86	
9C	630,40		1332,51		2,51		3343,79		70,00		74,82	
9D	585,60	659,20	1199,50	1324,08	2,32	2,38	2780,25	3172,07	73,00	74,50	73,19	73,69
10A	666,40		1556,88		1,94		3021,92		77,00		70,34	
10B	663,00		1652,59		1,81		2983,65		72,00		68,39	
10C	646,40		1450,36		2,25		3258,92		72,00		71,32	
10D	665,60	660,35	1488,95	1537,19	1,57	1,89	2337,20	2900,42	73,00	73,50	70,07	70,03

Crop characteristics in March and May 2006

March 2006	shoots/1m2	plants per 1m2	dry matter in 1 m sq(g)	% N	N in 1 m sq	weight of moisture	moisture content
1	596,8	149,2	100,90	2,00	202,41	12,76	68,99
2	574,4	143,6	73,35	2,75	201,11	14,65	73,92
3	840	210	120,78	2,99	352,56	18,08	74,85
4	760	190	104,44	3,00	317,14	17,93	75,37
5	952	238	106,41	3,10	327,54	12,00	74,13
6	969,6	242,4	95,30	3,26	312,97	10,70	76,96
7	768	192	99,29	4,00	395,95	16,60	76,54
8	1147,2	286,8	141,60	3,19	451,20	14,10	76,75
9	1203,2	300,8	180,08	2,90	522,17	21,03	75,96
10	609,6	152,4	72,35	4,02	290,81	15,98	77,04
11	1275,2	318,8	148,07	3,90	580,07	18,93	77,75

May 2006	dry matter	%N	N in 1msq	shoots
1	218,6397	2,628	571,1889	430,4
2	206,1068	2,1095	435,2244	432
3	384,2448	2,655	1023,969	648
4	336,1347	2,4625	831,4574	596,8
5	497,3544	2,2795	1114,68	764,8
6	335,5055	2,276	831,411	558,4
7	493,0657	2,5295	1231,562	793,6
8	505,4262	2,294	1168,203	708,8
9	631,3478	2,266	1430,377	854,4
10	308,461	2,8465	876,7863	558,4
11	417,4692	2,0345	859,2216	780,8
12	278,3577	2,544	707,5621	444,8
13	670,5504	2,4075	1615,421	811,2
14	731,9992	2,495	1801,074	996,8
15	399,4613	2,0695	819,7656	580,8

NDVI values from the Crop Circle and Field Scan sensors in 2005 and 2006

	April 2005		May 2005		June 2005	
site	NDV FSI	NDVI CC	NDVI FS	NDVI CC	NDVI FS	NDVI CC
1	0,74	0,49	0,87	0,64	0,86	0,73
2	0,81	0,58	0,88	0,69	0,87	0,71
3	0,79	0,51	0,85	0,68	0,83	0,68
4	0,84	0,62	0,87	0,75	0,85	0,71
5	0,85	0,60	0,87	0,74	0,87	0,74
6	0,82	0,56	0,87	0,66	0,86	0,71
7	0,84	0,62	0,86	0,73	0,83	0,65
8	0,81	0,59	0,87	0,73		
9	0,87	0,70	0,88	0,78		
10	0,85	0,67	0,88	0,75	0,84	0,72

March 2006	NDVI FS	NDVI CC
1	0,428403	0,3015
2	0,520765	0,381
3	0,544733	0,4075
4	0,587893	0,343
5	0,63949	0,4155
6	0,663948	0,49225
7	0,725245	0,5145
8	0,75554	0,584
9	0,76173	0,59825
10	0,663958	0,49775
11	0,73152	0,58575

May 2006	NDVI	NDVI CC
1	0,6604	0,3175
2	0,7101	0,4205
3	0,7742	0,4415
4	0,8045	0,4735
5	0,8365	0,6135
6	0,8386	0,5834
7	0,8827	0,6915
8	0,8631	0,64
9	0,8639	0,685
10	0,8658	0,6125
11	0,8602	0,624
12	0,7025	0,32
13	0,8012	0,478
14	0,8728	0,7095
15	0,8505	0,568

