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Sensing the Nitrogen balance in Potatoes

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Sensing the Nitrogen balance in Potatoes

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Abstract

Nitrogen (N) is the most important nutrient for the plant growth and development of the potato plant. However, N is often also the most limiting essential nutrient for potato growth. Therefore, the farmer needs to add nitrogen in large quantities to increase the plant-available amount of N for uptake by the potato crop. A proper rate and timing of N fertilization is crucial for optimizing the potato tuber yield and its quality, in combination with minimizing environmental pollution. However, nitrogen leaching from agricultural sources is a major environmental concern in Europe. The main objective in this study was to develop a nitrogen mass balance for an agricultural parcel of potato crops by using sensing based methods. A potato field located in the South of the Netherlands was used as a case study to develop this N mass balance. The first step was recognizing the parameters influencing the N-mass balance and defining the assumptions. The second step consisted of the actual measurements which were performed for 14 days spread over the entire growing season. On these days we obtained measurements of the plant spectral reflectances, chlorophyll content, leaf area index and the petiole plant sap NO_3^- concentrations. In addition, we also investigated the nitrogen content in the topsoil (0-20 cm) and the nitrate concentrations in the groundwater and the unsaturated zone at three different depths (25, 50 and 75 cm). These measurements were used to determine the effect of the different treatments of N-fertilizer inputs on the plant status and the nitrogen content in the soil and the groundwater. The spectral reflectances in combination with derived vegetation indices were used to determine the development of the aboveground plant nitrogen content over the growing season. The Fritzmeier Isaria Sensor is used to scale up the aboveground plant nitrogen content from canopy scale to field scale. The aboveground plant nitrogen is used as one of the output parameters in the N mass balance. The other parameters used in the N mass balance are the N fertilizer inputs, N mineralisation inputs and N deposition inputs. These inputs are equalized to the outputs. The outputs are identified as the N content in the aboveground plant plants, the N content in the potato tubers and the closing parameter N leaching, which comprises the leaching losses to the groundwater and gaseous losses via volatilization and denitrification pathways. The outcomes of this study showed that for this field N leaches losses are ranging from 57 to 73% of the total amount of N supplied, in combination with N uptake efficiencies of 28 to 45%. The results of this study showed that the N balance can be quantified by sensing based instruments, however for some parameters further research is necessary.

Keywords: Nitrogen, potato, Nitrogen mass balance, sensing, aboveground plant nitrogen content, leaching.

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List of acronyms, special terms and abbreviations

AGB	: Aboveground Biomass
AGN	: Aboveground Nitrogen
$CI_{red\ edge}$	: Red – Edge Chlorophyll Index
CI_{green}	: Green Chlorophyll Index
CNC	: Canopy Nitrogen Concentration
FAO	: Food and Agriculture Organization of the United Nations
Ha	: Hectare
LAI	: Leaf Area Index
LCC	: Leaf Chlorophyll Concentration
N	: Nitrogen
NDVI	: Normalised Difference Vegetation Index
NDRE	: Normalised Difference Red Edge
NO_3^-	: Nitrate
NUpE	: Nitrogen Uptake Efficiency
NUE	: Nitrogen Use Efficiency
PA	: Precision Agriculture
REP	: Red Edge Position
SOM	: Soil Organic Matter
TCARI	: Transformed Chlorophyll Absorption in Reflectance Index
TCARI/OSAVI	: TCARI combined with the Optimized Soil-Adjusted Vegetation Index
OSAVI	: Optimized Soil-Adjusted Vegetation Index
UAV	: Unmanned Aerial Vehicles
VIs	: Vegetation Indices
WDVI	: Weighted Difference Vegetation Index

1. INTRODUCTION

1.1 Context and background

The worldwide interest in potato (Solanum tuberosum L.) as a valuable food security crop is increasing (Pawelzik and Möller, 2015). Nowadays potato is the world's third most important food crop and produced on all continents except Antarctica (Brich et al., 2012). Due to a continuous growing human population to 2.3 billion people by the end of 2050, the global demand for agricultural crops is expected to continue growing in the coming decades (Tillman et al., 2011; Cambouris et al., 2014). An optimal food production, with high quality and high quantity yields is required to fulfil those high food demands of a growing human population. Potato has proven to be a very suitable crop to fulfil those requirements, because it is relatively easy to grow, containss of a lot of energy and proteins, it has high yields per unit area and as a result of that has a beneficial impact on human nutrition (Pawelzik and Möller, 2015).

To fulfil the growing food demands and to optimize the yield and quality of potatoes, an optimal management of nitrogen (N) is required. An optimal management of N is important to improve N uptake efficiency, and minimize N losses, while maintaining high yields and quality (Alva, 2004). This improvement in N use efficiency is especially important for potatoes, because of its relatively low ability to take up available soil mineral N (Goffart et al., 2008). Moreover, an optimal management of N will lead to a reduction in environmental pollution, due to less water pollution by nitrates and less atmospheric pollution in the form of nitrous oxides (Goffart et al., 2008; Alva, 2004). Therefore, the amount and timing of N application has economic and environmental implications and is consequently considered as an important issue in precision agriculture (Herrmann et al., 2010).

Despite intense efforts to optimise the N management in agriculture over the past two decades, nutrient losses and eutrophication by nutrients from agricultural sources remains a major environmental concern in Europe (D'Haene et al., 2014). To protect ground and surface water against pollution with nitrate (NO_3^-) the European Union (EU) imposed a maximum concentration level of 50 mg NO_3^-/L (Nitrates Directive, EC 1991). In Flanders (the Northern part of Belgium) is, due to an increasingly stringent legislation in combination with farmers' effort a downward trend in the NO_3^- concentration in ground and surface water observed. However at the moment still 26% of the sampling points in Flanders exceed the maximum concentration set by the Nitrates Directive (D'Haene et al., 2014). Therefore, the N use efficiency for potato cultivation needs to be increased, in order to reduce N leaching.

Potato is considered as a high-valuable crop, which is very sensitive to crop management and environmental conditions. Therefore, the potentials of using precision agriculture techniques in potato cultivation are large. This is due to the high costs of inputs such as seeds, fertilizers, irrigation, and pesticides, as well as labour and equipment for soil preparation, planting, and harvesting, which is all necessary for cultivating potatoes. Site-specific application of those inputs will improve yield, quality and profit (McKenzie and Woods, 2006). "Precision agriculture (PA) is defined as more precise seeding, fertilizer application, irrigation, and pesticide use, in order to optimize crop production for the purpose of increasing grower revenue and protecting the environment" (Cambouris et al., 2014). Precision agriculture applications in the N management for potatoes have the general goal to match the soil N supply with the crop N requirements in both space and time. This requires a precise characterization of the spatial distribution of crop N demand and soil N supply (Pan et al., 1997).

Remote sensing has been widely used in the agricultural sector for many years. The ability of producing repeatable measurements from a field, without destructive sampling of the crop, made remote sensing methods valuable methods to obtain information, which can be used for precision agriculture applications (Hatfield and Prueger, 2010). One of those applications in which remote sensing has proven to be a very successful technique is assessing the in-season potato crop nitrogen status. Various remote sensing based techniques exist to assess this crop nitrogen status. Those techniques vary from near, ground-based, air-borne or space-borne remote sensing techniques (Goffart et al., 2008).

1.2 Problem statement

The yield and tuber quality of potatoes depend on all kinds of parameters, such as temperature, duration of the day, initial amounts of nutrients in the soil, fertilizer application, solar radiation intensity, water availability etc. (MacKerron and Waister, 1985). Some of those (external) factors, such as light availability and temperature cannot be controlled by management of the farmer. Water and nutrient availability (in particular nitrogen) are widely recognized as the main manageable factors influencing potatoes health status, tuber growth, development, quality and yield (Ojala et al., 1990).

Nitrogen (N) is the most important nutrient for the plant growth and development of a potato. From the essential nutrients for potato growth, N is required in large quantities. Moreover it is the most mobile and dynamic nutrient in the soil system (Khosla et al., 2002). Insufficient amounts of available N reduce the leaf expansion rate, leaf emergence, root mass and potato tuber quality (Marouani et al., 2015). Therefore, nitrogen fertilization has become a critical source of input for the agricultural production of potatoes. Without fertilization the yields drop to unprofitable levels. However, excessive use of N-fertilizers has a lot of negative consequences for the environment, such as ground water contamination by nitrates. Excessive use of N-fertilizers can even contribute to climate change or ozone layer deterioration, due to an increase in the emission of greenhouse gasses in the form of nitrous oxides (Hyatt et al., 2010; Goffart et al., 2008; Alva, 2004).
A potato crop cannot only grow with a sufficient amount of nitrogen. It also needs sufficient amounts of other macro nutrients like potassium and phosphorus, but also micronutrients like zinc and magnesium are important (Westermann, 2005). Zinc is an essential micronutrient in the plant metabolism of potato crops. It has an important function in various enzyme systems for energy production, protein synthesis, and growth regulation. If a plant has a shortage of zinc it will not be able to grow as fast as plants, which do not have a shortage of zince (Brown et al., 2011).

Several studies showed that the within field spatial variability in chemical and physical soil properties strongly influences the quantity and the quality of the yield of potatoes (Redulla et al., 2002; Allaire et al., 2014). This spatial variability of physical and chemical soil properties strongly affects the availability, transport and uptake of nitrogen, but also of NO_3^- (Nitrate) and other compounds that can be formed with nitrogen in the soil and soil moisture (Khosla et al., 2002). To be able to come up with an accurate estimation of the N mass balance for an agricultural parcel of potato crops, it is important to map the spatial variability of the physical and chemical soil properties within the field. Knowledge of within field spatial variability of soil properties is essential for an adequate application of N fertilization and to prevent losses in the yield or a decrease in tuber quality. Moreover it will lead to a reduction in the environmental impacts of N fertilization. So, with knowledge of the spatial variability in soil properties and the N dynamics within the field, in combination with the available technologies in precision agriculture, farmers can manage their fields in such a way that an optimal yield can be obtained in combination with the smallest footprint for the environment.

In a research done by Giletto and Echeverria (2013) the nitrogen balance for potatoes has been studied for an experimental field in the southeast pampas region close to Buenos Aires (Argentina). In this study an agricultural parcel of McCain Argentina was studied for five successive growing seasons. The authors of this paper recognized the following N inputs:

$$N_{inputs} = N_{initial} + N_f + N_{min} \quad (1)$$

In which $N_{initial}$ is the initial amount of N present in the soil, N_f is the fertilization dose and N_{min} is the N derived from mineralization of soil organic matter. The amount of N mineralized was estimated from the incubated anaerobic amount of N. The initial amount of N was extracted from soil samples. The outputs that have been recognized are given in the following formula:

$$N_{outputs} = N_{tuber} + N_{aerial} + N_{final} + N_{vol} + N_{den} + N_{leaching} \quad (2)$$

In which N_{tuber} is the N in the tuber, N_{aerial} is the accumulated amount of N in the aerial (aboveground) plant part, which is the difference between the amount of N in the plant and he amount of N in the tuber. N_{final} is the residual available N, which is left in the soil after harvesting, N_{vol} is the N lost through volatilization, N_{den} the denitirificated amount of N and $N_{leaching}$ is the amount of N washed out through the soil profile. The unit of the components included in this nitrogen mass balance is kg/ha.

One of the main conclusions of the study by Giletto and Echeverria (2013) was that the amount of N accumulated in the tubers and the residual soil tends to increase with increasing N inputs. However, an increase of those N inputs, together with water drainage, leads also to an increase in N leaching for irrigated potato crop cultivation. Therefore, a good balance should be obtained in the amount of N fertilization (in combination with water drainage), which leads to the highest possible potato yields together with the lowest possible amounts of N leaching. However due to differences in environmental factors we are not sure whether this N-balance is also valid under different climates that the temperate-humid climate for this region in Argentina. Moreover, the experiment of Giletto and Echeverria (2013) was conducted for five successive growing seasons at the same experimental field, meanwhile in our case a study has been performed during one growing season on on agricultural parcel which was last year cultivated by sugar beets. Furthermore there are differences in cultivation systems between Argentina and western-Europe and the Typic Argiudoll soils as found in the southeast pampas (loam to clay loam texture) are also different from the sandy soils we find in our study. Therefore we cannot directly copy the N-balance of Giletto and Echeverria (2013) for this study.

In the book of Haverkort and MacKerron (2000) a nitrogen balance is estimated for potato cultivation under west-European conditions. However this book focusses in general about the management of nitrogen and water in potato production. In this book, the nitrogen balance is separated into a part about the crop nitrogen balance and the soil nitrogen balance. Haverkort and Mackerron (2000) recognized the following soil components of the N-balance:

$$N_{soil} = N_{org} + N_{min} \tag{3}$$

In which N_{min} is the amount of plant available N in the soil and N_{org}, is the nitrogen content in organic form. The nitrogen content in the plant is divided into three components; the leaves, the stems and the tubers. Those components of the N-balance are further subdivided into an organic and inorganic part.

$$N_{plants} = N_{leaves} + N_{stems} + N_{tubers} \tag{4}$$

However this nitrogen balance does not take losses by N leaching to the groundwater and N emissions to the air into account. Therefore this N-balance will not be a completely closed nitrogen mass balance.

Another N mass balance is designed by Prasad et al., (2015). In this study an estimation is made of the nitrogen pools in irrigated potato production on sandy soil for a study farm located in Middle Suwannee River Basin, Florida. The authors in this study focussed on the difference between the input and output of the N budget. This difference was considered as unaccounted N and used as a estimation of the seasonal environmental N loading rate. The unaccounted N in this study comprised leaching losses to the groundwater and gaseous losses via volatilization and denitrification pathways. Therefore the following mass balance equation was used to estimate the unaccounted N:

$$Nenv.load = NInitial + Nfertilizer - Ncrop - NFinal \tag{5}$$

Where, $N_{env.\ load}$ is the environmental N loading (or unaccounted N), $N_{initial}$ is the initial mineral N in the soil (0.3m) before planting the potatoes, $N_{fertilzer}$ is the amount N added by fertilizer application, N_{crop} is the crop N uptake and N_{Final} is the amount of mineral N present in soil (0.3m) when the potatoes were harvested (Prasad, et al., 2015).

All kind of (remote) sensing methods are available and capable for near real-time monitoring and diagnosis of the crop status within the field. However, the availability of consistent time-series of sensor data is a critical user requirement for the application of remote sensing in precision agriculture. Since sensors with a high spatial and temporal resolution are necessary to detect differences in crop development (Kooistra et al., 2013). The available (remote) sensing techniques can be subdivided into point based measurements or measurements at field level. Point-based measurements of the crop status include measurements by instruments like the Minolta SPAD-502 chlorophyll meter, the CropScan Multispectral Radiometer and the LAI-2000 instrument. At field scale we distinguish between satellite based remote sensing techniques and other sensing technologies like unmanned aerial sensing (UAS) or near-sensing system technologies mounted to a tractor. Imagery taken from unmanned aerial vehicles (UAV) have been recognized as a potential useful method for crop monitoring, given their potential high spatial and temporal resolution, and their high flexibility in image acquisition (Kooistra et al., 2013). An example of a sensing instrument mounted on a tractor is the Fritzmeier ISARIA sensor (see cover picture). This sensor is able to determine the N requirements of a crop based on the reflected light by the crop (Van den Borne Loonwerk GPS, 2015).

The challenge in this thesis is to combine the (accurate) point measurements for individual crops with the measurements at within field scale. Therefore, we need to find accurate correlations between measurements at crop level and measurements at field level and determine how sensing can be used for this upscaling by taking the spatial and temporal variability within the field into account. This should lead to an accurate estimation for the nitrogen content within the plant.

1.3 Research objectives and questions

The general goal of this research is to develop an nitrogen mass balance for an agricultural parcel of potato crops by using sensing based methods. The results of this thesis should provide the farmer more insights for site-specific management of nitrogen in precision agriculture applications. Furthermore, this thesis is used to assess whether (remote) sensing based methods are suitable to monitor specific components of the nitrogen balance in a cropping system with potatoes To fulfil those objectives we defined the following research questions:

Question 1: Which parameters, in the soil and in the crop influence the nitrogen balance?

Question 2: How does the spatial variability of soil properties (e.g., thickness and SOM content of the A-horizon) influence the variation in the nitrogen content of the topsoil?

Question 3: How accurate can the nitrogen concentration in the soil and crop be measured over the growing season by using remote and proximal sensing based methods?

Question 4: How is the nitrogen balance influenced by different treatments of N-inputs?

The research questions and objectives above are defined for an agricultural parcel of potato crops in the South of the Netherlands, close to the village of Reusel.

1.4 Overview of the report

In this thesis, the main goal is to develop an accurate estimation of the nitrogen mass balance for an agricultural parcel of potato crops by using proximal and remote sensing based methods.

Chapter one provides a context and background related to potato cultivation. Furthermore, it addresses the importance of nitrogen in potato growth and it describes the role precision agriculture has in N-management for potatoes. The nitrogen mass balance is for the first time mentioned and the N-mass balances designed in previous studies are described. Moreover, chapter one also provides the research objectives, research questions, and an overview of report.

Chapter two includes the theoretical background and literature review for this thesis. We describe the main developments in precision agriculture and its application in the N-management of potatoes. Furthermore we discuss the components of the Nitrogen mass balance and give an overview of some regulation about some of the parameters. We also provide an overview of the vegetation indices (Vis) used in this study and for some VIs we discuss how they are related to nitrogen. In the last section of chapter two we provide an overview of the nitrogen status assessment methods for potatoes.

Chapter three gives an overview of the methodology used in this thesis. It describes the study area, the materials used, and the available data to answer the research questions. Furthermore, it discusses the methodology used for the analyses and it provides two flowchart of the whole process, which includes all steps, from the data obtained until the final result. Chapter three starts with an introduction of the N-mass balance used in this study in combination with an overview of the assumptions we made. In the next subchapter an overview is given of the measurements done to determine some of the parameters of the N-mass balance. This subchapter is divided in several sections. In section 3.2.1 we discuss the experimental set-up of this study, followed by the N-fertilizer treatments in section 3.2.2 Section 3.2.3 describes the materials used and in section 3.2.4 we discuss the methodology used to measure some of the parameters of the N mass balance. In subchapter 3.3 we discuss the sensors that could be used in order to sense some of the parameters of the N-mass balance. This subchapter is divided into a section about the sensors (3.3.1) and a section in which we discuss how the use of these sensors has been assessed (3.3.2).

Chapter four presents the main results obtained for answering the research questions. We start presenting the results obtained to determine the N content in the soil. In which we discuss the spatial variability of the parameters influencing the N-content in the soil in section 4.1.1 and show the effect the different N-treatments has on the N-content in the topsoil, unsaturated zone and for the groundwater in section 4.1.2. In subchapter 4.2 we discuss the results obtained for the N content in the potato plant. In section 4.2.1 we show the results between the CropScan reflectances and the aboveground plant nitrogen content and the NO_3-N concentration in the petiole plant sap. In section 4.2.2 we discuss the effect the different N-treatments have on the parameters determining the current plant status. Section 4.2.3 mainly deals with a yield assessment based on the N footprint and the N use efficiency. In the last section of this subchapter we show the accuracy of the Frizmeier Isaria Sensor for determining the aboveground plant nitrogen content and present the maps showing the spatial variability of the aboveground plant N-content at field level. In section 4.3 we present the graphs showing the time series of the N balance parameters for some of the selected plots.

Chapter five discusses the insights gathered from the results in this thesis. Those results are mainly discussed in broader context and linked to scientific literature. The set-up of the discussion chapter is similar to the order in the results chapter.

Finally, chapter six summarizes the main conclusions obtained with regard to the objectives and we provide some recommendations on how to reduce the uncertainties based on the methodology of this study and provide some strategies related to the reduction of nitrate leaching into the groundwater.

2. THEORETICAL BACKGROUND

This chapter presents a literature review on the main topics that will be covered in this study. Those main topics are: Precision agriculture and its application for cultivating potatoes (Section 2.1); the main components of the nitrogen balance (Section 2.2); remote sensing based VIs adopted for precision agriculture (Section 2.3) and finally crop nitrogen status assessment methods for potatoes (Section 2.4).

2.1 Precision agriculture

In the Introduction chapter it is already briefly discussed what the potentials are of using precision agriculture techniques in potato cultivation. In this section we elaborate further on those opportunities for precision agriculture. In which we mainly focus on precision agriculture application in the N-management of potatoes. Those applications in the N management for potatoes have the general goal to match the soil N supply with the crop N requirements in both space and time. This requires a precise characterization of the spatial distribution of crop N demand and soil N supply (Pan et al., 1997). This will be discussed in more detail later on, but first we start with the definition of precision agriculture.

In the Introduction chapter the definition of precision agriculture of Cambouris et al., (2014) is already mentioned. However, in science multiple definitions for agriculture are used. A commonly used definition for precision agriculture is the definition by Gebers and Adamchuk (2010). They stated that “precision agriculture comprises a set of technologies that combines sensors, information systems, enhanced machinery, and informed management to optimize production by accounting for variability and uncertainties within agricultural systems”. Furthermore, Jacob Van den Borne, the farmer at whose farm this research took place, summarizes precision agriculture as “applying the right measure, at the right location at the right moment”. So precision agriculture, by adapting production inputs site-specifically within a field, allows a better use of resources to maintain the quality of the environment while at the same time improving the sustainability of the food supply. Therefore, we can conclude that precision agriculture provides a way to monitor the food production chain and at the same time manage both the quantity and the quality of the agricultural products (Gebers and Adamchuk, 2010) .

The basis of the increasing developments in precision agriculture is the increasing knowledge about spatial and temporal variability of soil and crop properties within a field (Zhang et al., 2002). In the past, before the agricultural mechanization took place, the agricultural fields were small, which allowed the farmers to manually monitor their fields and vary their treatments if necessary. After the land consolidation and enlargement of the fields mechanization was necessary to manage those larger fields. Due to this mechanization it became increasingly more difficult to take the within-field spatial variability into account (Stafford, 2000). From the mid-1970s to the early 1980s, better field investigation methods (including soil survey, soil sampling, aerial photography, and crop scouting) resulted in a better awareness of soil and crop condition variability within fields (Robert, 2002). At the same time new techniques like Global Positioning Systems (GPS), Geographic Information Systems (GIS), miniaturized computer components, telecommunications techniques and in particular remote sensing techniques in agriculture became available (Zhang et al., 2002;

Robert, 2002). Remote sensing applications in precision agriculture started with sensors for measuring differences in soil organic matter contents, and have quickly diversified to include satellite, aerial, and hand held or tractor mounted sensors (Mulla, 2013). Due to those newly available techniques, precision agriculture was initiated in the mid-1980s, mainly to improve the application amounts of fertilizers by varying input components and rates as necessary for the crops within the fields. Before the implementation of precision agriculture, large fields received under conventional management uniform amounts of fertilizers, pesticides, irrigation water, but also the seed quantity and seeding distance were kept constant. After the developments in precision agriculture we are now able to divide these fields into specific management zones that each receives customized management inputs based on varying soil types, soil quality differences, crop characteristics, landscape position, and management history (Mulla, 2013).

Cambouris et al., (2014) stated that potato, as a high value crop, is recognized as a crop in which precision agriculture can have a direct added value. This is due to the sensitivity of the potato yield quality and quantity to crop management and environmental conditions. Those great opportunities for the adoption of precision agriculture in potato cultivation are caused by the high costs of inputs such as seeds, fertilizer, irrigation and pesticides, as well as labor and equipment for soil preparation, planting, and harvesting (McKenzie and Woods, 2006). The applications of precision agriculture in cultivating potatoes are mainly present in phosphorus and potassium fertilizer management, nitrogen management, pesticide use and water management. In the rest of this section we mainly focus on the application of precision agriculture in Nitrogen management.

In general, precision agriculture applications in N-management involve matching the soil N supply with the crop N requirements in both space and time. This requires a precise characterization of the spatial and temporal distribution of crop N demand and soil N supply (Pan et al., 1997). Nowadays, proximal or remote sensors can be used to characterize this spatial and temporal variability in soil N supply and crop N demand, through more efficient, less time-consuming, and affordable approaches (Cambouris et al., 2014). Commercially available proximal sensors mounted on tractors, such as the N-Sensor ALS (YARA Ltd Company, Oslo, Norway), GreenSeeker (N Tech Industries Inc., Ukiah, Canada), Fritzmeier ISARIA Biomass Sensor (Fritzmeier Umwelttechnik GmbH & Co. KG, Großhelfendorf, Germany), measure Crop N status using canopy light reflection (Zebarth et al., 2012; Goffart et al., 2008). These devices are developed for N management in which automatically real-time fertilizer can be applied with varying fertilizer rates across the field based on the plant N deficiency monitored and assessed by the sensor readings and the computer equipment on-board of the tractors. Those instruments are in particular suitable for agricultural regions with large fields in combination with a large variation in soil properties. Under such conditions, the application of those high cost equipment which enables variable nitrogen rates is economically interesting because it improves the N use efficiency and therefore reduces the costs of fertilizer use (Goffart et al., 2008, Shanahan et al. 2008). Another aspect which is important in N-management and is possible due to precision agriculture is fertilization in split applications. Split fertilization can be considered as fine-tuning of within-field operations (McBratney et al., (2005). This split fertilization, which can be steered by (remote) sensing leads to a reduction of the amount of N which leaches to the environment and improves the nitrogen uptake over the growing season. Van Alphen and Stoorvogel (2000) showed that for winter wheat in The Netherlands by applying split fertilizer strategies fertilizer inputs can be reduced by 23% as compared with the regular fertilization procedure used by the farmer which was based on up-to-date fertilization advices by extension services.

Besides the positive effects precision agriculture has on the potato yield quality and quantity and a reduction of the costs of inputs such as seeds, fertilizer, and pesticides it will also lead in combination with site-specific management to a reduction in the environmental impacts of N fertilization and hence help to comply with environmental norms.

2.2 Components of the Nitrogen Balance

In this section the components of the Nitrogen mass balance are discussed, based on a combination of the studies of Giletto and Echeverria (2013) and Haverkort and MacKerron (2000). Furthermore, the concept of the nitrogen footprint in potato cultivation is discussed and an overview is given with some legislation about nitrate concentrations in groundwater.

Inputs

Nitrogen (N) is the most important nutrient for the plant growth and development of a potato. However, N is often also the most limiting essential nutrient for potato growth (Errebhi et al., 1998). Therefore the farmer needs to add nitrogen in large quantities to increase the plant-available amount of N for uptake by the potato crop. A proper rate and timing of N fertilization is crucial for optimizing the potato tuber yield and its quality, in combination with minimizing environmental pollution. N deficiency in the potato plant can substantially reduce the yield, whereas excessive N application can delay tuber maturity, lower tuber quality, and increase the chance of nitrate contamination of surface and ground water (Wu et al., 2007; Errebhi et al., 1998). This N can be added in several ways: 1) by applying organic manure to the soil before the growing season of the potatoes starts; 2) by applying chemical fertilizer as pellets to soil; 3) by adding chemical fertilizer in the form of liquid urea to the leaves. This liquid urea is easily absorbed by the plant leaves and is used as boost for the crop in a dry period. Nitrogen fertilization is the most important N-input pool for the N-mass balance of an agricultural parcel of potatoes.

A second nitrogen pool which is harder to estimate is the N which is already present in the soil at the moment when the potatoes were planted. This $N_{initial}$ depends on the residual available N after harvesting the crop from the previous year, but also on the amount of N mineralization which took place between harvesting the previous crop and planting the potatoes and whether or not a form of green manure has been applied in the winter period.

One of those other inputs for the nitrogen balance is the amount of nitrogen that comes from the air. This nitrogen deposition is estimated as 2250 mol/ha/year for the area around Reusel, which corresponds to a value of 31.52 kg/ha/year or 86.4 g/ha/day. Those values are high, compared to an average value of 1565 mol/ha/year (=21.92 kg/ha/year) for the Netherlands (Velders et al., 2010). Those relatively high values are caused by to agricultural sources (Pig farming) in the neighbourhood of the experimental field.

Another nitrogen pool which is harder to estimate is the amount of nitrogen which comes from mineralisation of organic matter, which is already present in the soil. An accurate estimation of the amount of N mineralized from soil organic matter (SOM) will improve the sustainability of agriculture because it allows farmers to determine the rate of N fertilizer application required to optimize crop yield and to minimize N losses to the environment (Ros et al., 2011). The study by Ros et al., (2011) showed that the content of mineralized N was more strongly correlated to variables reflecting the organic matter content than to any other variable. Van Haecke (2010) stated that the nitrogen mineralisation rate of organic matter is preliminary depending of the type of soil, carbon content in the soil, the percentage young organic matter content, the C-to-N ratio (An increase in the C-to-N ratio is associated with a decrease in the mineralization rate) and other soil and climatological conditions like temperature, moisture and the amount of oxygen.

Outputs

There are several parameters which form together the outputs of the N mass balance of a potato field. One of those outputs is the amount of N which is taken up by the plant. In this study this parameter is subdivided into the amount of N in the tuber (N_{tuber}) and the amount of N in the aboveground plant parts (N_{plant}; AGN). Nitrogen is in general taken up by the roots in the form of nitrate and ammonia, and enters afterwards into a soluble nitrogen pool. From this pool, nitrogen is used for the formation of plant components, such as chlorophyll and RuBisCO (an enzyme involved in carbon fixation) and as structural components in cell tissue. Those structural nitrogen contents increase as the crop develops and may comprise up to 30% of total nitrogen at the moments when the crop is in its mature stage (Jongschaap and Booij, 2004). Brown et al., (2011) stated that N is allocated to the plant parts based on the highest priority plant organ. If the minimum N demand of the highest priority organ is fulfilled, than N will be allocated to the second highest priority organ. The order of priority for potatoes is tuber > root > leaf > stem. Therefore, it is expected that when the potato tubers are increasing in size, the N content in the tubers increases as well. This theory is supported by the results of the study by Brown et al., (2011) in which for Russet Burbank potatoes in New-Zealand it was shown that the nitrogen content in the tubers increases linearly until a specific saturation level was reached. Furthermore, it was shown that at the moment when the N concentration in the tuber increases, the concentration in the leafs decreases as can be seen in figure 1.

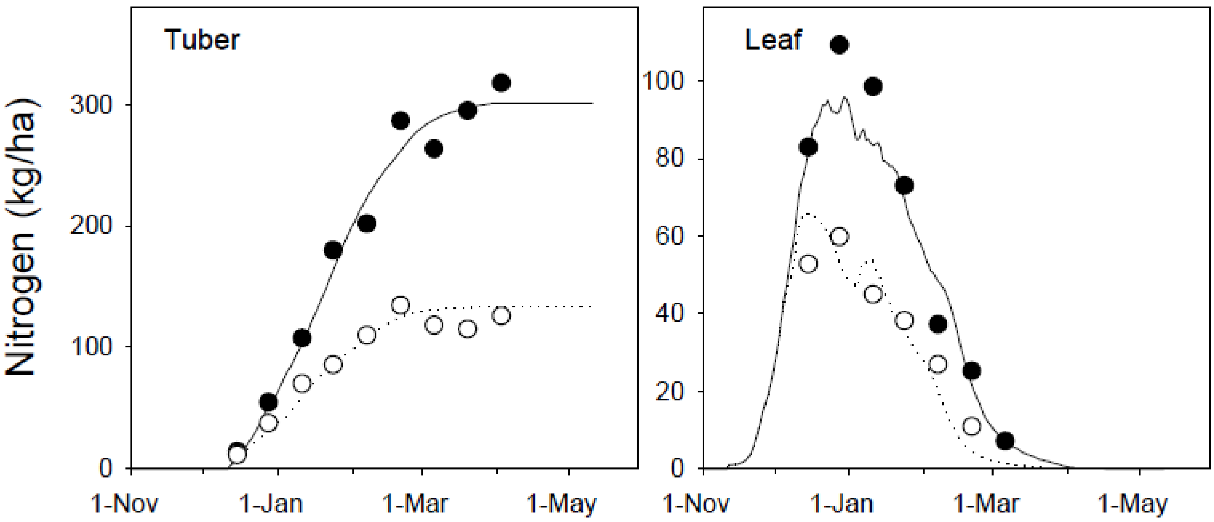

Figure 1. The development of the nitrogen content in the tuber and the leaf over the growing season for Russet Burbank potatoes grown in New Zealand. In which treatments with a ○ received 0 kg N/ha and with a ● received 300 kg N/ha.

Another significant output is the N content which is washed out through the soil profile and leaches to the groundwater. Nitrate leaching is a major issue in many cultivated soils (Gasser et al., 2003). It occurs often in areas with sandy soils, which are intensively cultivated with potatoes or other crops, which demand high N fertilizer inputs (Levallois et al., 1998). The result of nitrate leaching to the groundwater is that the groundwater gets contaminated and cannot be used for agricultural or drinking water purposes. Therefore an optimal management of N is necessary to reduce water pollution by nitrates.

Other outputs, which were recognized by the paper of Giletto and Echeverria (2013) are gaseous N losses which occur by ammonia volatilization (N_{vol}) and denitrification of oxidized N compounds (N_{den}). Shepherd and Postma (2000) stated that gaseous N losses by ammonia volatilization are low because the ammonia is absorbed by colloidal particles or rapidly transformed to nitrate, therefore there is little available for volatilization. However the paper of Gasser et al., (2002) showed that especially when organic N fertilizers are applied (such as cow or pig slurry) with a slurry spreading technique losses due to ammonia volatilization in the first 24 h after spreading could be roughly estimated as 21 – 30% of the total N applied.

Denitrification is the reduction of NO_3 or NO_2 via several intermediate products into the gases nitrous oxide (N_2O) and dinitrogen (N_2). This process occurs under anaerobic conditions (lack of oxygen) and is carried out by many different groups of bacteria. When denitrification takes place, in general when anaerobic conditions (heavy rainfall) occur in combination with the application of N, it results in a loss of nitrogen in the soil. In general N losses by denitrification of agricultural parcels cultivated by potatoes are an order of magnitude less than the losses by nitrate leaching (Shepherd and Postma, 2000). "However, in some circumstances, such as when heavy rainfall occurs after application of fertilizer in spring, denitrification might be as important as leaching for N losses" (Addiscott and Powlson, 1992).

The final output parameter left in the N mass balance is Residual available N after harvesting the potatoes (N_{final}).

Nitrogen Footprint Potato Cultivation

The N footprint is an often used indicator to quantify the total direct N-losses to the environment that occur for the production of one unit of food product (Leip et al., 2014). This indicator is generally measured in g N/kg food product and can be considered as an estimator for the environmental impact of the cultivation of a specific product. The N footprint is in general calculated as total N emission intensity for one unit of product according to the study by Leach et al. (2012). This N-footprint consist of the N losses by N leaching and runoff to the ground- and surface water and the N emission to the air. In general, models are used to predict the N footprint. Those models need to that take into account factors like the N-uptake, N fertilizer dissolution, nitrification at the soil surface and the amount of drainage water during the growing season. Leip et al., (2014) used two different models to estimate the N-footprint for cultivating potatoes in Europe. Both models estimated the N footprint of potato cultivation as 2 g N/kg potato. This means that for every kg of potato 2 gram of N is leached to the environment. In the section below.
Gasser et al. (2003) developed a different model, which predicts the amount of N-leaching to the groundwater. With an average application rate of 169 kg N ha^{-1} of N-fertilizer in potato crops and for potatoes cultivated on sandy soils, the mean nitrate-leaching losses measured

under the potato crop were 85 kg N ha^{-1}. In this model the tuber N-uptake was averaged on 97 kg N ha^{-1} and soil N mineralization was estimated at 43 kg N ha^{-1}.

Nitrate Concentration in groundwater

The production of potato on sandy soils has a high risk on nutrient leaching due to the shallow root system of potato plants in combination with the low water and nutrient holding capacity of the sandy soils (Prasad et al., 2015). Therefore it is important to know more about the behavior of nitrates in the topsoil, the unsaturated zone and the saturated zone.

The legislation about the nitrate concentration for member countries of the European Union (EU) stated that the nitrate concentration for shallow groundwater is not allowed to be higher than 50 mg/L in sandy soils (Nitrates Directive, EC 1991). In which shallow groundwater is defined to be in the first 5 m of the saturated zone. There are several ways to monitor the quality of this shallow groundwater. The Dutch government decided to monitor the quality of the uppermost meter of the saturated zone when they want to check whether the nitrate concentration exceeds the limit value. This uppermost meter is most susceptible to influences. Moreover, sampling deeper in the saturated zone attenuates seasonal variations in groundwater quality (Boumans et al. 2005). We decided to follow the approach of the Dutch government and sampled only the upper meter of the groundwater to monitor the nitrate concentration in the saturated zone.

2.3 Vegetation Indices

Several vegetation indices (VIs) have been developed for assessing the N content in vegetation. The majority of those VIs are based on indirect indicators of chlorophyll content (Daughtry et al. 2000). The chlorophyll content is proven to be physiologically linked to the amount of N, as the chlorophyll content is mainly determined by the N-availability (Herrmann et al., 2010). In this research we investigate both the direct and the indirect relationships between vegetation indices and the nitrogen content. In this section we provide an overview of the vegetation indices used in this study and for some VIs we discuss how they are related to nitrogen. But first we start with an introduction about reflection in vegetation.

There is a relation between (green) vegetation and their reflection of visible and infrared vegetation. Vegetation indices are based on this relation. The available pigments in living green vegetation are the cause that visible light (0.4-0.7 µm) is strongly absorbed, especially in the blue (0.45 µm) and red (0.65 µm) region of the electromagnetic spectrum. Due to the physiological structure of vegetation reflection takes place in the near-infrared region of the electromagnetic spectrum (1.0–2.7 µm). And due to the water content in the leaves absorption takes place in the middle infrared part of the electromagnetic spectrum. The electromagnetic spectrum of vegetation, soil and water is visualized in figure 2.

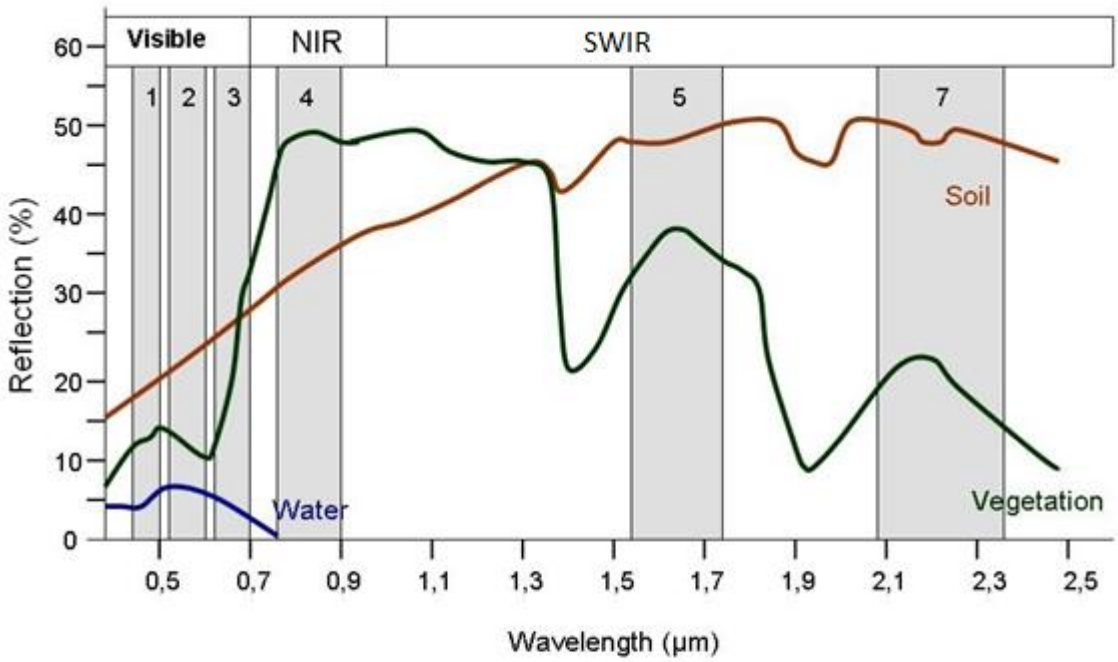

Figure 2. Spectral reflectance curve for vegetation, water and bare soil. (Source: http://www.seos-project.eu/modules/remotesensing/remotesensing-c01-p05.html)

Vegetation Indices (VIs) are combinations of surface reflectance at two or more wavelength bands built to emphasize a specific vegetation property, e.g. chlorophyll concentration, or N content. The development of different spectral band combinations, known as VIs, has a main purpose of decreasing the spectral effects caused by external factors such as atmosphere and soil background. Extracting spectral information related to N uptake by using various VIs has been developed to enhance the capability of detecting canopy N status differences (Blackmer et al., 1996). A major advantage of using spectral information in combination with VIs is that it provides N assessments without time-consuming and expensive laboratory analysis. However, as stated before, in general the chlorophyll content is being used in radiative transfer models, since the chlorophyll content is one of the main parameters describing the interaction between solar light and the canopy (Clevers and Kooistra, 2012).

The Normalized Difference Vegetation Index (NDVI) was developed by Rouse et al., (1973). This vegetation index is an index of the plant "greenness" or photosynthetic activity. The NDVI can be calculated in the following way:

$$NDVI = \frac{R(NIR) - R\ (red)}{R(NIR) + R(red)} \quad (6)$$

In which R(NIR) is the total measured near-infrared reflectance and R(red) the total measured red reflectance.

The Weighted Difference Vegetation Index (WDVI) was developed by Clevers (1989) and includes a correction of the infra-red reflectance for soil background in particular for differences in the soil moisture content and can therefore be used for estimating the LAI (Clevers, 1989). The WDVI is calculated as:

$$WDVI = R(NIR) - C * R(red), \text{ (in which } C = \frac{Rs(NIR)}{Rs\ (Red)}\text{)} \quad (7)$$

In which R(NIR) is the total measured near-infrared reflectance, R(red) the total measured red reflectance, Rs(NIR) the near-infrared reflectance of the soil and Rs(red) the red reflectance of the soil.

Clevers and Kooistra (2012) investigated CropScan reflectance datasets to find the best representative VI for estimating canopy chlorophyll and nitrogen content in a potato crop. Their study has been used as a starting point for developing relations between VI's and canopy chlorophyll and nitrogen content for our study.

A wide variety of vegetation indices have been derived to estimate the chlorophyll content. This chlorophyll content is so important because it is directly related to one of the basic plant physiological processes: photosynthesis. One of such a radiative transfer model that can be used to estimate the chlorophyll content from hyperspectral data is the Transformed Chlorophyll Absorption in Reflectance Index (TCARI), which was proposed by Haboudane et al., (2002). The TCARI vegetation index can be calculated in the following way:

$$TCARI = 3\left[(R700 - R670) - 0.2(R700 - R550) * \left(\frac{R700}{R670}\right) \right] \quad (8)$$

In which where R700, R670, R550 are the reflectance values at the wavelengths: 700, 670 and 550nm, respectively.

In a study done by Cohen et al., (2007) it was found out that for potato leaves and canopy TCARI values were inversely correlated to N-NO_3 levels. So, TCARI values increase with decreasing N levels. They found linear and exponential relationships with high correlations between TCARI and petiole N content.

In a previous study by Rondeaux et al., (1996), the Optimized Soil Adjusted Vegetation Index (OSAVI) was developed by using bidirectional reflectance in the near-infrared (NIR) and red bands. The OSAVI was developed to correct for the soil background effect, which is a major component controlling the spectral behavior of vegetation canopies. The OSAVI index has the following formulation:

$$OSAVI = \left(\frac{(1+0.16)(R800 - R670)}{R800 + R670 + 0.16}\right) \quad (9)$$

Where R800, R670 are the reflectance values at the wavelengths: 800 and 670 nm, respectively.

The TCARI and the Optimized Soil-Adjusted Vegetation Index (OSAVI) were combined into one index, the TCARI/OSAVI. The TCARI/OSAVI index was proposed for reducing the soil background effect, minimizing the sensitivity to differences in the canopy leaf area index (LAI) and enhancing the sensitivity to chlorophyll content" (Cohen et al., 2007; Herrmann et al., 2010). This vegetation Index was developed by Haboudane et al., (2002) and is structured in the following way:

$$\frac{TCARI}{OSAVI} = \frac{3\left[(R700 - R670) - 0.2(R700 - R550) * \left(\frac{R700}{R670}\right) \right]}{\left[\frac{(1+0.16)(R800 - R670)}{(R800 + R670 + 0.16)}\right]} \quad (10)$$

In which R800, R700, R670 and R550 are the reflectance values at the wavelengths: 800, 700, 670 and 550 nm, respectively.

Although other studies, e.g. the studies done by Jain et al., (2007) and Herrmann et al., (2010) showed that both TCARI and TCARI:OSAVI were insensitive to changes in N content in the canopy level of potato plants. Herrmann (2009) stated in his paper that if band 670 nm was replaced with band 1505 nm, TCARI:OSAVI was found sensitive to changes in the N content of the canopy of a potato plant.

The studies of Collins (1978) and Horler et al., (1983) were among the first studies in which the importance of the red-NIR wavelength transition was pointed out for vegetation studies. Horler et al., (1983) showed that both the position as the slope of this transition between red wavelengths and NIR wavelengths (red-edge) changes under stress conditions, which results in a shift of the slope towards shorter wavelengths. As an index is in general the position of the inflexion point on the red-NIR slope used (Clevers and Kooistra, 2012). This point is called the Red Edge Position (REP) and is influenced by both the LAI and the Chlorophyll Concentration. The red edge position is strongly correlated to the chlorophyll concentration, however at higher chlorophyll concentrations a saturation effect occurs. The Red Edge Position can be calculated by the index, which is established by Guyot and Baret in 1988. They defined the REP by the following linear model:

$$REP = 700 + 40\ \frac{\frac{(R670+R780)}{2} - R700}{R740 - R700} \quad (11)$$

For which R780, R740, R700 and R670 are the reflectance values at the wavelengths: 780, 740, 700 and 670 nm, respectively.

Another vegetation index which was highly correlated to the canopy chlorophyll concentration and also based on the red-edge position is the Red – Edge Chlorophyll Index ($CI_{red\ edge}$). Gitelson et al. (1996) presented this index based on a NIR band and a red-edge band. This $CI_{red\ edge}$ is calculated as follows:

$$CIred\ edge = \left(\frac{R780}{R710}\right) - 1 \quad (12)$$

For which R780 and R710 are the reflectance values at the wavelengths: 780 and 710 nm, respectively. Reflection near 710 nm was chosen because it was found to be a very sensitive indicator of the red-edge position as well as of the chlorophyll concentration. Furthermore it was shown that the ratio of reflectance's at 780 nm to that near 700 nm (R_{780}/R_{710}) was directly proportional to chlorophyll concentrations (Gitelson et al., 2009). Besides the so-called chlorophyll red-edge Gitelson et al. (1996) developed a variant using a green band instead of the red-edge band (CI_{green}). This CI_{green} is structured in the following way:

$$CIgreen = \left(\frac{R780}{R550}\right) - 1 \quad (13)$$

For which R780 and R550 are the reflectance values at the wavelengths: 780 and 550 nm, respectively.

A major advantage of this $CI_{red\ edge}$ and CI_{green} is the linear relationship with chlorophyll and the absence of a saturation effect compared with other REP based indices (Clevers and Kooistra, 2012). Several studies showed that the Red – Edge Chlorophyll Index ($CI_{red\ edge}$) is the most appropriate hyperspectral vegetation index for assessing potato Aboveground Nitrogen (AGN) concentration with a high N sensitivity (Mourier et al., (2015); Kooistra et al., (2015). This vegetation-index is suitable for detecting potato crop N stress and performs well in discriminating nitrogen status patterns (Cambouris et al., 2014). Furthermore, the paper of Clevers and Kooistra (2012) concluded that for the N content in potatoes: “the CIred edge shows the best predictive power, but some other indices are nearly as good as this index”.

Barnes et al., (2000) developed the Normalized Difference Red-Edge (NDRE) as a measure of the leaf chlorophyll concentration or nitrogen content in the aerial plant parts. This vegetation index is formalized in the following way:

$$NDRE = \frac{(R790 - R720)}{(R790 + R720)} \quad (14)$$

Where R790 and R720 are the reflectance values at the wavelengths: 790 and 720 nm, respectively. Several studies showed that there are good relations between the NDRE with the leaf nitrogen content for rice plants (Tian et al., 2011), estimating plant N uptake in summer maize (Li et al., 2014) and in detecting nitrogen stress in wheat (Karande et al., (2014). In this study the NDRE will also be tested for assessing the Nitrogen content in the aboveground plants parts.

Table 1 gives an overview of the vegetation indices used in this study and the reference on which those vegetation indices are based.

Table 1. Vegetation-Indices used in this study.