Appendix 3-2

2005 April

FS vs crop

Dependnt Variable	Test of SS Whole Model vs. SS Residual (2005)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
A_shoot per 1m sq	0,890994	0,793871	0,768105	76384,0	1	76384,0	19833,2	8	2479,14	30,81063	0,000541
A_dry matter in 1 m sq(g)	0,845198	0,714359	0,678654	47553,9	1	47553,9	19014,7	8	2376,84	20,00717	0,002075
A_% N	0,484855	0,235084	0,139470	0,3	1	0,3	0,9	8	0,12	2,45867	0,155515
A_N in 1 m sq	0,877907	0,770721	0,742061	845549,3	1	845549,3	251539,2	8	31442,40	26,89201	0,000837

CC vs crop

Dependnt Variable	Test of SS Whole Model vs. SS Residual (2005)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
A_shoot per 1m sq	0,890994	0,793871	0,768105	76384,0	1	76384,0	19833,2	8	2479,14	30,81063	0,000541
A_dry matter in 1 m sq(g)	0,845198	0,714359	0,678654	47553,9	1	47553,9	19014,7	8	2376,84	20,00717	0,002075
A_% N	0,484855	0,235084	0,139470	0,3	1	0,3	0,9	8	0,12	2,45867	0,155515
A_N in 1 m sq	0,877907	0,770721	0,742061	845549,3	1	845549,3	251539,2	8	31442,40	26,89201	0,000837

2005 May

FS vs Crop

Dependnt Variable	Test of SS Whole Model vs. SS Residual (2005)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
M_shoot per 1m sq	0,717747	0,515161	0,454556	25386,78	1	25386,78	23893	8	2986,6	8,500307	0,019424
M_dry matter in 1 m sq(g)	0,087396	0,007638	-0,116407	810,17	1	810,17	105260	8	13157,4	0,061575	0,810275
M_% N	0,424406	0,180120	0,077635	0,08	1	0,08	0	8	0,0	1,757531	0,221537
M_N in 1 m sq	0,194297	0,037751	-0,082530	39553,66	1	39553,66	1008192	8	126024,1	0,313858	0,590661

CC vs Crop

Dependnt Variable	Test of SS Whole Model vs. SS Residual (2005)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
M_shoot per 1m sq	0,856744	0,734010	0,700762	36171,6	1	36171,6	13107,8	8	1638,47	22,07636	0,001544
M_dry matter in 1 m sq(g)	0,757029	0,573092	0,519729	60787,7	1	60787,7	45282,0	8	5660,24	10,73942	0,011236
M_% N	0,113017	0,012773	-0,110631	0,0	1	0,0	0,4	8	0,06	0,10350	0,755909
M_N in 1 m sq	0,777455	0,604436	0,554990	633295,1	1	633295,1	414451,0	8	51806,38	12,22427	0,008123

2005 June

FS vs crop

Dependnt Variable	Test of SS Whole Model vs. SS Residual (2005)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
M_shoot per 1m sq	0,293513	0,086150	-0,066158	3087,56	1	3087,56	32751,8	6	5458,63	0,565630	0,480453
J_shoot per 1m sq	0,226339	0,051229	-0,106899	1137,05	1	1137,05	21058,2	6	3509,70	0,323973	0,589886
J_dry matter in 1 m sq(g)	0,325032	0,105646	-0,043413	24299,69	1	24299,69	205710,7	6	34285,12	0,708753	0,432127
J_% N	0,747320	0,558487	0,484901	0,10	1	0,10	0,1	6	0,01	7,589630	0,033075
J_N in 1 m sq	0,091831	0,008433	-0,156828	4588,54	1	4588,54	539533,3	6	89922,22	0,051028	0,828783