Index	Formulation	Reference
Normalized Difference Vegetation Index (NDVI)	$NDVI = \frac{R(NIR) - R\,(red)}{R(NIR) + R(red)}$	Rouse et al., (1973)
Weighted Difference Vegetation Index	$WDVI = R(NIR) - C * R(red)$, (in which $C = \frac{Rs(NIR)}{Rs\,(Red)}$)	Clevers (1989)
Transformed Chlorophyll Absorption in Reflectance Index (TCARI)	$TCARI = 3\,[\,(R700 - R670) - 0.2(R700 - R550) * \left(\frac{R700}{R670}\right)]$	Haboudane et al., (2002)
Optimized Soil-Adjusted Vegetation Index (OSAVI)	$OSAVI = (\frac{(1 + 0.16)(R800\ -\ R670)}{R800\ +\ R670\ +\ 0.16})$	Rondeaux et al., (1996)
TCARI/OSAVI	$\frac{TCARI}{OSAVI} = \frac{3\,[\,(R700 - R670) - 0.2(R700 - R550) * \left(\frac{R700}{R670}\right)]}{[\frac{(1 + 0.16)(R800 - R670)}{(R800 + R670 + 0.16)}]}$	Haboudane et al., (2002)
Red – Edge Position (REP)	$REP = 700 + 40\,\frac{\frac{(R670 + R780)}{2} - R700}{R740 - R700}$	Guyot and Baret (1988)
Red – Edge Chlorophyll Index ($CI_{red\ edge}$)	$CIred\ edge = \left(\frac{R780}{R710}\right) - 1$	Gitelson et al., (1996)

Chlorophyll Green Index (CI_{green})	$CIgreen = \left(\frac{R780}{R550}\right) - 1$	Gitelson et al., (1996)
Normalized Difference Red-Edge (NDRE)	$NDRE = \frac{(R790 - R720)}{(R790 + R720)}$	Barnes et al., (2000)

2.4 Nitrogen status assessment methods for potatoes

Accurate measurements of the nitrogen content in the potato crop and in the soil are important to be able to build an accurate estimation of the nitrogen balance for a potato field. The paper of Goffart et al. (2008) provides an overview of the most important and available methods to assess the crop nitrogen content and evaluate those methods for their accuracy, precision, sensitivity, sensibility and feasibility. Besides measurements of the nitrogen content in the crop, it is also important to have information about the in-season spatial variability of the nitrogen content in the soil under potato cultivation. The spatial variability of soil properties causes an uneven distribution of resources and controls the distribution and development of species living and growing in and on the soil. Quantification of the spatial variability is essential for understanding the relationships between soil properties and environmental factors and to estimate the attributes of the species living in that soil. The spatial variability of soil nutrients can provide guidance for a proper management of ecosystems and agriculture (Zhang et al., 2011). Therefore, it is important to have more information about the spatial and temporal variability of the nitrogen content in the soil. Kim et al., (2009) provided an overview of methods which can be used in precision agriculture to sense the soil macronutrient content. Those methods do not have the disadvantages that conventional soil testing methods have. Conventional soil sampling methods are in general costly and time-consuming. Those expenses limit the number of samples analysed per field, which makes it difficult to characterise the spatial or temporal variability in soil nutrient concentrations within the field (Kim et al., 2009). The within-field variability of soil and crop properties is important for optimizing productivity and reducing the environmental impacts of potato cultivation (Allaire et al., 2014).

The nitrogen status of potatoes can be determined in several ways. Crop N status assessment can be carried out at the tissue, leaf and canopy level. In section 2.1 it was already discussed how the nitrogen in the aboveground plant can be monitored by using precision agriculture applications, e.g. the Fritzmeier Isaria Biomass Sensor or the Yara N-Sensor ALS. In this section we discuss other ways to determine the N-content in the aboveground plant parts.

Analysis of the petiole NO_3-N concentration in previous studies have showed that the petiole NO_3-N concentration is a reliable index of the current N status of potatoes and is a sensitive indicator of N uptake activity throughout the growing season. (Errebhi et al., 1998). Several methods exist to determine this N content. Methods based on tissue analysis, such as Kjeldahl-digestion and Dumas-combustion (Muñoz-Huerta et al., 2013), have been widely used to determine the N content in the plant tissue due to their reliability in organic nitrogen determination, but they are time-consuming and destructive. Other drawbacks of those methods are that the Kjeldahl-digestion method only measures nitrogen bound to organic components and the incomplete combustion in the Dumas-combustion method causes loss of nitrogen (Muñoz-Huerta et al., 2013). To minimize the drawbacks from Kjeldahl-digestion and Dumas-combustion method, a different method to determine the petiole sap nitrate concentration is often used to assess the crop N status in the petiole plant tissue (Goffart et al., 2008). The use of the Horiba Cardy Nitrate meter as an instrument to measure this petiole sap nitrate concentration will be discussed in chapter 3.

N assessment at leaf or plant level involve the instruments that are normally used to measure leaf chlorophyll content. The chlorophyll content in a plant is indirectly related to the nitrogen (N) content (Clevers and Kooistra, 2012). The amount of chlorophyll in vegetation depends on soil nitrogen availability and on crop nitrogen uptake, which are important management factors in agriculture (Jongschaap and Booij, 2004). Therefore, measurements of the chlorophyll content in the crop can helps us to estimate the nitrogen content present in the plant. Instruments that can be used to determine the leaf chlorophyll content are Minolta SPAD-502 and the Dualex. The Dualex measures polyphenols (organic chemicals) in the leaves by means of chlorophyll fluorescence (Muñoz-Huerta et al., 2013). In this study, the Minolta SPAD and Dualex have been used to measure the crop chlorophyll concentration and can be used to assess the crop N status at leaf level.

At the canopy scale, N status assessment relies mainly on remote sensing methodology based on spectral canopy characteristics, which aims to estimate canopy structure parameters (Goffart et al, 2008). The most frequent tools for ground-based measurements and canopy level are the hand-held CropScan Multispectral Radiometer (Muñoz-Huerta et al., 2013). This CropScan Multispectral Radiometer measures canopy reflectances and based on those reflectances Vis can be determined, from which some of them are linked to the N-content in the plant. Other instruments used for determining the AGN are on tractor mounted sensors like the Fritzmeier Isaria Biomass Sensor, the Yara N-Sensor ALS and the GreenSeeker. Those instruments have been discussed in more detail in section 2.1.

Nowadays, satellites and in particular unmanned aerial vehicles (UAV) are used more often to determine the AGN. Wu et al., (2007) showed that high-resolution satellite imagery like QuickBird satellite imagery was able to detect N deficiency with QuickBird image-derived vegetation indices. However, those QuickBird images have also some disadvantages, due to spatial resolution of QuickBird imagery data (2.44 m for multispectral images) larger plots are necessary to extract canopy N variations, within the plots (Wu et al., 2007). Cohen et al., (2009) stated that the VENµS satellite (5.3 m resolution), which will be launched in 2016/2017, has a considerable potential for mapping spatial-temporal changes in the leaf N-content, since it can provide images of large areas every 2 days at low cost. Several studies showed the potentials of monitoring the N-content by using UAV's for agriculture crops. For example, Li et al., (2015) showed how the canopy nitrogen concentration of rice plants can be accurately determined and Agüera et al., (2012) showed the potentials of UAVs in measuring sunflower nitrogen status. However, in this thesis imagery obtained from UAV's will not be used to determine the N-content.

In this study we will combine petiole sap nitrate concentrations determined with the Horiba Cardy Nitrate meter, measurements at leaf level with the Minolta SPAD-502, canopy measurements with the CropScan Multispectral Radiometer and canopy/field measurements with Fritzmeier Isaria Biomass Sensor. A combination of those measurements should lead to an accurate estimation of the aboveground nitrogen concentration in the potato plant.

3. MATERIAL AND METHODS

This chapter gives an overview of the methodology used in this study. In subchapter 3.1 we discuss the N-mass balance used in this study in combination with an overview of the assumptions we made. In subchapter 3.2 an overview is given of the measurements done to determine some of the parameters of the N-mass balance. This subchapter is divided in several sections. In section 3.2.2 we discuss the experimental set-up of this study. Section 3.2.3 describes the materials used and in section 3.2.4 we discuss the methodology we followed to measure some of the parameters of the N mass balance. In subchapter 3.3 we discuss the sensors that could be used in order to sense some of the parameters of the N-mass balance. This subchapter is divided into a section about the sensors (3.3.1) and a section in which we discuss how the use of these sensors has been assessed (3.3.2).

3.1 N-mass Balance

In this subchapter we describe the N-mass balance used in this study. In section 3.1.1 we discuss the parameters used in the N-mass balance. Section 3.1.2 describes the main assumptions we had to make before we were able to estimate the N-mass balance. In section 3.1.3 we discuss based on the flowchart how we determined those parameters.

3.1.1 Parameters N-mass Balance

This section starts by recognizing the parameters which influence the nitrogen balance of an agricultural parcel of potatoes. This has been done based on previous studies. The studies of Giletto and Echeverria (2013), Prasad et al., (2015) and Haverkort and MacKerron (2000) provide a good starting point to continue developing a nitrogen mass balance of an agricultural parcel of potatoes. They recognized the components as mentioned in the problem definition (formula 1, 2, 3, 4 and 5). The unit of the components included in this nitrogen mass balance are in kg/ha.

Based on those N-mass balances we developed the following N-mass balance, in which we assume that the inputs are equal to the outputs:

$$Ninputs = Noutputs \tag{15}$$

In which

$$Ninputs = Ninitial + Nfertilizer + Ndeposition + Nmineralisation \tag{16}$$

$$Noutputs = Naerial + Ntuber + Nleaching + Nvolatilzation + Ndenitrification + Nfinal \tag{17}$$

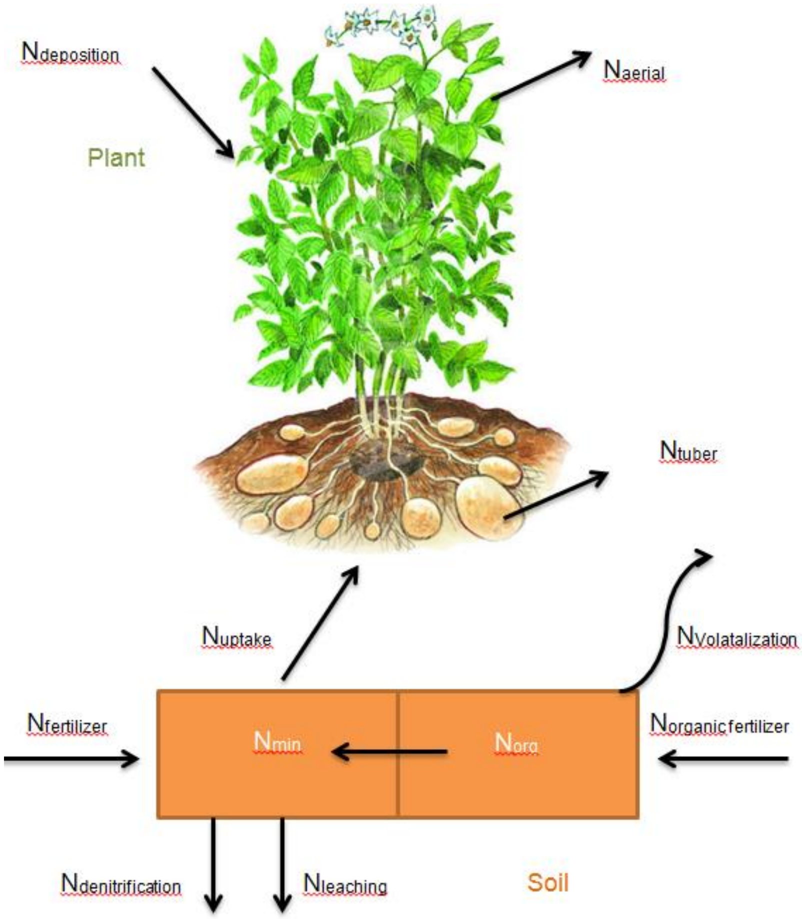

Figure 3. Schematic overview of the components of the N-mass balance.

In figure 3 a schematic overview of the components of the N-mass balance is presented for an agricultural parcel of potatoes. The inputs of the N mass balance, as given in formula 16 are: the initial amount of N in the soil which was already present at the moment when the potatoes were planted ($N_{initial}$), the amount of N added as fertilizer ($N_{fertilizer}$), the amount of N which is deposited from the air ($N_{deposition}$) and the change in the plant available amount of N in the soil (N_{min}), which becomes available due to mineralization of organic matter. The outputs as recognized in formula 17 are: the amount of N in the tuber (N_{tuber}), the amount of N in the aboveground plant plant (N_{aerial}), the gaseous N losses which occur by ammonia volatilization ($N_{volatilization}$), the amount of nitrogen which leaches to the groundwater ($N_{leaching}$) and denitrification of oxidized N compounds (N_{den}) in the soil. The last parameter, N_{final}, is the final amount of nitrogen left in the soil after harvesting the potatoes and consist of nitrogen present as soil organic matter and crop residues.

The N-mass balance as formula in figure 15, 16 and 17 is the N balance as defined based on literature studies and how we would estimate it in an ideal situation. However, we needed to make some assumptions, which will be described in more detail in section 3.3.3. Those assumptions in combination with the data of the measurements we have available, enabled us to simplify our N-mass balance as:

$$Ninputs = Noutputs \quad (18)$$

In which

$$Ninputs = Nfertilizer + Ndeposition + Nmineralisation \quad (19)$$

$$Noutputs = Naerial + Ntuber + Nleaching \quad (20)$$

In which $N_{leaching}$ consists in this case of the losses due to leaching to the groundwater and gaseous losses via volatilization and denitrification pathways as in the study by Prasad et al., (2015). In our study we used $N_{leaching}$ as the closing parameter of the N-mass balance as in formula. Table 2 gives an overview of the data used to quantify the parameters in the N-mass balance.

Table 2. Parameters of the N-mass balance and the corresponding data source, spatial characteristics and temporal characteristics.

Parameter	Data source	Spatial characteristics	Temporal characteristics
$N_{fertilzer}$	Measurements	Per plot is a specific amount of N- fertilizer applied based on Fritzmeier Isaria Sensor.	1x initial fertilization level (organic manure), 3x sensor based in season chemical fertilization, 4x Urea addition.
$N_{deposition}$	Literature; Netherlands National Institute for Public Health and the Environment (RIVM)	RIVM estimation of 86.4 g N/ha/day. (Field level)	Average daily value
$N_{mineralisation}$	Literature; Van Haecke (2010).	Field level	Average monthly value
N_{aerial}	Measurements + literature; Brown et al., (2011)	Estimation is based on AGN lab analysis by TTW in combination with CropScan spectral reflectances. (Plot level)	3x AGN lab analysis TTW (22-06, 16-07, 11-08) + 14x CropScan measurements.
N_{tuber}	Measurements	Estimation is based on tuber analysis by TTW. (Plot level)	3x tuber lab analysis TTW (16-07, 10-09, 07-10)
$N_{leaching}$	Closing parameter	Plot level	

3.1.2 Assumptions N-mass Balance

The overall goal of this thesis is to come up with an accurate estimation of the nitrogen mass balance for an agricultural parcel of potato crops by using sensing based methods. However, to be able to succeed in this objective we need to make some assumptions first, because we were not able to measure or sense all parameters as defined in the theoretical N-balance (formula 15, 16 and 17). In this section we present an overview of the main assumptions we made. We will start with the assumptions on the inputs and finish with the outputs. We simplified the theoretical mass balance into the one presented in formula 18, 19 and 20, based on these assumptions. Moreover, we present at the end of this section in table 3 an overview of the assumptions made.

Inputs

For the initial amount of nitrogen present in the soil, we have for the field next to our study area measurements of the total amount of N present in the soil available. However, from this amount of N only a very small part of N can be directly absorbed by the plant. So, we do not have measurements of the initial amount of mineral N in the topsoil. Due to this and since we focus in this N mass balance on pools instead of stocks, we assumed that the input $N_{linitial}$ is equal to the output N_{final}.

One of those other inputs for the nitrogen balance for which we needed to make some assumptions is the amount of nitrogen that comes from the air. This nitrogen deposition is estimated as 2250 mol/ha/year for the area around Reusel, which corresponds to a value of 31.52 kg/ha/year or 86.4 g/ha/day. Those values are high, compared to an average value of 1565 mol/ha/year (=21.92 kg/ha/year) for the Netherlands (Velders et al., 2010). Those relatively high values are caused by to agricultural sources (pig farming) in the neighbourhood of the experimental field.

Another nitrogen pool which is harder to estimate is the amount of nitrogen which comes from mineralisation of organic matter, which is already present in the soil. The study by Ros et al., (2011) showed that the content of mineralized N was more strongly correlated to variables reflecting the organic matter content than to any other variable. Van Haecke (2010) stated that the nitrogen mineralisation rate of organic matter is preliminary depending on the type of soil, carbon content in the soil, the percentage young organic matter content, the C-to-N ratio (an increase in the C-to-N ratio is associated with a decrease in the mineralization rate) and other soil conditions like temperature, moisture and the amount of oxygen. Since we do not have direct measurements of this N-pool available, we tried to provide a proper estimation based on literature studies. The amount of nitrogen which becomes available by mineralisation of organic matter can be calculated by multiplying the total amount of soil organic matter with the nitrogen fraction in the soil and the specific N mineralisation rate for this soil. However, we do not have measurements available of the nitrogen fraction and the N-mineralisation rate. Therefore, we decided to use values found in literature to estimate $N_{mineralisation}$.

The report by van Dijk and van Geel (2012) stated that the Nitrogen (N) pool can be estimated as 1 (±0,2) kg N per ha per day until 1 August for consumption potatoes. Starting from 25 April, the date when the potatoes were planted, this makes a total of 98 kg/ha. The potatoes cultivated at the farm of Van den Borne Aardappelen are considered as consumption potatoes used to make fries. However this estimation does not take the type of soil and the amount of organic matter into account.

In a study done by Hacin et al., (2001), the amount of N which is available by mineralisation of organic matter for the same type of soil, Humic Gleysol, is estimated as 150 kg/ha without any additional fertilization. Taking into account an additional N-fertilization in spring of 50 kg/ha in combination with Potassium (K) and Phosphorus (P), the estimated values of N are around 180 kg/ha. However, there are some major differences between the study area in the paper of Hacin et al., (2001) and our study-area. One of those differences is that the study area in the paper of Hacin et al., (2001) is characterised with relatively shallow groundwater tables (60cm), compared to our study area in which the groundwater tables are around 150 cm below ground. In the study by Hacin et al., (2001) it was stated that the influence of the groundwater table on N-mineralisation cannot be neglected. In that study it was clearly shown that in the soil type Humic Gleysol lower N-mineralisation happened at lower groundwater tables. Another major difference between both study sites is that the Humic Gleysol in our study area was covered by potato crops and the Humic Gleysol in the study of Hacin et al., (2001) under natural meadows in the Ljubljana marsh in Slovenia.

A third study performed by Van Haecke (2010) estimated the amount of nitrogen which becomes available from mineralisation of organic matter in the period between the beginning of May until the end of September by 140 kg/ha. For every month the exact amount differs. This estimation is performed for sandy soils with a carbon number of 1.8, which is an average number for sandy soils in “De Kempen” (Van Haecke, 2010). The study area in this thesis is part of the natural region called “De Kempen”. However, again some major differences are present between both studies. One of those differences is that this study is mainly based for Floriculture and it does not take into account differences in the organic matter content within the soil.

We decided to use a combination of the report published by van Dijk and van Geel (2012) and the study by Van Haecke (2010) in order to estimate the N_{min} in this study. This has been done by assuming the monthly values as discussed in the study by Van Haecke (2010) by taking into account that the Nitrogen (N) pool does not exceed 1 (±0,2) kg N per ha per day as stated by van Dijk and van Geel (2012). We decided to use those two sources because van Dijk and van Geel (2012) clearly mention the amount of N which comes available for consumption potatoes in the Netherlands and secondly because the study performed by Van Haecke (2010) estimates N_{min} for sandy soils in “De Kempen”, which has very similar conditions. We estimated the nitrogen mineralisation from organic matter for the period between planting the potatoes until the moment they are harvested.

Outputs

One of the outputs for which we needed to make some assumption is the amount of N in the tubers. We had exact measurements of the nitrogen content in the tuber available for 16 July, 10 September and at 7 October. In between those measurements we estimated the nitrogen content based on the dry matter content (kg/ha) and the % of nitrogen in the tuber of one week earlier and one week later. However from the planting date (25 April) until 16 July we did not have any measurements of the tubers available. We used the results of the study performed by Brown et al., (2011) to estimate the nitrogen in the tuber in this period. In this study a deterministic potato crop model was built with a particular focus on dry matter and nitrogen in tuber, leaf and stem. The model predicted that for Russet Burbank potatoes in New Zealand the nitrogen content starts developing 6 weeks after planting them. Furthermore it showed that the nitrogen content in the tubers increases linearly until a specific saturation level was reached. This linear increase was proven for multiple fertilization rates. For the period between 6 weeks after planting and 16 July, the N content is based on a linear increase of the nitrogen content. Therefore, we extrapolate the linear part of the graph to determine the N content in the tubers before 16 July.

Some of the other outputs for which we needed to make some assumptions are gaseous N losses which occur by ammonia volatilization (N_{vol}) and denitrification of oxidized N compounds (N_{den}). Postma et al., (2000) concluded that gaseous N losses by denitrification and volatilization are depending on several factors (temperature, soil moisture and pH, soil type, fertilizer type, improper irrigation and drainage) and is highly variable over space and time. Furthermore, Shepherd and Postma (2000) stated that gaseous N losses by ammonia volatilization are low because in general ammonia is absorbed by colloidal particles or rapidly transformed to nitrate, therefore there is only little N available for volatilization. However, the paper of Gasser et al., (2002) showed that especially when organic N fertilizers are applied (such as cow or pig slurry) with a slurry spreading technique losses due to ammonia volatilization in the first 24 h after spreading could be roughly estimated as 21 – 30% of the total N applied. A different study by Liu et al., (2007) showed the effect of ammonia volatilization from soils under potato production for agricultural soils in southern Florida. They measured volatilization losses ranging from 6.3 - 25.7% of the applied N. Those differences are caused by different kind of soil types, differences in pH values, temperature effects and soil water content effects. However, those typical agricultural soils found in southern Florida have high pH values ranging from 7.2 to 8.2, compared to the pH values at our study area ranging from 6.0 - 6.3. He et al. (1999) reported that ammonia volatilization is strongly dependent on the soil pH, with the greatest losses at pH > 7.5. Therefore, we were not able to use the results of the study by Liu et al., (2007) to estimate N_{vol} in our study. Furthermore for our study area the organic manure was injected and since we did not have particular measurement of N-losses by ammonia volatilization (N_{vol}), we considered these N-losses being small in magnitude.

Denitrification is the reduction of NO_3 or NO_2 via several intermediate products into the gases nitrous oxide (N_2O) and dinitrogen (N_2). This process occurs under anaerobic conditions (lack of oxygen) and is carried out by many different groups of bacteria. When denitrification takes place, in general when anaerobic conditions (heavy rainfall) occur in combination with application of N, it results in a loss of nitrogen in the soil. N losses by denitrification of agricultural parcels cultivated by potatoes are an order of magnitude less than the losses by nitrate leaching (Shepherd and Postma, 2000). However, under some circumstances, such as when heavy rainfall occurs directly after the application of fertilizer in spring, denitrification might be as important as leaching for N losses (Addiscott and Powlson, 1992).

To determine $N_{leaching}$, the amount of nitrogen which leaches from the topsoil (0-20cm) to the deeper soil layers and even to the groundwater, we performed several measurements, however we also needed to make some assumptions. We had weekly measurements of the Nitrate concentration in the groundwater available. This was possible since four wells have been placed in the field. The nitrogen content in unsaturated zone could be measured, due to the rhizons at three different depths (0.25cm, 0.50cm and 0.75cm) which were placed. The experimental set-up and the locations of the wells and the rhizons is visualized in figure 4 (chapter 3.3.1). So, the rhizons and the wells have been used to determine the nitrogen concentration in the unsaturated zone and the groundwater. In appendix 1 the assumptions for the measurements of the N content in the rhizons and the wells is presented. A difficulty of the design of the N-mass balance as given in formula 15, 16 and 17 in combination with this type of measurement of the N-content in the groundwater and the unsaturated zone, is that we have stocks and pools in one N-mass balance. The N-concentration in the topsoil, unsaturated zone and the groundwater are for example stocks; concentrations of N that were measured on a specific moment. However the N input by fertilization is a N pool. The goal of our N mass balance is to come up with a closing N-mass balance in which the sum of the inputs equals the sum of the outputs. Therefore, we need to convert those measured concentrations in the unsaturated zone and the groundwater into the amount of N that leaches away. However, we did not have background concentrations available of the nitrogen content in the unsaturated zone and in the groundwater. So we cannot correct those concentrations for the amount of N which is naturally present in the groundwater or in the unsaturated zone. Therefore we decided to simplify our N-mass balance for this term and considered $N_{leaching}$ as the rest term or the closing parameter. This approach is similar with the study of Prasad et al., (2015) in which an estimation is made of the nitrogen pools in irrigated potato production. In this study the unaccounted N losses comprised the leaching loss to the groundwater and gaseous loss via volatilization and denitrification pathways. In our study we followed the approach of Prasad et al., (2015) to determine the N losses. In which we use the measurements of the N-concentration in the unsaturated zone and in the groundwater to validate whether those N losses do not exceed the concentrations as we measured them.

Table 3. Overview of the parameters of the theoretical N-mass balance (formula 15, 16 and 17) and whether or not there are measurements available, which assumption is used and whether or not these parameters are included in the final N-mass balance.

Parameter	Measurements available	Assumption	Included in final N-mass balance
$N_{initial}$	No	$N_{initial} = N_{final}$	No
$N_{fertilizer}$	Yes	-	Yes
$N_{deposition}$	No	Based on RIVM estimation	Yes
$N_{mineralisation}$	No	Based on estimation by Van Haecke (2010) and Van Dijk & Van Geel (2012)	Yes
N_{aerial}	Measurements TTW + CropScan reflectances	-	Yes
N_{tuber}	Measurements TTW	Linear increase in between measurements based on + Brown et al., (2011)	Yes
$N_{volatilization}$	No	-	Yes, included in $N_{leaching}$
$N_{denitirification}$	No	-	Yes, included in $N_{leaching}$
N_{final}	No	$N_{final} = N_{initial}$	No
$N_{leaching}$	No (only concentrations in groundwater and the unsaturated zone)	Closing parameter in balance	Yes, combined with $N_{volatilization} + N_{denitrication}$

Table 3 presents an overview of the assumption used for the parameters of the initial nitrogen mass balance as presented with formula 15, 16 and 17. Furthermore it summarizes whether we have measurements available for a specific parameter and whether or not this parameter is included in the final N-mass balance used for the analysis in this study. This final N-mass balance is presented in with formula 18, 19 and 20.

3.1.3 Flowchart N-mass Balance

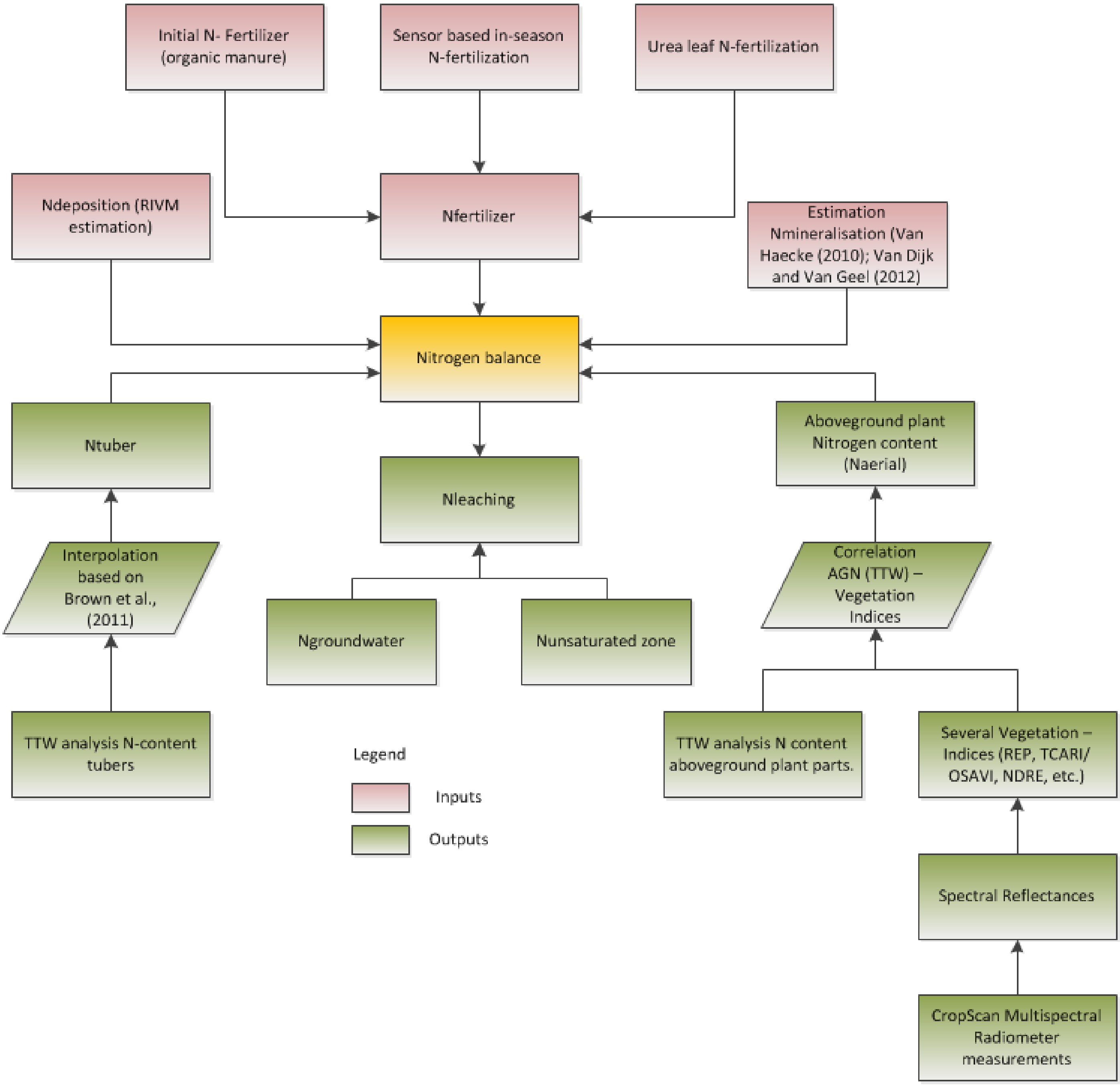

Figure 4. Flowchart of the steps used to calculate the N-mass balance

In this section we describe the flowchart as presented in figure 4. The red parameters in this figure are the inputs of the N mass balance and the green parameters are the outputs. We will start discussing the N-inputs and finalize with the outputs.

The amount of N fertilizer, which was added to the plot consists of three forms: 1) An initial amount of organic manure before the potatoes were planted, 2) sensor based in-season N-fertilization as chemical fertilizer pellets, 3) Urea leaf N-fertilization. This last component was spread on the leaves in the form of liquid urea. In section 3.2.2 we discuss how much N is added per plot. $N_{deposition}$ is estimated for the whole parcel based on estimates from

Netherlands National Institute for Public Health and the Environment (RIVM). $N_{mineralisation}$ is estimated based on the studies of Van Haecke (2010) and Van Dijk & Van Geel (2012) as has been discussed in section 3.1.2.

For the outputs we will start with the N-content in the tubers. For the N-content in the tubers we had for three particular dates lab analyses by TTW available (16-July, 10 September and 7 October). Based on those lab analysis and with the results of the study by Brown et al., (2011) we interpolated the development in the N-content in the tubers over the growing season. This process has been described more extensively in section 3.1.2. The N-content in the aboveground plant parts was determined by using the spectral reflectances obtained with the CropScan. Based on those CropScan multispectral reflectances we can calculate several vegetation indices. Those VIs have been related to the aboveground plant N-content analysis done by TTW. Similar as for the tubers we have for three dates measurements of the AGN determined by TTW (22 June, 16 July and 11 August). The relation between a specific vegetation index and the above ground plant nitrogen content which had the highest correlation is used to determine the AGN for the other dates. This results in N_{aerial} as presented in formula 20. The closing term of this N-mass balance consists of the unaccounted N losses comprised the leaching to the groundwater and gaseous loss via volatilization and denitrification pathways. We determined this term by stating that N_{inputs} are equal to N_{ouputs}, which lead to this leaching term. For which we used the measurements of the N-concentration in the unsaturated zone and in the groundwater to validate whether those N losses did not exceed the concentrations as we measured them.

3.2 Measurement based N-assessment

In this subchapter we describe how we assessed the N content for some of the parameters of the N mass balance. In section 3.2.1 we discuss the study area and escribe the experimental set up of the field we investigated in this study. In section 3.2.2 we discuss the different N-fertilizer treatments, which were applied. 3.2.3 we discuss which instrument we have used to determine the specific parameters of the N-balance. In section 3.2.4 we discuss the methodology we have used.

3.2.1 Study area

The nitrogen balance of potatoes has been investigated for an agricultural parcel (51° 19' 04.55" N and 5° 10' 11.29" E) in the South of the Netherlands, close to the village of Reusel (figure 5). This study was performed for a field of 12.7 ha belonging to the farm of Van den Borne Aardappelen. On this farm, a yearly area of 400-500 ha of potatoes is cultivated and even 1600 ha of land is within the rotation cycle. This rotation cycle means that only once in four years potatoes will be cultivated on a specific parcel. With only 30% of owned land this means that over 1100 ha of land is rented from other farms. As a result the knowledge on soil conditions in the year of potato cultivation and variation within parcels is in general limited and uncertain. Based on previous studies at this farm we can assume that the soils at this farm are in general sandy with a thick black A horizon on top of shallow non-developed B horizon followed by densely packed sandy C horizon. Based on the FAO World Refence base for Soil Resources this type of soil can be classified as a Humic Gleysol/Typic Haplaquod (Kooistra et al., 2015; Bakker, 2014).

This research took place at the farm of Van den Borne Aardappelen. Since 2010, Van den Borne Aardappelen has a cooperation with the Wageningen University and Research Centre, TTW and BLGG AgroXpertus. In which TTW is commercial company active in the agricultural sector focussing on advice and research for cultivation and processing. This cooperation led to a research project called “Making Sense” and is intended to collect as much data as possible and to combine those precision agriculture data into fertilizing formulas (Van den Borne, 2015). For this Making Sense project a lot of data about plant growth and soil fertility is collected by using different kind of precision agriculture techniques. In consultancy with the farmer a particular agricultural parcel was selected to perform this research.

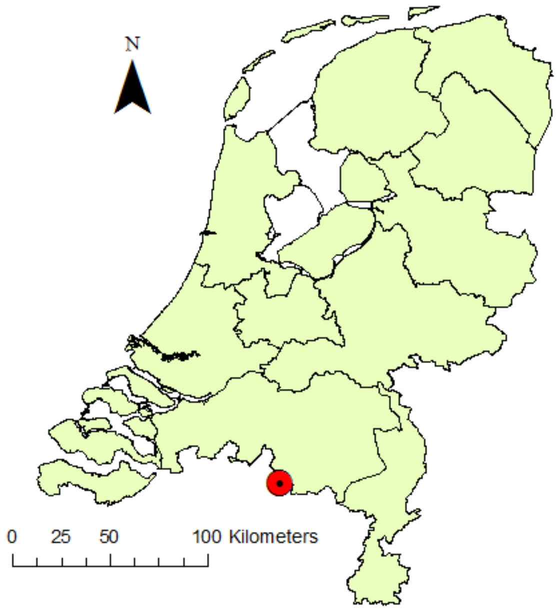

Figure 5. The location of study area is visualised by the red, which is near the village of Reusel at the border between Belgium and the Netherlands.

The experimental set-up of this field is based on previous studies performed at this farm. By keeping the experimental set-up similar we are able to make a comparison between the results of this year and the results of previous years. However the chosen location of the treatments (the strips as can be seen in figure 6) is based on the electro conductivity measurements with the Dualem-21s instrument in combination with the driving lanes of the tractors. Two strips have been identified. Each strip consists of 4 blocks, so in total we have 8 blocks (figure 6). Those four blocks were created by the four different initial fertilizer levels, which have been applied. The four distinct initial nitrogen fertilization rates (0, 90, 162 and 252 kg N/ha) were applied to the field in the beginning of the 2015 growing season (19 April). Those initial fertilizer levels are visualised by the yellow/brown colours in figure 6. In every block a 30 x 30m plot was created, consisting of 18 planting rows at each side of the driving path. The difference between the two strips was caused by the fact that one of the two strips (plots A, C, E, G) only received the initial amount of fertilizer and no further management practices during the growing season compared to the other strip (plots B, D, F, H) which received additional fertilization. Furthermore, there are also wells and rhizons installed in the field to measure the nitrogen concentration in the groundwater and the unsaturated zone. The location of those wells and rhizons are visualised by the dots in figure 6. This experimental set-up enabled us to monitor the effect of management of N fertilization on the

N mass balance during the growing season. A map of the farmer experimental set-up of this agricultural parcel is provided in figure 6.

3.2.2 N-fertilizer Application

The potato plants were monitored every week with the Fritzmeier ISARIA instrument, to determine the amount of fertilization which was required by the crops. Based on the N-requirements monitored by this instrument, the crops received a specific treatment. A variable rate technology was used to control the fertilizer level in the experimental fields. As the Fritzmeier sensor attached on the tractor detected nitrogen deficiencies, additional fertilizer was applied automatically to the plants. In figure 6 the strip, which received in season N fertilization is visualised in green.

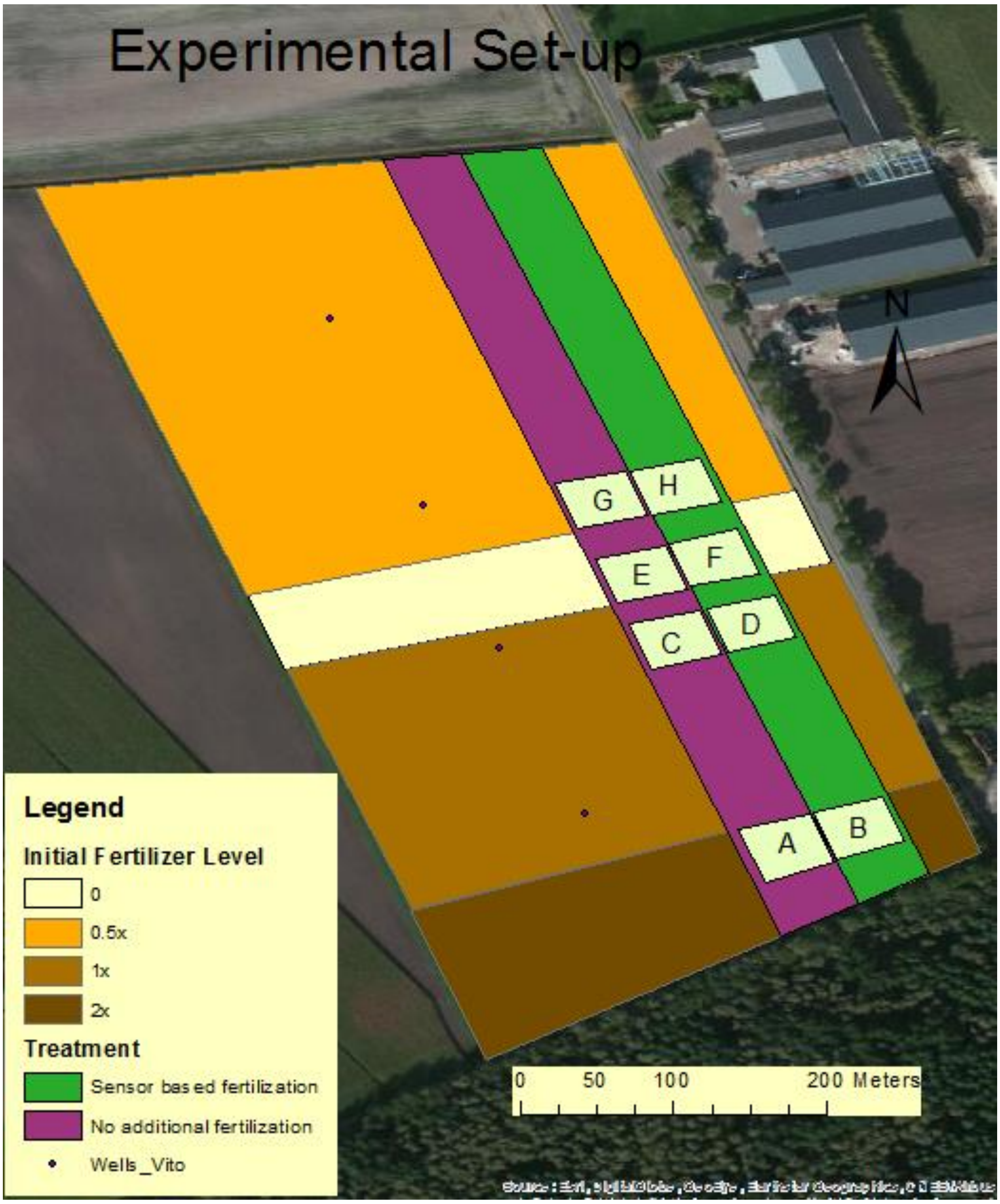

Figure 6. Schematic overview of the experimental set-up. The square blocks correspond to the 8 plots which receive a different N-input. The dots are the locations of the groundwater wells.

Table 4 provides an overview of the initial, additional and the total N fertilization in kg per hectare (ha) applied to the experimental plots over the growing season. At three different moments (17 June, 4 July and 3 August) additional chemical fertilizer has been applied. The amount of applied additional N fertilizer is based on the N-crop requirements determined with the Fritzmeier Isaria Sensor. Furthermore, we calculated the total amount of N added in kg/ha and in kg per plot (table 4).

Table 4. The initial, additional and total N fertilization in kg per hectare (ha)

Plot	Organic Manure ($N_{initial}$) kg/ha	Chemical Fertilizer ($N_{add,1}$) kg/ha (17-06)	Chemical Fertilizer ($N_{add,2}$) kg/ha (04-07)	Chemical Fertilizer ($N_{add,3}$) kg/ha (03-08)	Total N kg/ha	Total N in plot (kg/plot)
A	252	0	0	0	252	22.7
B	252	6.4	40.5	27.1	326	29.3
C	162	0	0	0	162	14.6
D	162	18.2	29.8	31.0	241	21.7
E	0	0	0	0	0	0
F	0	41.9	48.9	39.3	130.1	11.7
G	90	0	0	0	90	8.1
H	90	64.7	21.7	47.8	225.2	20.3

Besides the application of chemical fertilizer as pellets visualised in table 4, also additional chemical fertilizer is spread on the leaves in the form of liquid urea. This liquid urea is easily absorbed by the plant leaves and is used as boost for the crop in a dry period. Furthermore, it is also added, because it protects the leaves from burning during hot periods. A study done by Russchen and Mager (2005) showed that the urea fertilization on the leaves led to a higher NO_3^- concentration in the leaflets of consumption potatoes and a slower reduction of this NO_3^-concentration than when the same amount of chemical fertilizer pellets were applied. In table 5 are the dates and the amounts of Urea in kg/ha and N in kg/ha, which were added to the specific plots visualised. Those amounts were the same for all plots. So in total 36.8 kg N ha^{-1} was added per plot. In the last strip the total amount of N which was added in the different fertilizer forms is presented for every plot.

Table 5. The dates and the amount of Urea added in kg per hectare (ha). The last column presents the total amount of N added to the specific plots.

Plot	Urea added 20 kg/ha – 9.2 N kg/ha (16-07)	Urea added 20 kg/ha – 9.2 N kg/ha (27-07)	Urea added 20 kg/ha – 9.2 N kg/ha (06-08)	Urea added 20 kg/ha – 9.2 N kg/ha (15-08)	Total Urea added in N kg/ha	Total N-fertilizer (kg/ha)
A	9.2	9.2	9.2	9.2	36.8	288,8
B	9.2	9.2	9.2	9.2	36.8	362,8
C	9.2	9.2	9.2	9.2	36.8	198,8
D	9.2	9.2	9.2	9.2	36.8	277,8
E	9.2	9.2	9.2	9.2	36.8	36,8
F	9.2	9.2	9.2	9.2	36.8	166,9
G	9.2	9.2	9.2	9.2	36.8	126,8
H	9.2	9.2	9.2	9.2	36.8	261

3.2.3 Materials

In this section we provide an overview and description of the instruments that were used. Besides that, we discuss the data obtained with those instruments. We start discussing the equipment used for determining the crop characteristics. Next we will continue with the instruments used for the soil characteristics.

Measurements of the 8 experimental subplots were obtained on a weekly basis between May 29, 2015 and September 10, 2015. A total of 14 measurement days have been included. For the CropScan, LAI2000 and Minolta SPAD and petiole plant sap measurements the same sampling approach has been applied. This approach consisted of 24 measurements per plot. Those 24 measurements were equally split over 4 rows (row 4 and 10 on the left-hand side and row 4 and 10 on the right-hand side of the driving lane). Four times six makes the total of 24 measurements per plot. Figure 7 shows a schematic drawing of the 30 by 30 meters plots is provided. The red lines represent line 4 and line 10 on both sides of the driving lane (orange arrow) and the green circles are the locations were the CropScan, LAI-2000, SPAD and Petiole plant sap measurements took place.

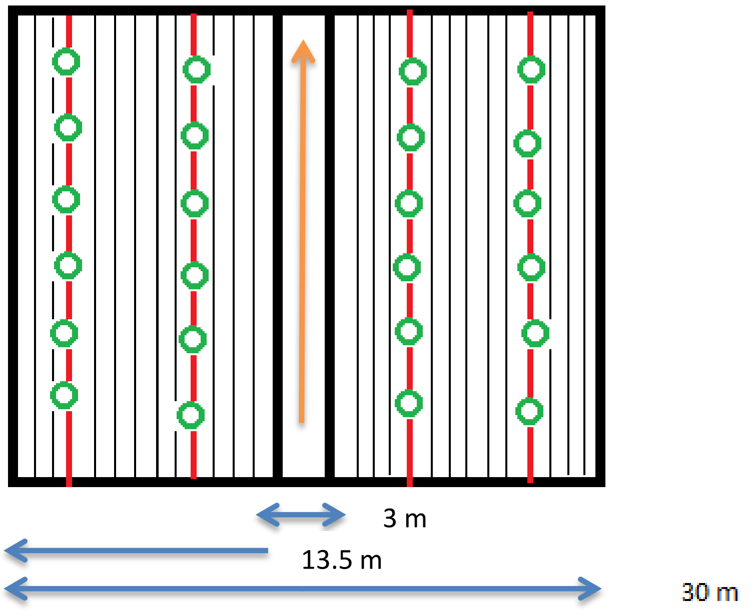

Figure 7. Schematic drawing of the 30 by 30 meter plots.

Minolta SPAD-502 chlorophyll meter

The Minolta SPAD-502 chlorophyll meter has been used to measure the leaf chlorophyll concentration (LCC) of the potato crops. Measurements with this handheld device take place at leaf level and can be considered as point measurements. SPAD readings have been taken at the terminal leaflet of the second leaf from the apex of the shoot, following the approach of Vos and Bom, 1993 and Minotti et al., 1994). The measurements were made at a central point on the leaflet between the midrib and the leaf margin as suggested by Wu et al., (2007). The meter was shielded from direct sunlight by the operator during each measurement. Twenty-four plants were sampled in one plot, for which we took three leaves per plant and averaged them. This is done to cover the variability within the plant. Afterwards the readings were averaged per row and for the whole plot, so in the end we have a single

SPAD value for each row and each treatment plot.

The Minolta SPAD-502 chlorophyll meter measures the transmittance of two wavelengths of the electromagnetic spectrum through leaflets of the potato plant. The transmittance will be measured in the red (650nm) and the near-infra red (940nm) part of the electromagnetic spectrum. Chlorophyll strongly absorbs radiation in the red at 650 nm, and hardly at other wavelengths (940 nm). By comparing the transmittance at these two wavelengths, a characteristic is calculated, which is related to the chlorophyll content (Jongschaap and Booij, 2004; Vos and Bom, 1993). The leaf chlorophyll concentration will be displayed as a digital number in a range from 0 to 50 (Goffart et al., 2008).

However, we are not able to directly translate these SPAD measurement values into the LCC. The SPAD measurement values are the relative amount of chlorophyll present in the leaves. Several relations exist to translate SPAD readings into leaf chlorophyll concentration values. An example of such a relation is the exponential regression proposed by Uddling et al. (2007). The leaf chlorophyll concentration can be calculated using the following formula:

$$y = 0.913e^{0.0415x} \quad (21)$$

Where y = chlorophyll concentration in g/m^2 and x = SPAD-502 value. This relationship had a coefficients of determination of 0.46 for potatoes. The chlorophyll concentration is expressed in the unit g/m^2.