CC vs crop

Dependnt Variable	Test of SS Whole Model vs. SS Residual (2005)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
J_shoot per 1m sq	0,392858	0,154337	0,013394	3425,56	1	3425,56	18769,7	6	3128,28	1,095028	0,335673
J_dry matter in 1 m sq(g)	0,041050	0,001685	-0,164701	387,60	1	387,60	229622,8	6	38270,47	0,010128	0,923117
J_% N	0,524709	0,275320	0,154540	0,05	1	0,05	0,1	6	0,02	2,279513	0,181834
J_N in 1 m sq	0,286180	0,081899	-0,071118	44562,96	1	44562,96	499558,9	6	83259,81	0,535228	0,491990

2006 March FS

Dependnt Variable	Test of SS Whole Model vs. SS Residual (Zošit1)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
dry matter	0,545713	0,297803	0,219781	3156,1	1	3156,1	7441,8	9	826,86	3,81691	0,082476
%N	0,698964	0,488550	0,431722	1,8	1	1,8	1,9	9	0,21	8,59703	0,016701
N in 1msq	0,819657	0,671837	0,635374	96997,6	1	96997,6	47379,1	9	5264,35	18,42538	0,002013
shoots	0,742365	0,551106	0,501229	341950,4	1	341950,4	278529,4	9	30947,71	11,04930	0,008883

2006 MArch CC

Dependnt Variable	Test of SS Whole Model vs. SS Residual (Zošit1)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
dry matter	0,608534	0,370313	0,300348	3924,5	1	3924,5	6673,3	9	741,48	5,29282	0,046952
%N	0,626103	0,392004	0,324449	1,4	1	1,4	2,2	9	0,25	5,80274	0,039321
N in 1msq	0,841112	0,707469	0,674966	102142,1	1	102142,1	42234,7	9	4692,74	21,76598	0,001176
shoots	0,767070	0,588396	0,542662	365087,9	1	365087,9	255391,9	9	28376,87	12,86568	0,005867

2006 May FS

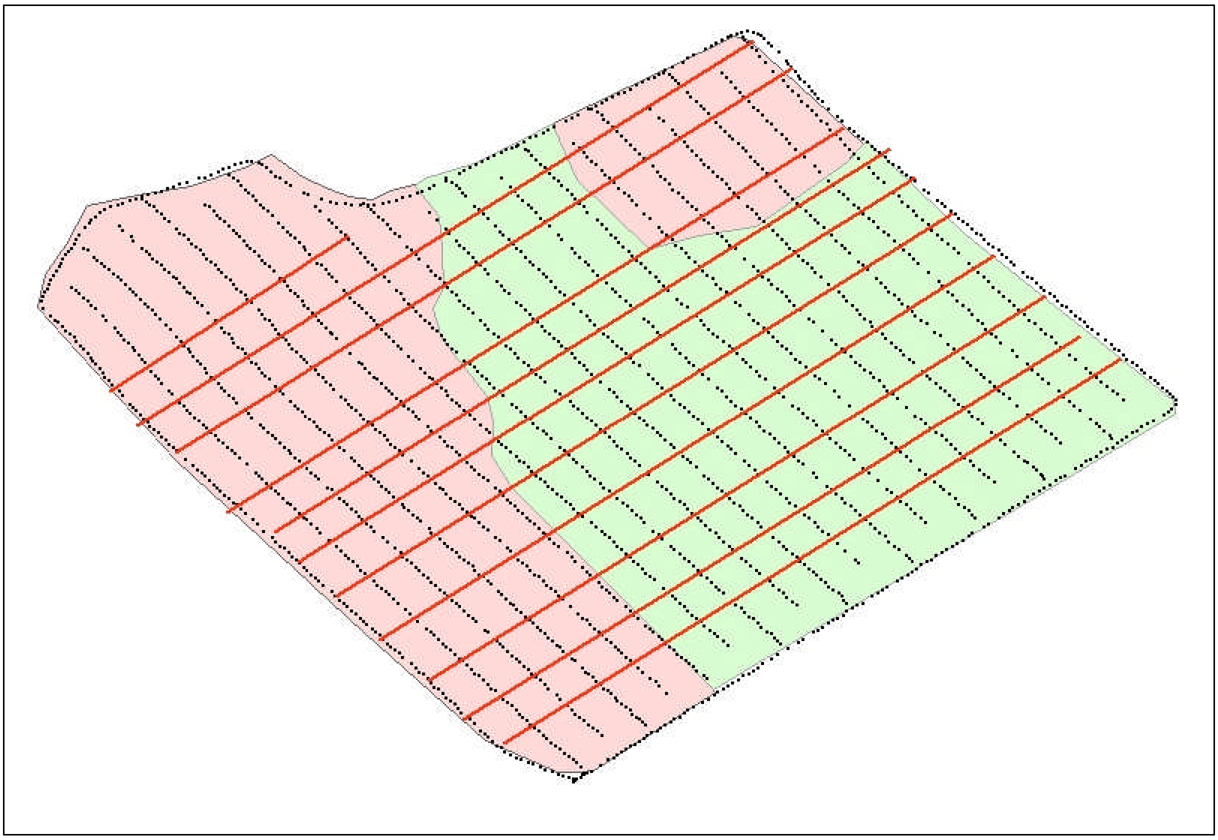
Dependnt Variable	Test of SS Whole Model vs. SS Residual (2006b)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
dry matter	0,632393	0,399920	0,353760	142858,7	1	142858,7	214359	13	16489,16	8,66379	0,011415
%N	0,179464	0,032207	-0,042238	0,0	1	0,0	1	13	0,06	0,43263	0,522178
N in 1msq	0,597015	0,356426	0,306921	715445,3	1	715445,3	1291828	13	99371,38	7,19971	0,018785
shoots	0,724266	0,524562	0,487990	210727,1	1	210727,1	190993	13	14691,79	14,34319	0,002262