Li-Cor LAI 2000 Instrument

The Li-Cor LAI-2000 instrument determines the amount of leafs or foliage and the orientation of this foliage by measuring the attenuation of diffuse sky radiation at five zenith angles simultaneously. Therefore, first measurements of the incoming radiation above the canopy need to be done, followed by some below canopy measurements.
The LAI-2000 is an instrument designed to measure the leaf area index (LAI) of green canopies. It encompasses five sensors, each simultaneously measuring light intensities in the range between 320 and 490 nm (blue range) in five concentric Field of Views (FOVs). Those FOVs are centred at zenith angles of 7, 23, 38, 53 and 68 degrees, and generally referred to as Plant Canopy Analyser Sensor (PCA Sensor) 1, 2, 3, 4 and 5. Usually, below- and above-canopy readings are simultaneously acquired and divided to calculate the canopy gap fraction, which represents the probability of light penetration (Nackaerts et al., 2000). The LAI is estimated by an inversion model comparing the transmittances, calculated simultaneously for each sky sector, measured above and below the canopy (Cuttini et al., 1998).

Measurements with the LAI 2000 instrument were acquired on the same day as the Minolta SPAD and CropScan Multispectral Radiometer measurements. At the beginning and at the end of each measurement row the incoming radiance was measurement by holding the instrument above the canopy and within each row six measurements were taken below the canopy. Each reading per plot was the average value from 24 LAI readings and each reading per row the average of 6 LAI readings in that row. Those average values were based on the LAI-2000 processing software.

A study done by Hu et al., (2014) showed that the LAI for potato crops was very sensitive to the N supply. Moreover, it is stated in the paper by Hu et al., (2014) that there is a linear relationship between the LAI and the Nitrogen Nutrition Index (NNI). The NNI is defined as the ratio between the actual plant N concentration (%N) and the critical plant N concentration (%Nc) corresponding to the same biomass of the crop (Hu et al., 2014; Lemaire et al., 2008). This critical plant N concentration can be derived from the relationship between the crop N uptake and the dry matter production (Hu et al., 2014; Lemaire et al., 1989). In this thesis the LAI is mainly used for calculating the Canopy Chlorophyll Concentration and as an indicator for the development stage of the potato plant. It is not directly used to determine the N-content in the plant.

CropScanTM Multispectral Radiometer

The CropScan Multispectral Radiometer is a 16-band multispectral radiometer, which measures simultaneously the reflected and incoming radiation in 16 spectral bands (Kooistra et al., 2013). Specifications of the CropScan MSR16R System are given in table 6. Reflectance is measured through a 28 field-of-view (FOV) aperture and incoming radiation is measured through a cosine-corrected sphere. The CropScanTM scanner will be hold horizontally at about 0.6m above the canopy. Calibration of the CropScan is performed by pointing the 28 FOV aperture towards the sun using an opal glass (Clevers and Kooistra, 2012). Using this calibration, the radiance and irradiance for each wavelength band can be stored. Thereafter, the spectral reflectances can be derived and several vegetation indices will be calculated. The CropScan dataset of the 8 subplots in combination with the 14 observation moments over the growing season, has been used to calculate eight VIs. Those vegetation indices can be used to determine the leaf nitrogen content for a potato crop.

Table 6. Specifications of the CropScan MSR16R System (Clevers and Kooistra, 2012).

Spectral band position (nm)	Band width (nm)
490	7.3
530	8.5
550	9.2
570	9.7
670	11
700	12
710	12
740	13
750	13
780	11
870	12
940	13
950	13
1000	15
1050	15
1650	200

Horiba B341 Cardy NO_3^- meter

The paper of Goffart et al. (2011) presented two methods to measure the petiole sap concentrations of potatoes. Those methods to determine the petiole sap nitrate concentration

(PSNC) are an ion-specific potentiometer method in which nitrate-specific electrodes will be used. The other method consist of nitrate test strips combined with a reflectometer. In this study we make use of the Horiba B341 Cardy NO_3^- meter (Horiba Ltd., Kyoto, Japan), which measures nitrate ions using a selective membrane.

Every week we determined the Petiole Sap Nitrate (NO_3-N) concentrations with the Cardy Nitrate meter. The petiole NO_3-N concentration was measured by sampling 24 of the youngest and fully expanded leaves from different plants within a plot. Those 24 leaves are the same leaves as have been examined with the Minolta SPAD-502 chlorophyll meter. From these 24 leaves, 3 times 8 leaves were selected, after which we squeezed the plants sap out of the leaflets. This plants sap is collected in the Horiba B341 Cardy NO_3^- meter, which measures the nitrate concentration in ppm or mg/L. Per plot we have three NO_3^- measurements per measurement day.

As is stated by in the study done by Aguilera et al., (2014), nitrate measured in the sap of leaf petioles by the Cardy meter had a significant correlation with leaf petiole total N. Therefore it is a good estimator for the total N in the leafs. Furthermore, Mackerron et al., (1995) showed that the petiole sap nitrate-N concentration (NO_3-N) changes with the time and the development stage of the crop. The results of their study showed that a decreasing trend in the nitrate-N concentration over the development of the crop. However, an increase of the nitrate-N concentration has been observed after either supplemental application of a nitrogen fertilizer or due to rainfall after a long dry period.

Nitrachek reflectometer

The Nitrachek reflectometer is a field instrument which, digitally measures the nitrate content in water or in a watery extract of soil or crop. It enables the user to measure the nitrate content by a point sampling approach. To be able to determine the nitrate content in the soil, the soil will be mixed with demineralized water and filtered. The method is based on read-out of nitrate test strips. After a test strip is held in the solution it is placed in the optical read-out apparatus. The measuring range is 5 - 500 ppm or mg/l nitrate. The reading accuracy is 1 mg/l (Eijkelkamp, 2015).

Every field measurement day (14 in total) we took one or two soil samples within every plot. Those samples consisted of 50 ml mixed soil particles from the topsoil, the layer from 0-20cm. After taken the samples 100 ml demineralised water was added and the samples were shuffled. Next we left the samples untouched for one hour so the soil particles could settle. After an hour the aqueous samples were analysed with the Nitracheck reflectometer to determine the nitrate concentrations from the topsoil (0-20cm). Nitrachek reflectometer readings are in ppm or mg/L. By the end of the growing season we had a good overview of the development of the Nitrate content in the topsoil. To determine the nitrogen content we needed to divide the Nitrate concentration by a factor 4.42.

Haverkort and MacKerron (2000) stated that mineral N (mineral N is the term used to describe NO_3^- and NH_4^+) is in general present in NO_3^- form. However, mineral N is just a small proportion of the soil's total N. Consequently most nitrogen is taken up by crops as NO_3^- (Haverkort and MacKerron (2000). Therefore it is important to know the exact amount of nitrate available in the soil. With these nitrate measurements we want to determine what the change is in the nitrogen/nitrate content in the topsoil over the growing season and what the effect is of fertilization.

Spectroquant Nova 60 – Nitrate cell test
The Spectroquant Nova 60 – Nitrate cell test is a photometer which has been used to measure the nitrate concentration in the groundwater and the unsaturated zone. This photometer determines the transmittance of a light beam through a prepared sample. Based on the transmittance/absorbance of the light beam the nitrate concentration is measured in mg/L.

The samples in the unsaturated zone were extracted by the rhizons. The spectroquant Nova 60 measures the nitrate concentration in mg/L. We have for the four wells groundwater data available for 20 dates from 22 May until 21 November. For the 12 rhizons we have 15 measurement dates available from 29 May until 04 October, this is due to the removal of the rhizons when the potatoes were harvested. However for the rhizons we have not for every measurement date samples available, because in a dry period the rhizons were not able to extract water from the unsaturated zone. Therefore, we have in general rhizon measurements available after a period of somewhat more rain or when the farmer irrigated the field.

3.2.4 Methods

In this section we describe the methods we used to determine the individual parameters of the N-mass balance in the soil and in the plant. For the soil, we are particularly interested in the N content in the topsoil and how we can determine the spatial variability of the N-content in the topsoil. For the plant we are mainly interested in the aboveground plant nitrogen content, but also in other parameters, which give us information about the crop status of the potato plant over the growing season. Table 7 provides an overview of the instruments used combined with the parameters of interest we obtained with those instruments and the frequency of measurements we have available over the growing season. At the end of this section we present in a flowchart (figure 9) which steps were needed to convert the input parameters to the final results.

In order to determine the spatial variability of the N-content in the soil, a relationship is established between soil properties, the thickness or SOM content of the A-horizon, and the nitrogen content in the top soil. The A-horizon is the top soil horizon, usually dark coloured and contains in general more humus than other soil horizons. The spatial variability in the thickness of the A-horizon is established after taking samples in the field. The field measurements took place before the farmer starts cultivating and fertilizing his parcel. To have a good coverage of the spatial variability inside the parcel we walked a number of transects over the plot and measured the thickness of the A-horizon every 25 meter. The locations where we took the samples can be seen in figure 8a. The spatial variability of the thickness in the A-horizon is analysed and in combination with the kriging interpolation technique we were able to give an accurate estimation of the thickness of the A-horizon for every single location in the field. Besides measurements of the thickness of the A-horizon we also analysed the percentage of organic matter in the topsoil for 25 locations (figure 8b). We mapped the spatial distribution of the organic matter content and estimated for every location in the field the organic matter concentration by using kriging as the interpolation technique. Furthermore, we mapped the spatial variability of the total organic matter content in the soil. This map is created by multiplying the percentage of organic matter with the bulk density for this soil (=1.13 g/cm3; Bakker, 2014) and the A-horizon depth.

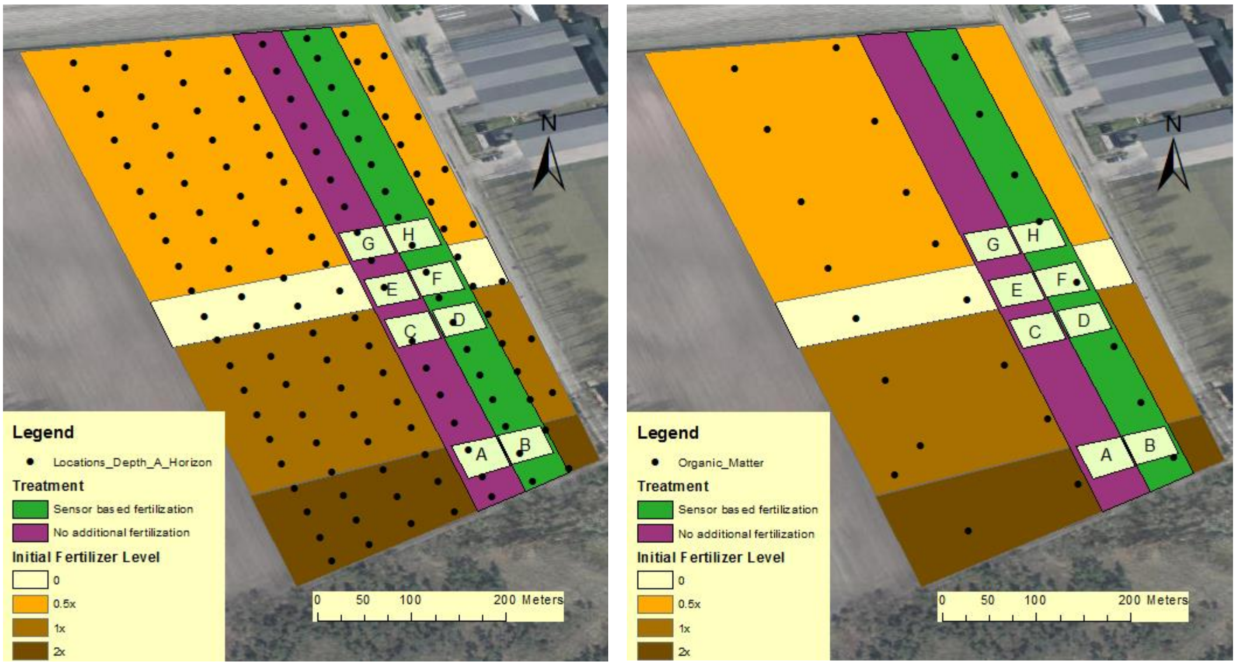

Figure 8a (left). Schematic overview of the location of the where the depth of the A-horizon has been determined. Figure 8b (right). Locations which have been used to determine the organic matter content.

Furthermore, measurements of the electrical conductivity of the soil, at the start of the growing season, are available. This data has been acquired by students of the University of Ghent, for which a Dualem-21s instrument has been used. We have continuous electrical conductivity data available for four different layers in depth (0-0.5m, 0-1.0m, 0-1.5m and 0-3.0m), for the whole agricultural parcel. A study done by Eigenberg et al. (2006) showed that the electrical conductivity in the soil is a good measure for effective identifying the dynamic changes in the plant-available amount of N in the soil. Therefore, a map of continuous electrical conductivity measurements enabled us to determine the spatial variability of nitrogen available in the soil. Koumanov et al., (2001) studied the relationship between the electrical conductivity and the nitrate nitrogen (NO_3^-N) concentrations for three types of non-saline soils in Bulgaria. They derived the following second degree regression equation based on a total of around 500 soil samples for three soil types (Fluvisol, Luvisol and Vertisol):

$$y = 84.801x^2 - 10.059x \tag{22}$$

Where x is the soil electrical conductivity in dS/m, and y is the concentration of NO_3-N in mg/kg. They found a R^2 of 0.78 for this relationship. Based on those results Koumanov et al., (2001) stated that the concentration of NO_3-N in non-saline soils can be estimated directly from soil electrical conductivity values, irrespective of the soil-type. In this study the relationship by Koumanov et al., (2001) has been used to estimate and map the N-content based on the EC measurements of the field. This map of the N-content will be visually compared with the spatial distribution of the total organic matter in the soil. Since this organic matter content in the soil can be assumed to be directly related to N content.

Besides these maps showing the distribution of the N content in the topsoil we have also measurements available of the nitrate concentration in the topsoil of the plots determined with the Nitracheck. Those nitrate measurements are converted into nitrogen concentrations and have been used to determine the effect of the different N fertilizer treatments on the topsoil within the plots. In the flowchart shown in figure 9 this process is shown by the red colours. Furthermore we have measurements available of the N-content in the unsaturated zone and in the groundwater. This is possible due to the rhizons and the wells which have been installed (see figure 6 for the exact locations of the wells and the rhizons). The assumptions used to determine the N concentrations in the unsaturated zone are presented in appendix 1. These concentrations have been used to determine the effect of the different N treatments on leaching. Furthermore, these measurements are used to validate the magnitude of the leaching parameter in the N mass balance.

In order to determine the effect of the different N-treatment on the plant status we investigated several crop characteristics. One of those parameters is the aboveground biomass (AGB; kg/ha), which was determined by a destructive sampling approach in which a number of plants in row 3 at the left-hand side (when facing to the North) of the plot were harvested. This destructive sampling was done for one linear meter at each time (0.75 m^2). The fresh weight (kg) of the aboveground material was measured with a scale and by taking into account the surface area of the sample the AGB, was calculated (kg/ha). Afterwards the plant material was dried for 24 hours at 70°C in a laboratory, this resulted into the dry weight and the dry matter content. By using the Dumas combustion method the N concentration was determined (Hansen, 1989). By multiplying the dry matter content with the N concentration we calculated the aboveground nitrogen concentration (AGN; kg/ha) (Kooistra et al., 2015). In this way fresh and dry aboveground weights, dry matter contents, total N concentration in the aboveground plant parts (AGN) and the total N content was determined. The AGB and the parameters to calculate the AGN were measured by TTW. The sampling rate for AGB was every two weeks over the growing season, while we have for three dates during the production phase of the potato growth AGN (22 June, 16 July and 11 August) data available. Besides the N-content in the aboveground plant parts also measurements of the N-content in the tuber are available. We have N_{tuber} measurements for three dates; 16 July, 10 September and 07 October (when the potatoes were harvested). To have data of the N_{tuber} for the whole growing season we used the results of the study of Brown et al., (2011) as described in section 3.1.2. This N_{tuber} is used as one of the outputs for the N-mass balance, but also to assess the effect of the different treatments on the plant status. The yield at the end of the growing season is also used to assess the effect of the different N-treatments.

Another parameter used for assessing the effect of the different N-treatments on the potato plant is the leaf chlorophyll concentration (LCC) determined with the Minolta SPAD-502 and by using the regression relation of Uddling et al., (2007). Furthermore, the LAI-2000 measurement were used to determine the leaf area index (LAI). The LAI is used to assess the coverage of the plant canopy. By multiplying the LAI with the leaf chlorophyll concentration (LCC) we calculate the canopy chlorophyll concentration (CCC). Furthermore spectral reflectances based on measurements with the CropScan Multispectral Radiometer have been used. These reflectances are used to calculate some vegetation indices. Some of those vegetation indices are closely related to the nitrogen content in the plant (CIre, NDRE), other vegetation indices are more related to the plant status (WDVI). In this study we tested for all vegetation indices mentioned in table 1 the correlation with the AGN measurements obtained by TTW's lab analysis. For this purpose, we used the data of this year combined with the results of 2012 and 2013, in which a similar experiment was performed. In the next step we selected those vegetation indices which are closely related to the aboveground plant nitrogen concentration (AGN) and used these relationships to estimate the AGN based on the reflectance measurements of the CropScan. Besides the AGN, this assessment gave us also information about the quality of the specific vegetation indices in assessing the AGN. These obtained aboveground nitrogen content have been used as one of the output parameters of the nitrogen balance. Besides the aboveground nitrogen content in the plant we are also interested in the nitrogen content in the petiole plant sap. Analysis of the petiole NO_3-N concentration in previous studies have showed that the petiole NO_3-N concentration is a reliable index of the current N status of potatoes. (Errebhi et al., 1998). In the paper of Cohen et al., (2007) it was found that for potato leaves TCARI values at the canopy were inversely correlated to NO_3-N levels in the petiole plant sap. So, TCARI values increase with decreasing NO_3-N levels. In this study this relationship is tested to determine whether the CropScan Multispectral Radiometer can be used for monitoring the NO_3-N concentration in the petiole plant sap. Similar like for the relationship between the AGN and the VI's mentioned in table 1, we assessed the correlation between the different VI's and the NO_3-N concentration in the petiole plant sap for this year.

Besides the effect of the different treatments on the plant status and the nitrogen content in the topsoil, unsaturated zone and the groundwater, we are also interested in the nitrogen efficiency of the different treatments. The efficiency of nitrogen fertilization is most commonly assessed by the magnitude of either quantitative or qualitative parameters of the yield (Kolodziejcyk, 2014). The N uptake efficiency (NUpE) is such a parameter often used to define the efficiency of nitrogen fertilization. This parameter is defined as the plant N accumulation per unit of N supply to the crop (Zebarth et al., 2008). Furthermore we are also interested in the N-use efficiency (NUE). The N use efficiency (kg/ha kg/ha^{-1}) is calculated as the ratio of tuber yield weight to the N supply. In which the N supply is the sum of mineral nitrogen added to the soil, mineralized N, and N fertilizer (Kolodziejcyk, 2014).

Table 7. Overview of the instruments used in this study, the parameter of interest obtained with those instruments and the frequency of measurements we have available.

Instrument	Parameter of Interest	Frequency
Minolta Spad-502	Leaf Chlorophyll Concentration (LCC) & Canopy Chlorophyll Concentraion (CCC)	Weekly
LiCor LAI-2000	Leaf Area Index (LAI) & Canopy Chlorophyll Concentration (CCC)	Weekly
CropScan Multispectral Radiometer	Spectral reflectances used to determine aboveground plant N content and NO_3-N levels in the petiole plant sap	Weekly
Horiba B341 Cardy NO_3^- meter	NO_3-N concentrations in the petiole plant sap	Weekly
Nitracheck reflectometer	N content in the topsoil (0-20cm)	Weekly
Spectroquant Nova 60 – Nitrate cell test	N concentration in the unsaturated zone and in the groundwater	Weekly
TTW lab analysis	Aboveground plant nitrogen content (AGN) and N-content in the tubers	3x over the growing season
Fritzmeier Isaria Sensor	Fertilizer inputs & aboveground plant nitrogen content (AGN) at field scale (section 3.4.2)	Weekly

Figure 9. Flowchart of the actual measurements we have and how they result in the current plant status, a map of the spatial variability in the NO_3-N concentration, the Nitrogen Concentration in the topsoil or in the Nitrogen concentration in the topsoil.

3.3 Sensor based N-assessment

In this subchapter we discuss the materials and methods used for a sensor based assessment of some of the parameters in the N mass balance. In section 3.3.1 we discuss some of the sensors which have been used in this study. In section 3.3.2 we discuss the methodology used for the assessment of these sensors in determining N in the aboveground plant parts and in the groundwater.

3.3.1 Sensors

In this section we provide an overview of the sensors used to determine the N-content in the above ground plant parts (Fritzmeier Isaria Sensor) and in the groundwater (S::can Spectrometer Probe).

Fritzmeier ISARIA Sensor
The Fritzeier ISARIA sensor is able to determine the N requirements of a crop based on the reflected light by the crop (Van Den Borne Loonwerk GPS, 2015). This sensor enables the user to have continuous profile of the nitrogen content of the crops within a field. The Fritzmeier ISARIA sensor determines a vegetation index which is calculated from the reflectance values at five specific bands of the electromagnetic spectrum. Due to the availability of measurements at five specific bands, measurements of the Fritzmeier ISARIA sensor are suitable to calculate multiple vegetation indices. An example of such a vegetation index, which can be derived from Fritzmeier ISARIA measurements, is the Red-Edge Position (REP) (Kooistra, 2011). For each plant type, a specific amount of nitrogen can be assigned to a vegetation index value depending on the growth stage. Based on this vegetation index value the Fritzmeier ISARIA sensor is able to determine the precise nitrogen level and the yield potential within the field (Fritzmeier Umwelttechnik, 2015).

The Fritzmeier ISARIA Sensor provides us different kind of datasets, including two vegetation indices. The first VI that can be derived from this sensor is the IRMI, which reflects the current nitrogen supply of the crop. This VI is used to determine the amount of nitrogen, which needs to be applied. Therefore the sensor measures the quantity of nitrogen, which has already been absorbed by the crop up to that point-in-time, compares this number with the target value of the current European Community stage and then calculates the missing nutrient, which has to be balanced out (CAN Newsletter, 2014). The IRMI vegetation index can be simply used to calculate the Red Edge Position REP by adding 700 to the IRMI value.
The second VI that can be derived from the Frizmeier ISARIA instrument is the IBI (International Biochar Index) biomass index. This index gives us information about the crop density. If the IBI falls below a particular threshold value, for example due to drought or frost damage in the field, the spread rate of the fertilizer will be adjusted (CAN Newsletter, 2014).

S::can Spectrometer Probe
The S::can spectrometer probe (Messtechnik GmbH, Vienna, Austria) is used to measure the nitrate concentration in the groundwater. This spectrometer measures the absorption of a light beam, which is emitted by a lamp. The substances present in the medium weaken this light beam which moves through this medium. After contact with the medium its intensity is measured by a detector over a range of wave-lengths. Each molecule of a dissolved

substance absorbs radiation at a certain and known wave-length. The concentration of the dissolved substances determine the size of the absorption of the sample – the higher the concentration of a certain substance, the more it will weaken the light beam (Manual S::can spectrometer probe, 2007). Based on this principle we were able to measure several parameters (turbidity, nitrate concentration, oxygen concentration, temperature etc.) in the groundwater.

The S::can spectrometer probe measures the nitrate concentration in the groundwater. To actually save this data we need to install a data logger connected with the S::can Spectrometer Probe. In this study the nitrate sensor. measures the nitrate concentration in the groundwater once every hour. Even though this combination was already installed at the beginning of the growing season it took us a while before we finally could make it operating and got useful data from the data logger. One of the reason was that the S::can Spectrometer Probe, which is normally used to measure concentrations of substances in rivers, was never used before to measure substances in groundwater. Furthermore, the groundwater in our study area is turbid and therefore we needed to order a special casing. This casing was used to shorten the path of the light beam was shorter, so we were still able to sense the nitrate concentration. Another disadvantage due to turbid groundwater was that the emitter and the receiver of the light beam needed to be cleaned with acid regularly, because after a couple of days the emitter and receiver were to dirty to measure. Therefore we have only for three weeks nitrate concentrations measured by the S::can Spectrometer Probe available (24/07 – 30/07, 19/08 – 25/08, 23/09 - 27/09).

3.3.2 Methods

Besides measurements of the N content within the plots we were also interested in measurements of the N content of the crops within the whole field. Therefore, we use the Fritzmeier ISARIA sensor. In this section we discuss how the Fritzmeier Isaria sensor has been used for scaling up to field level. Furthermore we discuss here how the assessment of the S::can spectrometer probe has been done, to evaluate the use of this sensor in determining the nitrate concentration in the groundwater.

Fritzmeier ISARIA Sensor

For almost every week in the growing season measurements of the IBI biomass index and IRMI vegetation index at field scale were obtained with the Fritzmeier ISARIA. By adding 700 to the IRMI vegetation Index the Red Edge Position (REP) can be determined. The REP determined by the Fritzmeier has been correlated to the aboveground plant nitrogen (AGN) measurements of TTW. Based on this correlation we estimated the N content in the aboveground plant parts for the whole field. This data has been interpolated by using the kriging interpolation technique. Based on this interpolation we were able to map the spatial variability of the AGN of the field and can compare it for different moments in time.

Furthermore an accuracy assessment of the Fritzmeier in determining the REP has been made. This has been done by comparing the values of the REP measured with the Fritzmeier with the REP values determined with the CropScan Multispectral Radiometer. This validation is done to perform an accuracy assessment of the Fritzmeier ISARIA sensor in monitoring the REP and the N content of an agricultural parcel of potatoes. This accuracy assessment determines how suitable sensing with the Fritzmeier ISARIA sensor is to monitor the aboveground nitrogen content in the plant.

S::can Spectrometer Probe

An accuracy assessment of the S::can Spectrometer Probe in determining the nitrate concentration in the groundwater is hard, especially with the data we have available in this study. Since the S::can Spectrometer Probe has been used to measure every hour the nitrate concentration in the groundwater and the samples we analysed of the nitrate concentration in the groundwater are point measurements taken at one specific moment, often even when the sensor was not working anymore. Furthermore as has been discussed in section 3.4.1 we have only data available of the S::can Spectrometer Probe for 3 weeks. Therefore we cannot determine how accurate the nitrate S::can Spectrometer Probe is in determining the nitrate concentration and whether this sensing approach is feasible for the determining the nitrate concentration in the groundwater. The only comparison we could make is checking whether range in the nitrate concentrations measured with the S::can Spectrometer Probe correspond with the range of measurements of the nitrate concentration determined with the Spectroquant Nova 60 – Nitrate cell test.

4. RESULTS

In this section we discuss the main results obtained in this study. We will start with presenting the results obtained to determine the N content in the soil. In which we discuss the spatial variability of the parameters influencing the N-content in the soil in section 4.1.1 and show the effect the different N-treatments has on the N-content in the topsoil, unsaturated zone and for the groundwater in section 4.1.2. In subchapter 4.2 we discuss the results obtained for the N content in the potato plant. In section 4.2.1 we show the results between the CropScan reflectances and the aboveground plant nitrogen content and the NO_3-N concentration in the petiole plant sap. In section 4.2.2 we discuss the effect of the different N-treatments on the parameters determining the plant status. Section 4.2.3 mainly deals with the yield, in which we present a map of the spatial variability in the yield. Furthermore we present the results of the N footprint assessment and the assessment of the N use efficiency. In the last section of this subchapter 4.2.4 we show the accuracy of the Frizmeier Isaria Sensor for determining the aboveground plant nitrogen content and present the maps showing the spatial variability of the aboveground plant N-content at field level. In section 4.3 we present the graphs showing the time series of the N balance parameters for some of the selected plots.

4.1 Soil Nitrogen Parameters

In this subchapter we discuss the spatial and/or temporal variability of the soil parameters affecting the nitrogen content in the soil. Furthermore we discuss the development in the N-content in the topsoil (0-20cm), unsaturated zone and the saturated zone over the growing season.

4.1.1 Parameters affecting N-content soil

Figure 10 shows the spatial variability in the organic matter content for this field. In this map we observe that low organic matter contents have been found in the centre of this agricultural parcel, especially for the area close to the plots G and H we found a relatively low organic matter content of between 3.7 – 3.9%. Relatively high percentages of organic matter are found in the upper right corner of the parcel and also in the area close to the forest (lower right corner of the plot). This relatively high percentage of organic matter for area including the plots A of B will support the available amount of N in this area, because more N will become available from N mineralisation of organic matter compared with the area including plots G and H which are located in the low organic matter zone.

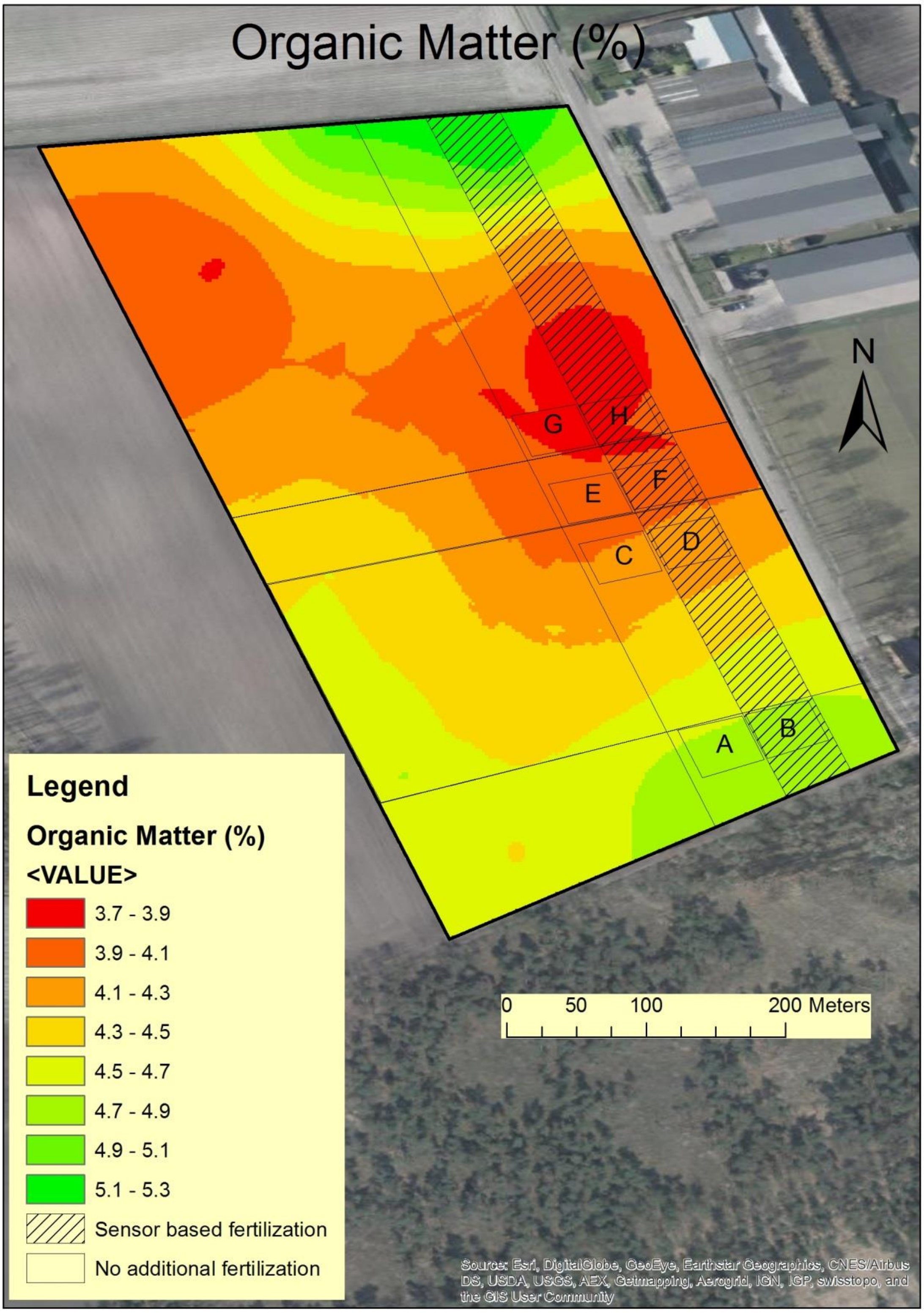

Figure 10. Map of the spatial variability in the organic matter content (%).

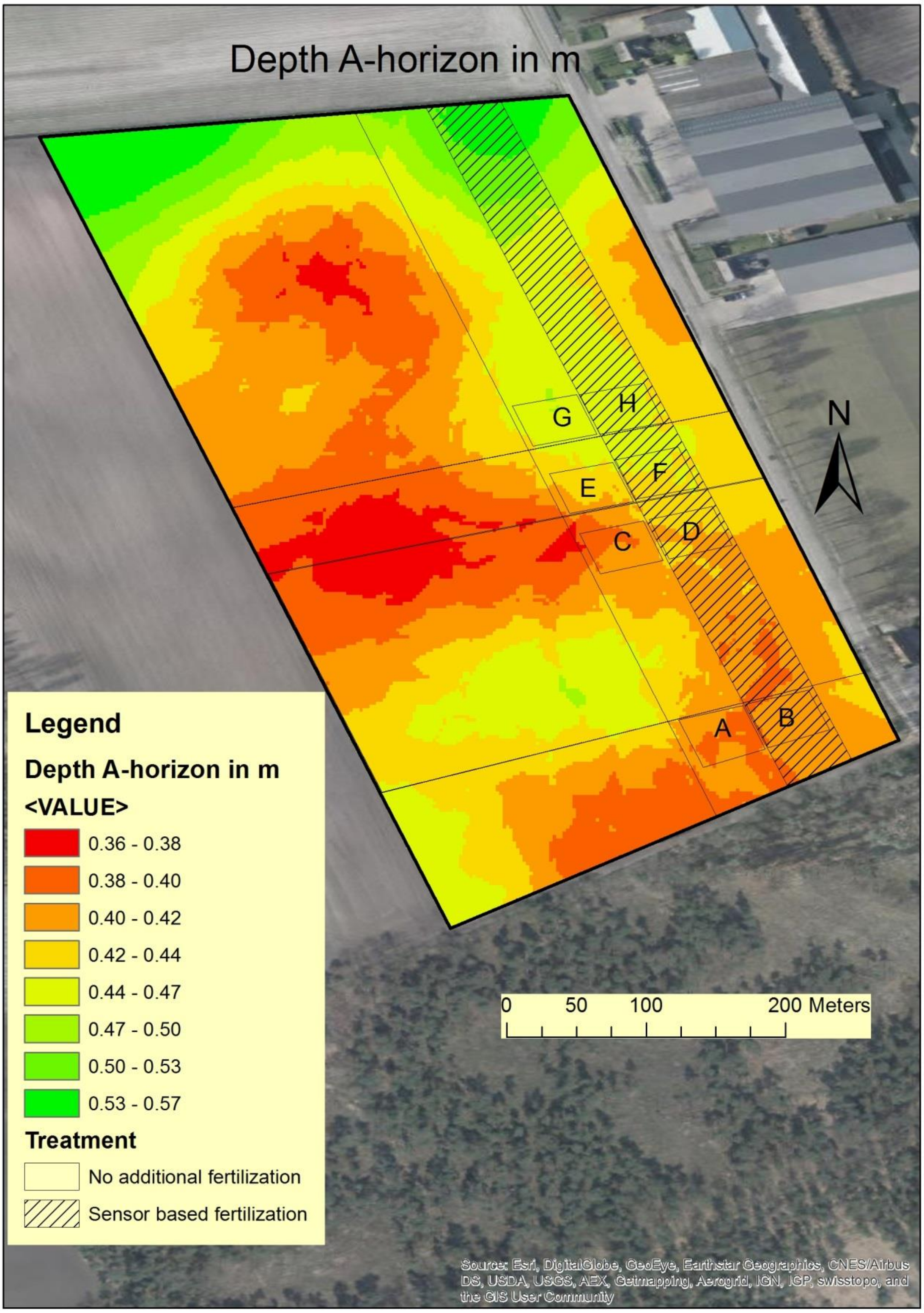

Figure 11. Map of the spatial variability in the depth of the A-horizon in meter.

In figure 11 the spatial variability in the depth of the A-horizon is visualised. The A- horizon is the dark coloured top horizon, which contains in general more humus than other soil horizons. As can be seen in this map there is one area in the centre of this map, left to plot E and C in which the A-horizon is relatively shallow with a depth between 36-38 cm. In the upper area (North) of this parcel the measured depth of the A-horizon has the highest values, with a A-horizon depth up to 57cm. Potatoes have a rooting depth up to maximum 1 meter (Smit and Groenwold, 2005). We assume that the organic matter content and the N content is equally distributed in this A-horizon. Based on that we can state that the depth of the A-horizon influences the amount of N which can be taken up by the plants. By looking at the specific plots we observe that plot G and H, the plots which were located in the zone with the lowest organic matter content have the thickest A-horizon, compared to the other plots. Their A-horizon depth is between 44-47 cm. Especially plot A and plot B, which were located in an area with high organic matter contents are now located in areas with a thin A horizon between 38-42 cm.

Figure 12 shows the spatial variability in the total soil organic matter content. This map is calculated by multiplying the organic matter map (%) with the A-horizon depth (m) and the bulk-density (g/cm^3). This map shows that the highest total soil organic matter content is found in the right upper area with values ranging between 27.000 and 33.000 ton/ha. If we look at the spatial differences between the plots we observe that plot E and plot C are partly located in the zone with the lowest total SOM content of 16.900 – 19.000 ton/ha. Plot D, F, G and H are located in an area with a total calculated SOM content of 19.000 – 21.000 ton/ha. Plot A and B, the plots which received the highest initial fertilization rate are also located in the area with the highest total SOM content between the plots. For these plots the total SOM content ranges from 21.000 – 23.000. The higher total SOM contents for these plots are not caused by the higher initial fertilization rate, because the samples were already taken before the organic manure was applied to the soil.

Figure 13 shows the spatial variability in the Electrical Conductivity (EC) for the soil layer between 0-0.5 m. The EC-values for this field are uniform distributed. Only in the upper area of this map (North) higher values in the electrical conductivity can be found. This is also the area where we measured the thickest A-horizon and the highest organic matter contents. This part of the parcel is also the wettest zone of the field, for which soil moisture is closely related to the electrical conductivity. If we look in more detail to the EC values for the plots we observe that between the plots there are no major differences in the electrical conductivity observed. In the appendix 2 we present more maps of the spatial distribution of the EC for this field. Those maps shows the EC for the soil layer 0-1m, 0-1.5m and 0-3.0m.

Figure 14 shows the spatial distribution of the NO_3-N content for the 0-0.5m soil layer. Since this map is based on the EC measurements for the same layer, more or less the same patterns as in the EC-map are visible in this map. So, high concentrations in the NO_3-N content have been found in the upper area (north side) of the parcel and for the rest of the field more or less constant values of around 0.1-6.0 mg/kg NO_3-N have been found. If we look specifically at the differences between the plots we observe that plot H is completely and plot G and F partly covered with a higher NO_3-N content of around 2.0-4.0 mg/kg for this layer. We found the lowest NO_3-N concentrations of 0.1-1.0 mg/kg for the plots A and B. For the other plots we found values for the NO_3-N concentrations between 1.0-2.0 mg/kg.

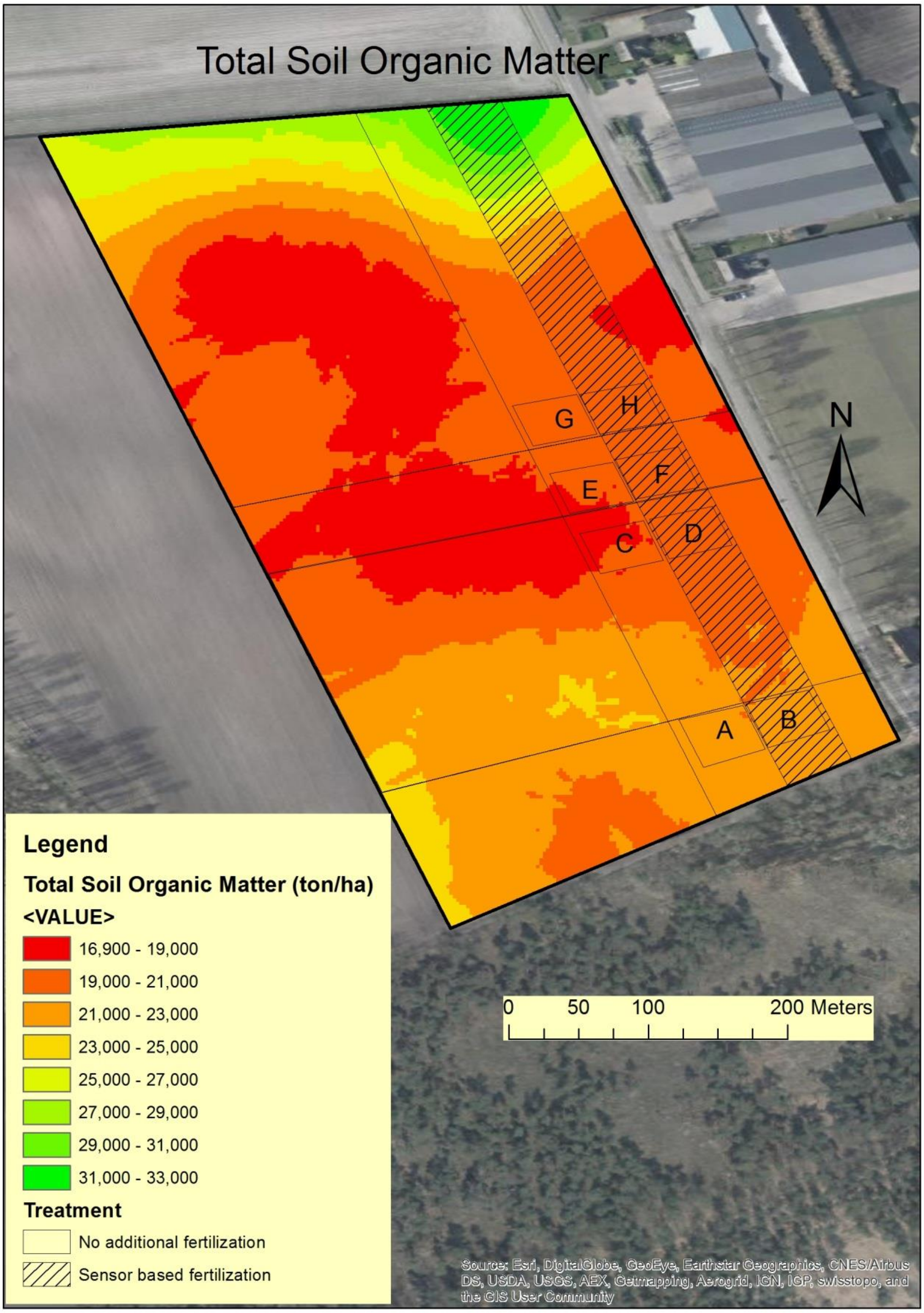

Figure 12. Map of the spatial variability in the Soil Organic Matter content (ton/ha).

Figure 13. Map of the spatial variability in the electrical conductivity for the soil layer 0-0.5m in mS/m.

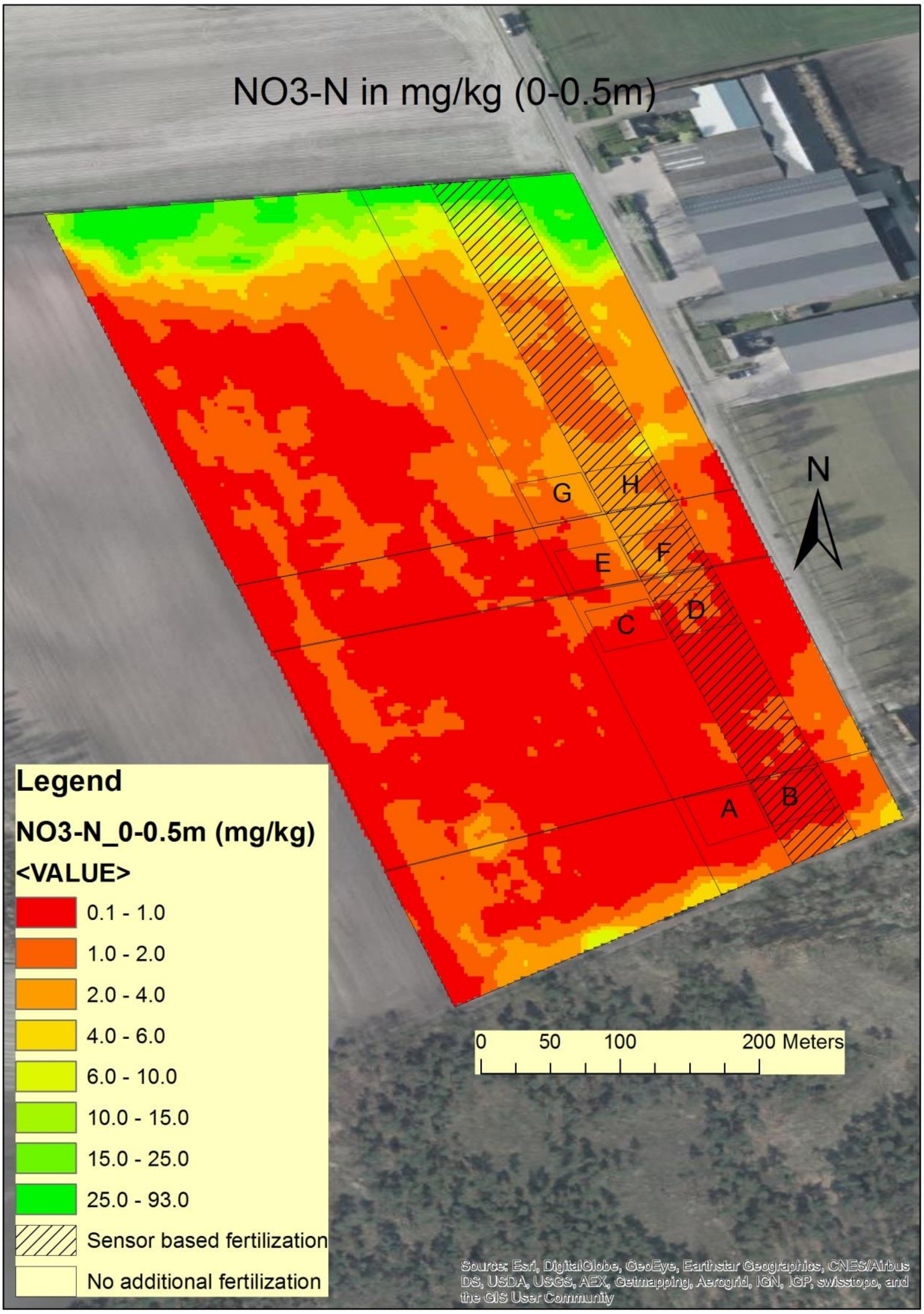

Figure 14. Map of the spatial variability for the NO_3-N content in the soil layer 0-0.5m in mg/kg.

4.1.2 Dynamics of N in the topsoil, unsaturated zone and groundwater

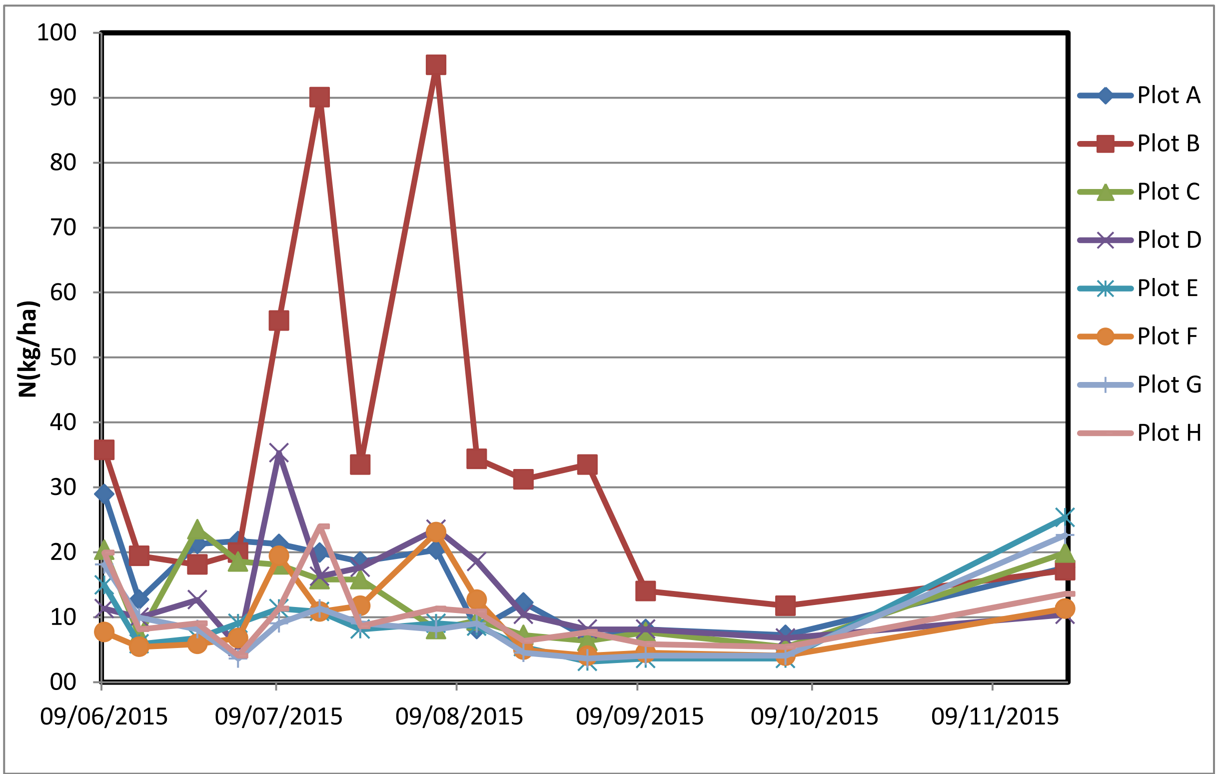

Figure 15. Development of the N content in the topsoil (kg/ha) over time for the different plots.