2006 MAy CC

Dependnt Variable	Test of SS Whole Model vs. SS Residual (2006b)										
	Multiple R	Multiple R2	Adjusted R2	SS Model	df Model	MS Model	SS Residual	df Residual	MS Residual	F	p
dry matter	0,66151	0,43759	0,39433	156318,	1	156318,	20090	13	15453,8	10,1151	0,00723
%N	0,22225	0,04939	-0,02372	0,0	1	0,0	1	13	0,0	0,6755	0,42595
N in 1msq	0,61679	0,38043	0,33277	763630,	1	763630,	124364	13	95664,8	7,9823	0,01431
shoots	0,77043	0,59357	0,56230	238450,	1	238450,	16327	13	12559,2	18,9860	0,00077

Appendix 4-1

Design of separating values for Factorial analyses below.



Results of factorial analyses using “Statistica 7”

GENERAL Effect	Univariate Tests of Significance for values (VFA MPhil yield) Sigma-restricted parameterization Effective hypothesis decomposition				
	SS	Degr. of Freedom	MS	F	p
Intercept	1,234651E+10	1	1,234651E+10	1015,846	0,000000
sensor	1,351757E+07	2	6,758787E+06	0,556	0,574284
zone	1,217101E+08	1	1,217101E+08	10,014	0,001784
sensor*zone	4,129971E+06	2	2,064985E+06	0,170	0,843863
Error	2,552323E+09	210	1,215392E+07		

Appendix 4-2

Soil maps of the experimental area:

After: King. D.W. (1969):