Figure 15 presents the development of the N content in the topsoil. This graph clearly shows the effect of the sensor based N fertilization. This fertilization leads to the peak concentrations in the plots B, D, F and H. We observe in this graph that the N content in plot B reaches very high concentrations (>90 kg N/ha) the next measurement day after sensor based fertilizer application. This could be caused by the high initial fertilization rate this plot already received in the beginning of the growing season and therefore the added N is not directly taken up by the plants. The effect of the high initial fertilization rate can also be seen in the graph by the higher values we measured for plot A and B at the start of the growing season. If no additional fertilization took place in the plot, like in plot A, C, E and F, the N content in the topsoil decreases fast until a specific level is reached (8-10 kg N/ha) afterwards it stays constant. We observe that after the potatoes were harvested the N content in the plots increases again to values between 10 and 25 kg N/ha. The pattern for the plots which received in-season nitrogen fertilization (B, D, F and H) shows resemblance with figure 21 showing the NO_3-N in the petiole plant sap.

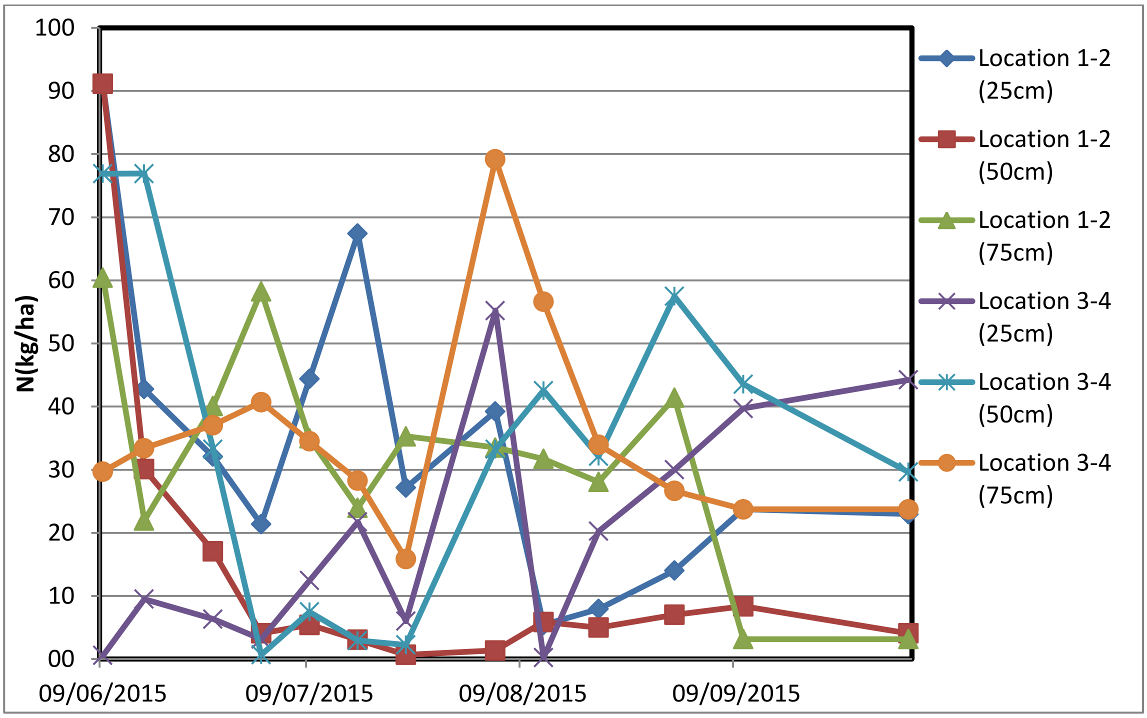

Figure 16. Development of the N content in the unsaturated (kg/ha) over time for combined locations of monitoring wells at three different depths. In which location1 and 2 received an initial fertilization level of 162 kg N/ha and location 3 and 4 an initial fertilization level of 90 kg N/ha.

Figure 16 shows the time course of the N content at two locations over three depths. Location 1 and 2 and location 3 and 4 are combined because for every individual location not a sufficient amount of water was extracted by the rhizons for every measurement day. Furthermore the initial fertilization rates for location 1 and 2 are equal and the same is true for location 3 and 4. The dates when irrigation took places in for this lane were 08 June, 16 June, 25 June and 06 August. Due to this irrigation 25 mm of water is added to the plant and soil in a very short period of time. Due to this irrigation N can be washed out from the topsoil and leach to the unsaturated zone and the groundwater. Those irrigation dates combined with the sensor based fertilizer application dates of 17 June, 04 July and 03 August might clarify some of the peak values measured. For example the peak values measured at location 3-4 (75cm), location 3-4(75cm), location 3-4 (25cm), location 1-2 (25cm) around 09 August could be caused by the fertilizer application at 03 august in combination with the irrigation of 06 august. This could lead to N leaching, if this N was nothing taken up by the plants yet. However, we do not have a direct cause for some other peak values. In general we observe that the N content in the unsaturated zone at the beginning of the growing is lower than the N-content by the end of the growing season.

In figure 17 the time course of the N content in the groundwater is shown for the four monitoring wells. Monitoring well 3 and 4 are located in the management zone which received a higher initial fertilization rate than monitoring well 1 and 2 (figure 5). The effect of the higher initial fertilization rate can only be seen in the groundwater measurements of well 3. Furthermore we observe that at the beginning of the growing season the N concentration in the groundwater were high with values between 160 to 340 kg/ha over a groundwater depth of one meter. When the growing season develops those N concentrations decrease until +/- 22 July when we observe a peak value in the N content of the groundwater for all four monitoring wells. Afterwards the N content in the groundwater decrease until +/- 22

September. After 22 September the N content in the groundwater increases again and at the final measurement day on 21 November values where measured between 140 kg N/ha for monitoring well 4 and 220 kg N/ha for monitoring well 3. The effect of the irrigation dates in combination with the fertilizer application dates as discussed for the N content in the unsaturated zone does not lead to a direct increase in the N in the groundwater. The increase in the N groundwater from mid-September onwards can be explained by the start of the autumn, in which in the third week of September high precipitation amounts where measured at the closest KNMI weather station in Eindhoven. Those high precipitation amounts might by the cause of the increase in the amount of N in the groundwater in combination that the potato plants were killed around that time.

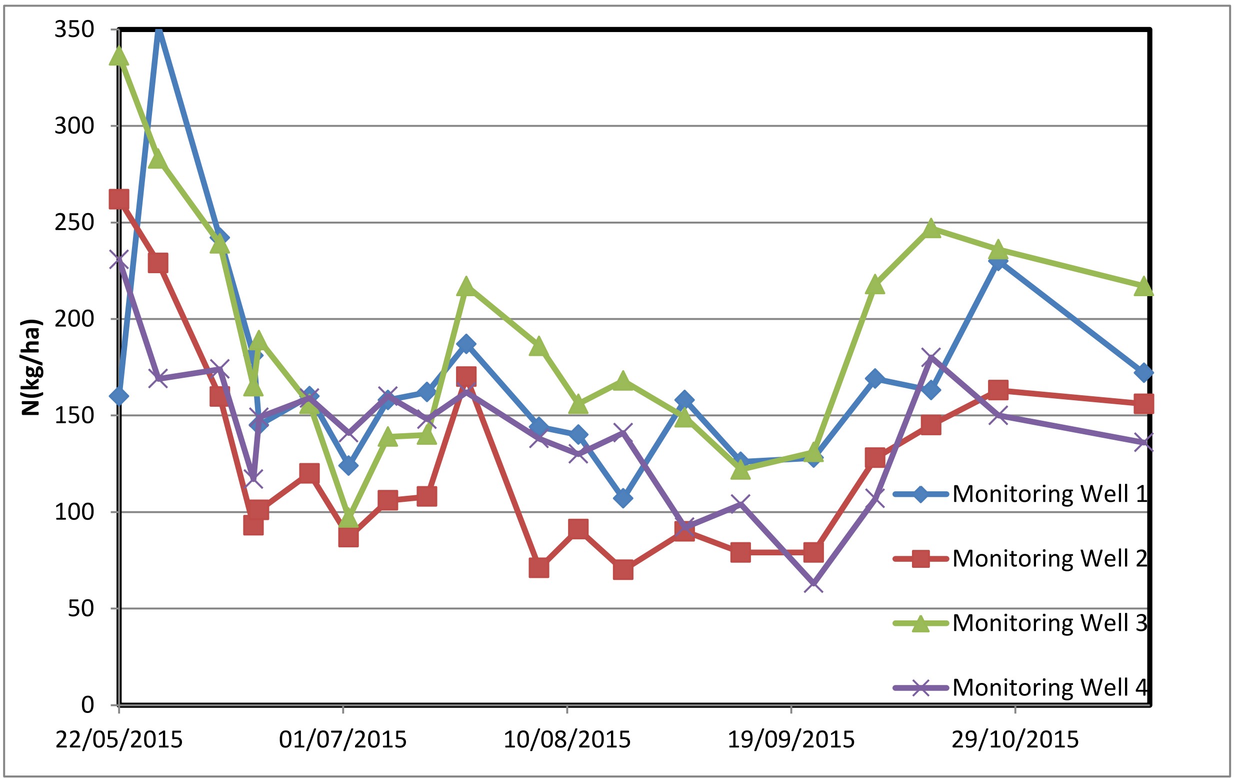

Figure 17. Development of the N content in the groundwater(kg/ha) over time for the four monitoring wells. In which monitoring well 1 and 2 received an initial fertilization level of 162 kg N/ha and monitoring well 3 and 4 an initial fertilization level of 90 kg N/ha.

Figure 18 shows the development of the nitrate concentration (NO_3^-) over time for the four monitoring wells. This graph shows the same patterns as the graph in figure 17, however to this graph we added the legislation limit of 50 mg/L NO_3^-. The results of this graph show that the groundwater samples taken in some of the monitoring wells (monitoring well 1 and 3) exceeds almost continuously over the growing season the legislation limit. However other monitoring wells, e.g. monitoring well 2, only exceeds the legislation limit at the beginning of the growing season and by the end of the growing season, after the potato plants were destroyed. Furthermore the peak values measured at 22 July result in a higher NO_3^- concentration than the legislation limit. This difference between the NO_3^- concentrations cannot be related to the initial fertilization zones, since the initial fertilization zones of monitoring well 1 and 2 are equal and also the initial fertilization zones for monitoring well 3 and 4.

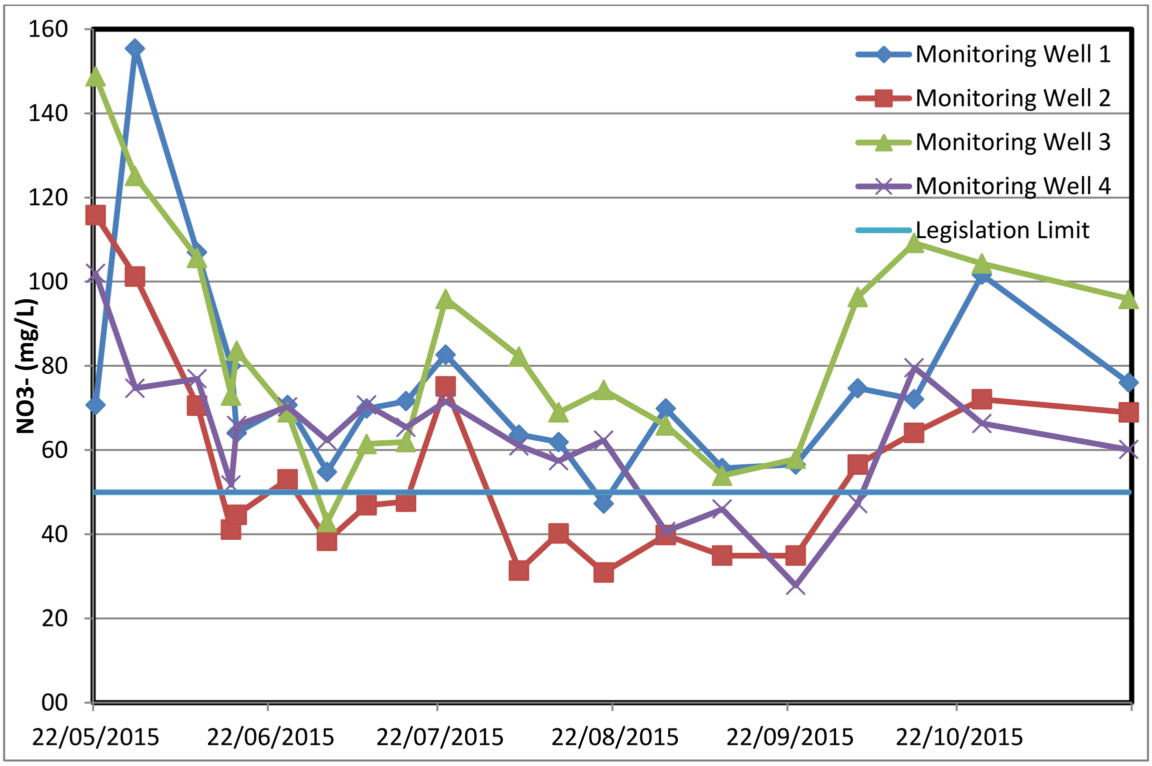

Figure 18. Development of the nitrate concentration in the groundwater(mg/L) over time for the four monitoring wells.

4.2 Plant Nitrogen Parameters

In this subchapter we discuss the results obtained for the measurements of the potato plant. In section 4.2.1 we show the results of the correlations between the CropScan determined vegetation indices and the aboveground plant nitrogen content and the NO_3-N concentration in the petiole plant sap. In section 4.2.2 we discuss the effect of the different N-treatments on the parameters determining the plant status. Section 4.2.3 mainly deals with the yield, in which we present a map of the spatial variability in the yield. Furthermore we present the results of the N footprint assessment and the assessment of the N use efficiency. Finally, in section 4.2.4 we show the accuracy of the Frizmeier Isaria Sensor in determining the aboveground plant nitrogen content and present the maps showing the spatial variability of the aboveground plant N-content at field level.

4.2.1 Vegetation indices related to aboveground plant N-content and petiole plant NO_3-N concentrations.

Table 8 presents an overview of the vegetation indices used in this study and their relation to the aboveground plant nitrogen content and the petiole plant NO_3-N content. We combined the data for the years 2012, 2013 and 2015 to determine the relationship between the vegetation indices and the above ground nitrogen content in which n=11 (nr. of dates in those three years). For the relationship between the VI's and the petiole plant NO_3-N concentration we only used the data for 2015 (n=12 dates in 2015). As can be seen in table 8, the best fit relationship between the VI's and the aboveground plant nitrogen or petiole plant NO_3-N concentration is in general given by an exponential curve. However for some relationships the correlation curve is best represented by a linear relationship. A disadvantage of this exponential relationship is the saturation effect which occurs. This saturation effect becomes clear for larger values of the specific vegetation index, for which a small increase in the vegetation index value results in a large increase in the AGN. Therefore, we decided to represent the correlation by a linear relation if the difference in the coefficient of determination R^2 between the linear and the exponential relationship was very small or if exponential component in the equation was very small.

The results of the assessment for the different VI's in estimating the aboveground plant nitrogen content shows that the highest coefficient of determination (R^2) is found for the chlorophyll red edge index (CIre). For this correlation we found an R^2 of 0.62. Other vegetation indices resulting in a relatively high coefficient of determination are the chlrophyll green index (CIgr), Optimized Soil Adjusted Vegetation Index (OSAVI) and the Weighted Difference Vegetation Index (WDVI).

For the relation between the different VI's and the petiole plant NO_3-N content we found in general lower coefficient of determinations than found for the relation between the VI's and the AGN. The highest coefficient of determination (0.44) is found for the relation between the TCARI/OSAVI vegetation index and the petiole plant NO_3-N concentration. In figure 17 the curve for this relationship is shown.

Table 8. Vegetation Indices used in this study with their relations to the aboveground plant nitrogen content and the petiole plant NO_3-N concentration and the corresponding coefficient of determination (R^2)

Vegetation Index	Relation to AGN	R^2	Relation to petiole plant NO_3-N	R^2
REP	y = 6,4594x - 4624,9	0.10	y = 404,22x - 289603	0.10
TCARI	$y = 16,724e^{8,3535x}$	0.21	y = -37422x + 7408,3	0.24
OSAVI	$y = 1,0461e^{5,0134x}$	0.58	$y = 1284,6e^{0,5779x}$	0.01
TC/OS	$y = 23,19e^{4,1692x}$	0.05	y = -49005x + 11007	0.44
WDVI	$y = 9,0265e^{3,7787x}$	0.53	$y = 1417e^{0,7862x}$	0.02
NDRE	$y = 8,8666e^{16,936x}$	0.48	$y = 539,08e^{12,396x}$	0.09
CIre	$y = 6,5684e^{0,9438x}$	0.62	$y = 1152,8e^{0,349x}$	0.08
CIgr	y = 23,704x - 54,75	0.61	$y = 691,77e^{0,2357x}$	0.12

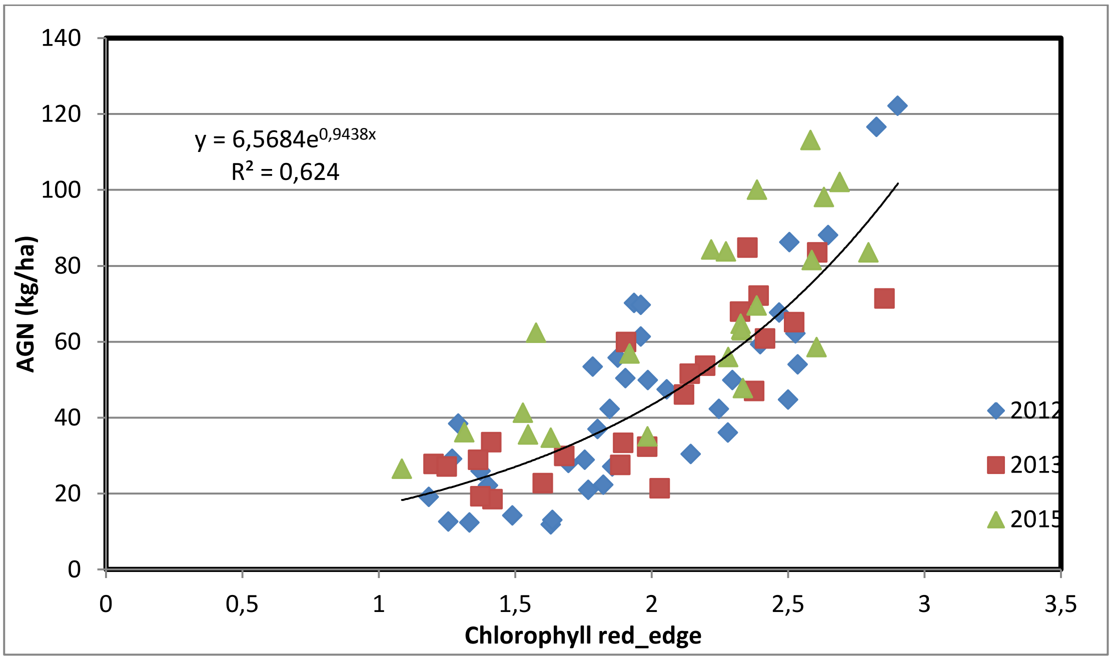

Figure 19. Relation between the aboveground plant nitrogen content and the chlorophyll red edge.

Figure 19 shows the relationship between the aboveground plant nitrogen content and the chlorophyll red edge (CI_{re}). To establish this relationship, we made use of the AGN lab analysis of TTW and the CropScan reflectances for the same day. If we look at the differences between the years 2012, 2013 and 2015 (figure 19), we do not observe that one year has higher values than another year. The correlation between the aboveground plant nitrogen content and the chlorophyll red edge (CI_{re}) for those three years combined can be best fitted with an exponential curve for which the corresponding correlation equation can be found in table 8 and figure 19. This correlation equation has been used to determine the AGN at plot level and to calculate one of the outputs in the N-mass balance.

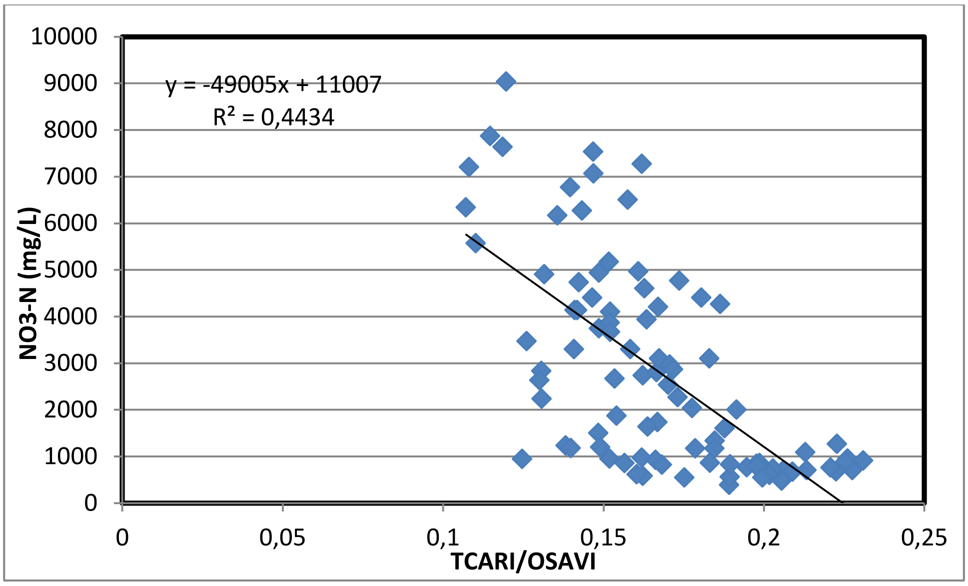

Figure 20. Relation between the petiole plant sap nitrogen concentration and the Transformed Chlorophyll Absorption in Reflectance Index over the Optimized Soil-Adjusted Vegetation Index (TCARI/OSAVI) for the data of 2015.

As can be seen in figure 17 TCARI/OSAVI values have been found to be inversely correlated to N-NO_3 concentrations in the petiole plant sap. So, TCARI values increase with decreasing N levels. We found a linear with a high coefficient of determination of 0.44 between TCARI/OSAVI and the petiole N content. We are interested in this relationship because we want to know whether we can estimate the N-concentration in the petiole plant parts based on (remote) sensing techniques.

4.2.2 Plant status assessment

One of the parameters determining the current plant status is the petiole sap nitrate-nitrogen (NO_3-N) concentration. In figure 21 the development of the petiole sap NO_3-N concentration is given. This graph shows for the plots which do not receive any additional fertilization over the growing season (plot A, C, E and G) a decrease in the NO_3-N concentrations in the petiole plant sap, until a certain minimum is reached. Where after the NO_3-N concentrations in the petiole plant sap stays more or less constant. For the plots which did receive sensor based additional fertilization is the fertilization effect clearly visible. Directly after the crops in the plots B, D, F and H receive a specific amount of additional fertilizer, the NO_3-N concentrations in the petiole plant sap increases. This can for example be clearly seen in plot F, in which the next measurement day after the fertilization application date (17 June, 04 July and 03 August) the NO_3-N concentrations in the petiole plant sap directly increase. This causes the peaks in the curves for those plots.