16 - MILTON -clayed brown, gravely and loamy drift

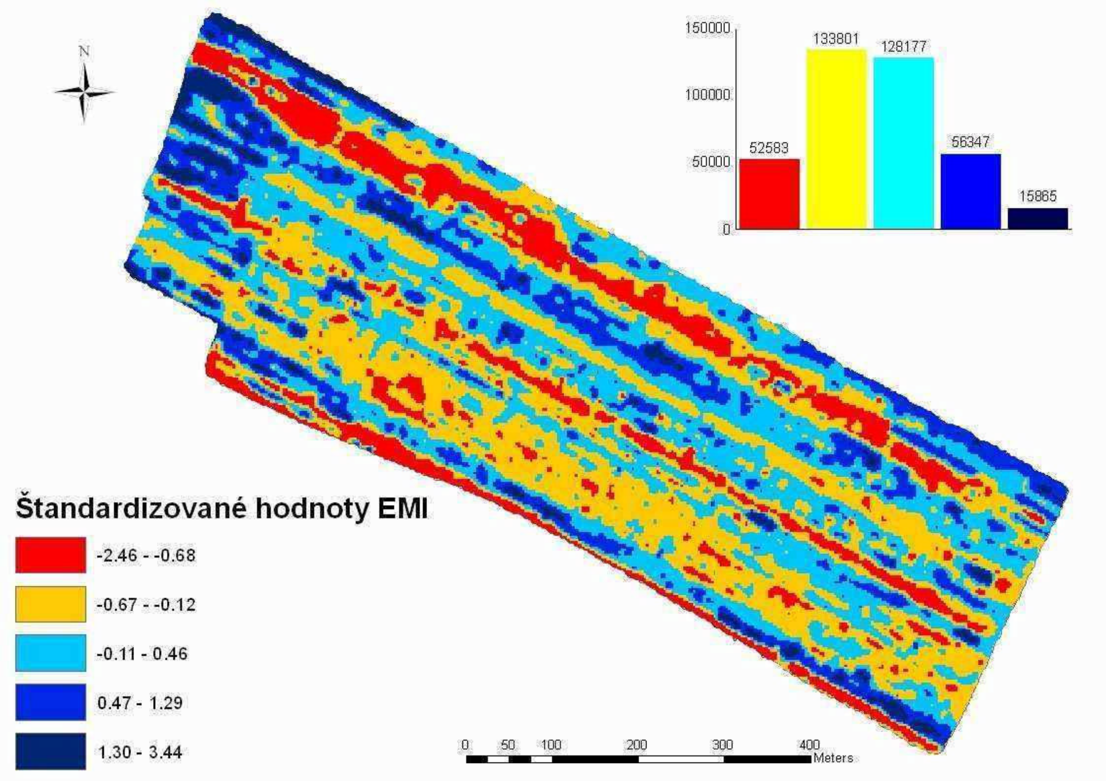
21 – ROWSHAM - Non calcareous clay soil, gravely and loamy drift

After: Mackney et al. (1983):

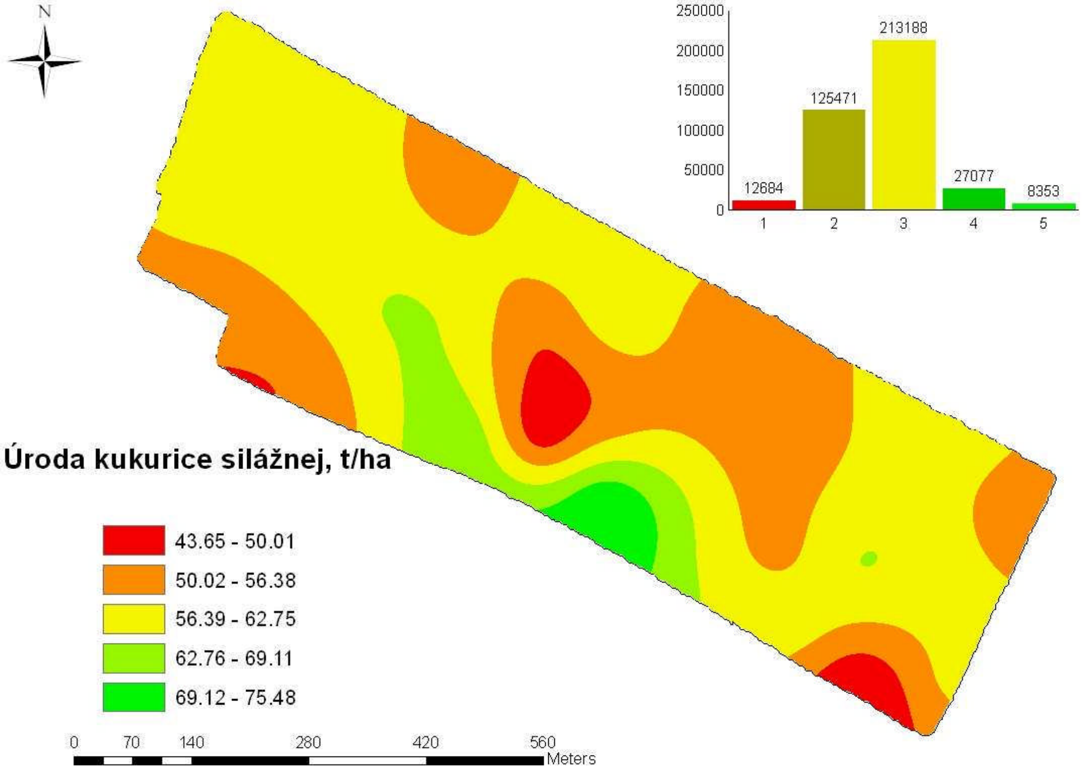
411c - EVESHAM –clay loam, deep clay

571s – EFOORD1 – loamy solid well drained gravel

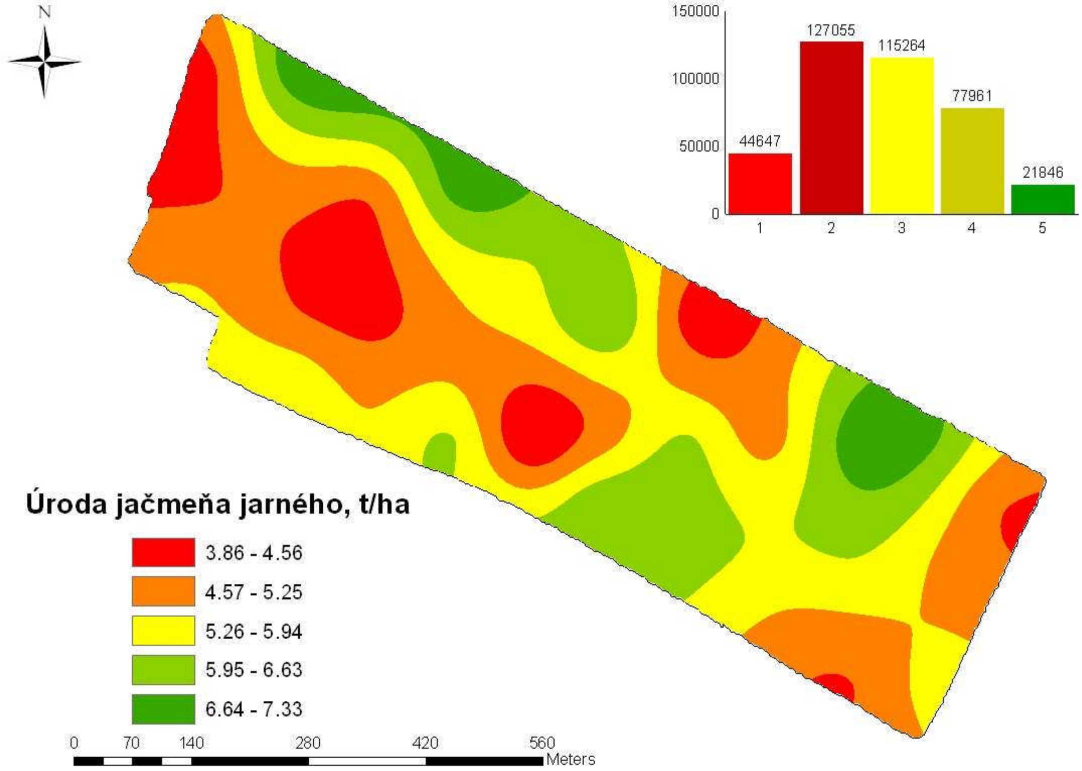
Appendix 5-1



Map of standardized values of electrical conductivity of the field in Oponice (EM 38 device



Yield of silage corn in t/ha in 2005



Yield of spring barley in t/ha in 2004.

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