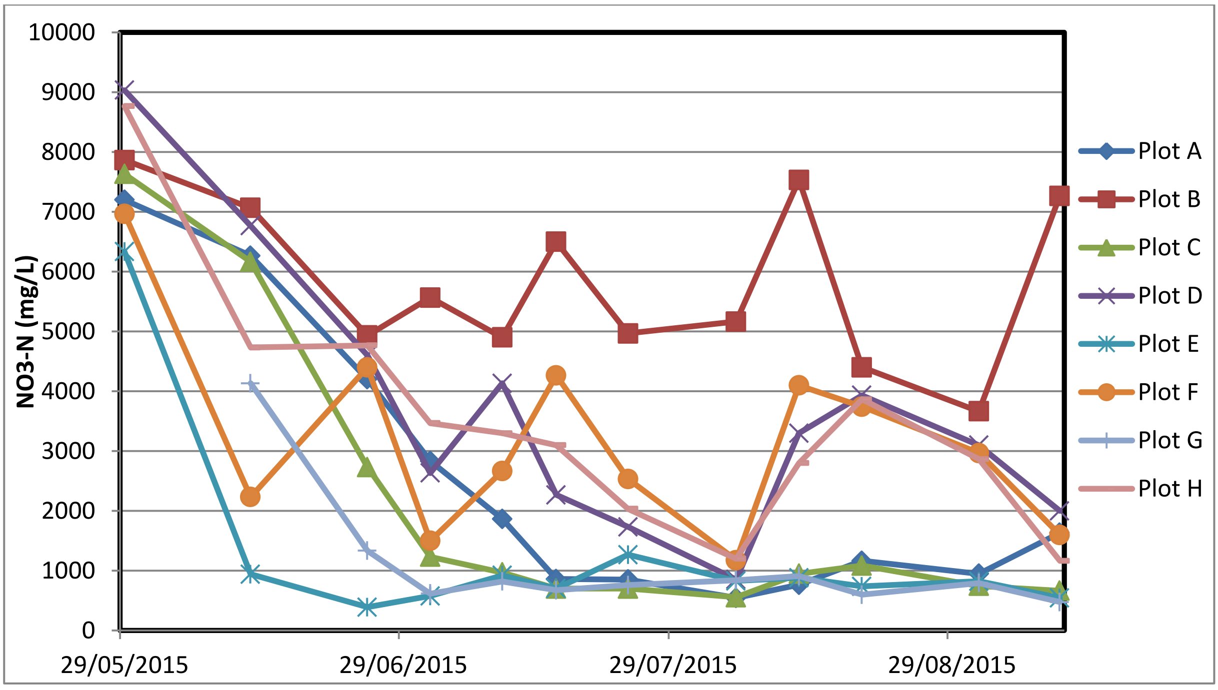

Figure 21. Development of the petiole sap nitrate (NO_3^-) concentration over time for the different plots.

Figure 22 shows the development of the nitrogen content in the aboveground plant parts. For calculating the AGN we used the formula given in figure 19 and the reflectance values obtained with the CropScan. From this graph it can be observed that the AGN concentration increase for all plots until a maximum is reached. This maximum is observed at the beginning of July. Afterwards the AGN concentrations decrease until the end of the growing season. Only the plots that receive sensor based fertilization have some small peaks in the AGN values 1-2 weeks after the fertilizer was applied. From mid-July onwards we see that the

AGN values in the plots that did not receive any sensor based fertilization decrease faster than in the plots that received a specific amount of in-season sensor based fertilization. Therefore by the end of the growing season Plot A, C, E and G had a lower AGN content than Plot B, D, F and H. The high peak values for the AGN measured at 3 July, occurred at a day with temperatures above 30°C. Therefore the temperature effect could be one of the reasons for these peak values. However, as can be seen in appendix 7, which shows the time course of the chlorophyll red-edge (Clre) over the growing season we observe for this day an extreme peak value for this VI. Therefore we can conclude that the CropScan measurements were also influenced by the warm weather in combination with the drooping potato plant leaves

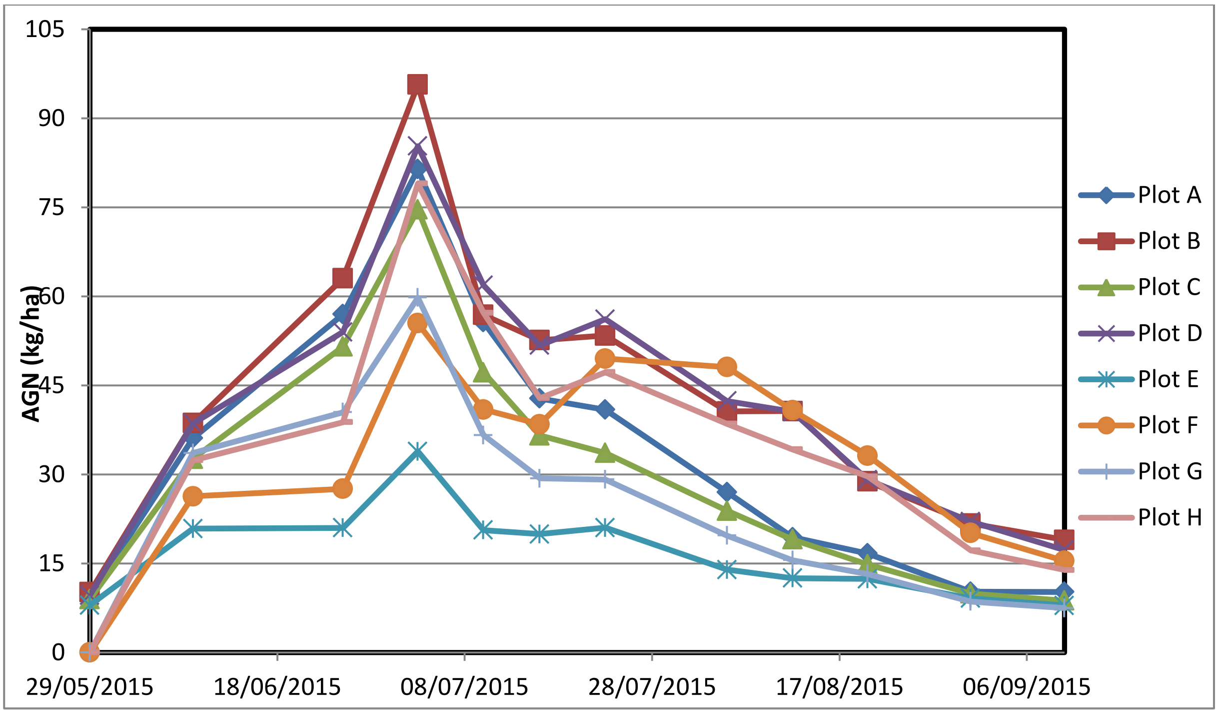

Figure 22. Development of the Nitrogen content in the aboveground plant parts over the growing season in (kg/ha).

In figure 23 we plotted the time course of this amount of Nitrogen in the tubers. This graph is based on three actual measurements of the N-content in the tubers (16 July, 10 September and 7 October, represented by the black lines in figure 23). For the period between those measurements we interpolated the N-content in the tubers. To estimate the N content in the period before 16 July we extrapolated by assuming a linear increase in the N content of the potato tubers as can be seen in Figure 23. Based on the linear relations we observe that for this type of potatoes, Fontane, and under this particular field conditions the nitrogen content in the tubers starts increasing 7-8 weeks after the potatoes have been planted. Furthermore we observe that the N content in the tubers at the end of the growing season has the highest values for plot D followed by plot B. What can also be observed in this graph is that the N content for the tubers in Plot F, which is the plot located in the 0 initial fertilization management zone reaches the same level after the sensor based fertilization as the plots who did have a higher initial fertilization amount applied, but did not receive any sensor based fertilization. The 0 plot E has clearly the lowest N content in the tubers.

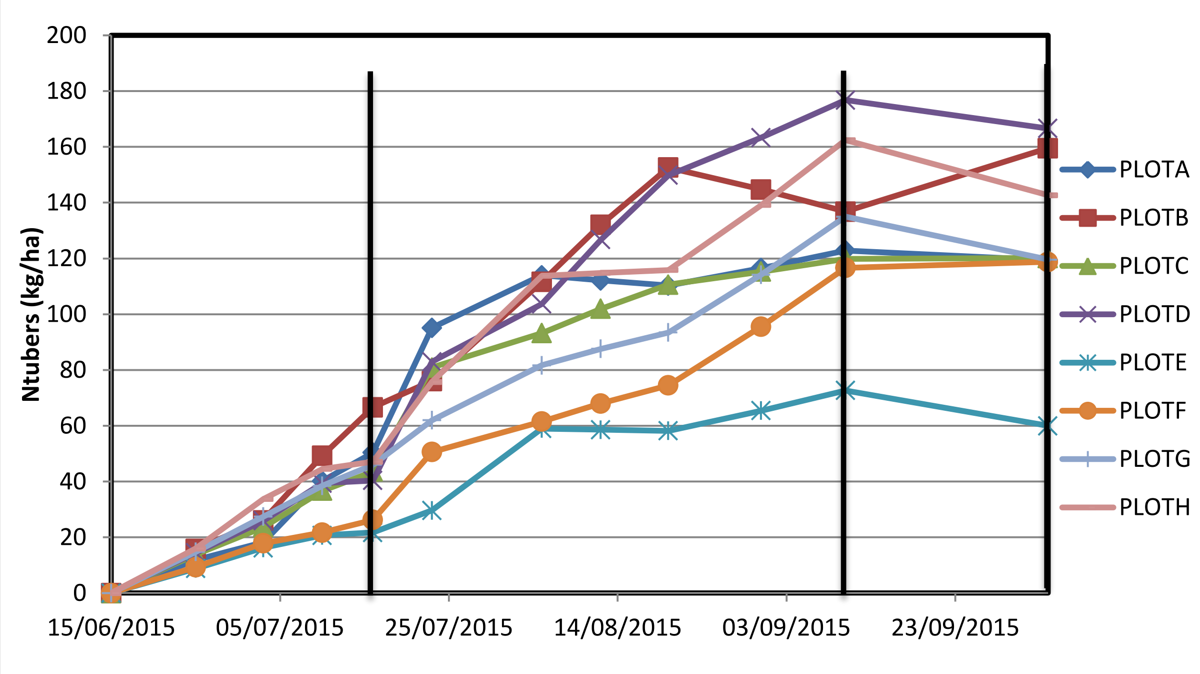

Figure 23. Development of the Nitrogen content in the tubers over the growing season in kg/ha. In which the black lines indicate the actual measurement days.

4.2.3 Yield assessment

Table 9 gives an overview of the yield in kg/ha per plot. The lowest yield (46300 kg/ha) was harvested in plot E. Plot E is the plot that did not receive any initial fertilization and did also not receive any additional sensor based fertilization. The highest yield (96300 kg/ha) was harvested in plot D, which had the second highest initial fertilization rate (162 kg N/ha) and also received additional sensor based fertilization, leading to a total of 277 kg N/ha applied.

Table 9. Overview of the yield per plot, N_{tuber}, $N_{fertilizer}$ and the N-footprint based on the study of Leip et al., (2014) in kg/ha.

Plot	Yield (kg/ha)	$N_{fertilizer}$ (kg/ha)	N_{tuber} (kg/ha)	N-footprint in kg/ha (Leip et al., 2014)
A	82300	288,8	119.4	164.6
B	83600	362,8	159.5	167.2
C	84300	198,8	120.2	168.8
D	96100	277,8	166.6	201.4
E	46300	36,8	60.0	92.6
F	74700	166,9	118.8	149.4
G	72700	126,8	119.6	145.4
H	79800	261.0	142.6	159.6

Besides the yield also the final N_{tuber} is presented in table 9. Based on the results presented in this table we observe that a high yield (kg/ha) does not directly correspond to a high N content in the tubers. Based on the yield we can make the following order for the plots: D>C>B>A>H>F>G>E and based on the N content in the tuber D>B>H>C>G>A>F>E. In which we observe that for the yield the initial N fertilization is more important, because plot A, B, C and D received all a higher initial fertilizer input than plot E, F, G and H. Furthermore we observe that for the yield the second highest initial fertilization rate of 162 kg N/ha leads to a higher yield and the highest initial fertilization rate. However, for the N content in the tuber we observe that sensor based in-season fertilization becomes more important, because plot H is now in the top 4 and this plot received the second lowest initial fertilization rate. The plots which received both a high initial fertilization rate and a sensor based in-season fertilization have the highest N-content in the tuber by the end of the growing season. Furthermore the N-footprint as discussed in section 2.2 is presented in table 9. For the N-footprint we observe a similar order than discussed for the yield.

In table 10 the N-uptake efficiency and the N-use efficiency per plot is given. Furthermore shows this table the total N-supply, which is calculated as the sum of mineral nitrogen fertilizer added to the soil before planting, mineralized N, and N fertilizer. Based on the N-uptake efficiency we have the following order for the plot: G>D>F>H>C>E>B>A. These results show that a high initial N fertilization does not lead to an efficient N-uptake, since plot A and B have the lowest N-uptake efficiency. Furthermore we are also interested in the N-use efficiency. For the N-use efficiency we observe the following order for the plots: D>G>E>C>F>H>A>B. Based on this order we observe that the highest N use efficiency is obtained for the plot in which we also measured the highest yield. For this plot the second highest initial fertilization rate of 162 kg N/ha in combination with in-season sensor based N fertilization has been applied.

Table 10. Overview of the yield per plot, the N-supply and N_{tuber} in kg/ha and the N-uptake efficiency and the N-use efficiency in kg/ha kg/ha^{-1}.

Plot	Yield (kg/ha)	N-supply (kg/ha)	N_{tuber} (kg/ha)	N-uptake efficiency (kg/ha kg/ha^{-1})	N-use efficiency (kg/ha kg/ha^{-1})
A	82300	427.4	119.4	0.28	192.56
B	83600	501.4	159.5	0.32	166.73
C	84300	337.4	120.2	0.36	249.85
D	96100	416.4	166.6	0.40	345.93
E	46300	175.4	60.0	0.34	263.97
F	74700	305.5	118.8	0.39	244.52
G	72700	265.4	119.6	0.45	273.93
H	79800	399.6	142.6	0.36	199.70

In figure 24 the spatial variability of the yield in ton/ha is visualized. The zero fertilization plot E is clearly visible with a low yield. Another area with a very low yield is the area which suffered from problems with the irrigation system, which basically destroyed the potatoes in that area. However, in this map the driving lanes get also a lower yield, which is not completely correct. Since the potato plants within those two tire lanes normally have a higher yield, because they receive more sunlight (less shadow). Furthermore what is also striking is that the initial fertilization management zones are not visible anymore by the end of the growing season. The strip in which plot A, C, E and G are located did not get any additional in-season fertilization, which can also be observed in the yield map, resulting in a slightly lower yield than the other strips. Furthermore, for the third strip (counting from the left border), indicated with the black arrow, we observe a slightly lower yield as well. This is probably due to another experiment performed by the farmer.

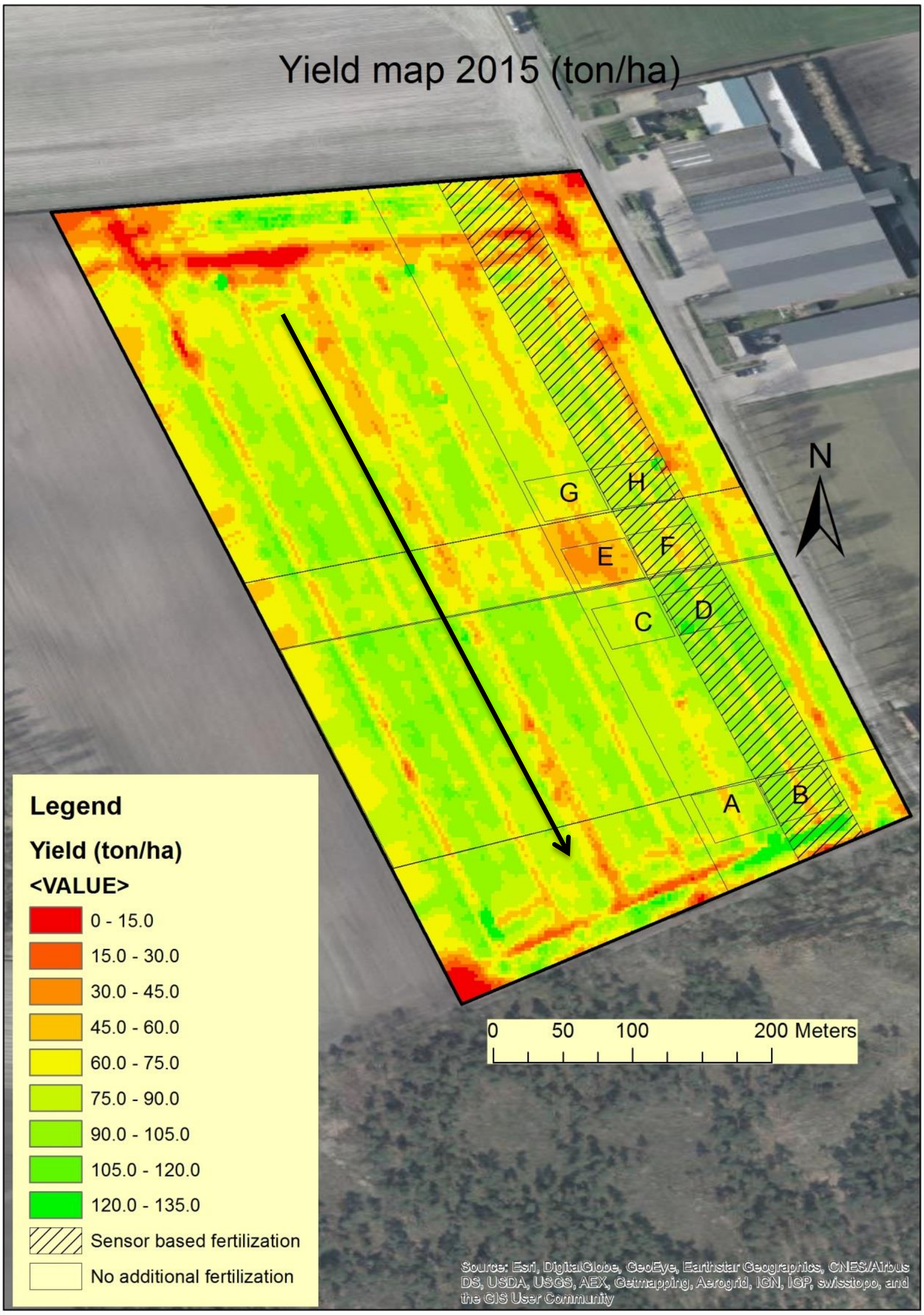

Figure 24. Map of the spatial variability in the potato yield in ton/ha.

4.2.4 Sensor based N-assessment at field scale

In this section we discuss the results we obtained by using the Fritzmeier Isaria Sensor to estimate the aboveground plant nitrogen content at field scale. First we show the results of the accuracy assessment of the Fritzmeier sensor compared with the reflectances measured by the CropScan Multispectral Radiometer..

To perform an accuracy assessment for the REP determined by the Fritzmeier we compared its value with the REP determined by the CropScan for the same plot and for more or less the same day. We did not use the data in our comparison if the time difference was more than 2 days. In figure 25 the results of this comparison of the REP Frizmeier with the REP CropScan are presented. In this comparison we observe that the REP Fritzmeier is in general 3 REP units lower than the REP CropScan. The coefficient of determination for this relation is 0.28.

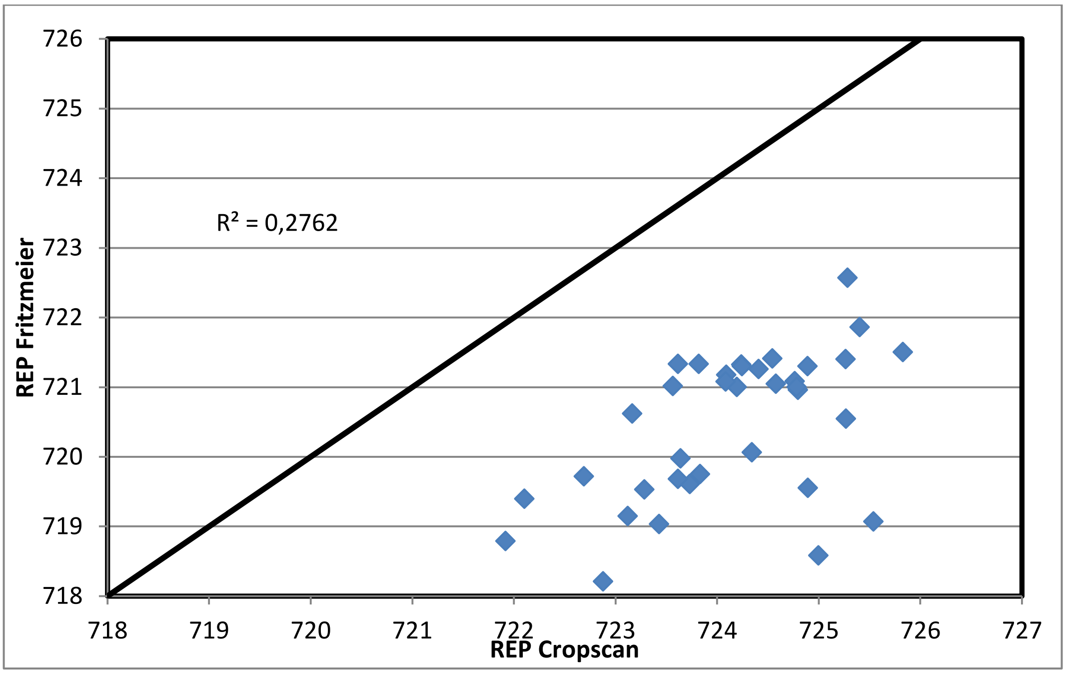

Figure 25. Relation between the Red Edge Position (REP) determined with the Fritzmeier Isaria Sensor and the REP determined with the Cropscan.

In the next step we correlated the REP determined with Fritzmeier to the lab analysis of the aboveground nitrogen content determined by TTW as discussed in section 3.3.2. This has been done to develop a relation which can be used to map the spatial variability of the N in the aboveground plant parts for the whole field. Figure 26 shows the relationship between aboveground nitrogen content and the red edge position determined with the Fritzmeier. For which an increase in the REP values leads to an increase in the AGN values. For this relation we found a coefficient of determination (R^2) of 0.49. The resulting regression relation as given in figure 26 has been used to calculate with the REP Fritzmeier the aboveground plant nitrogen content at field scale. This enables us to determine the spatial variability in the AGN over the field. For three dates during the growing season AGN maps were prepared, so we are able analyze the development in the spatial and temporal variability of the AGN over the growing season.

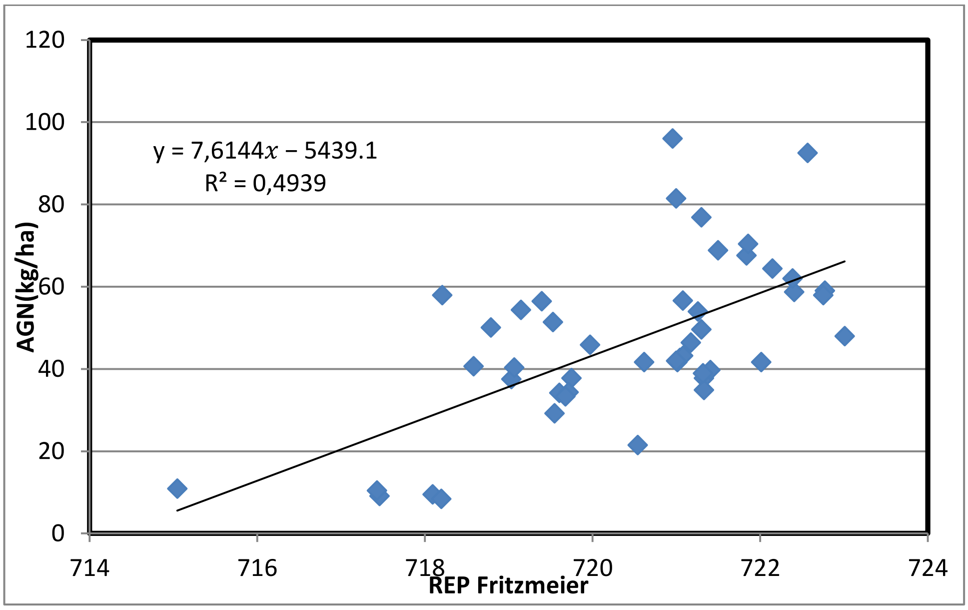

Figure 26. Relation between aboveground plant nitrogen content in kg/ha and the red edge position determined with the Fritzmeier Isaria sensor.

Figure 27 shows the spatial variability of the aboveground plant nitrogen content for three dates over the growing season. For those three maps we used three times the same legend as given in the map for 24-07.

The upper left map in figure 27 shows the spatial variability of the aboveground plant nitrogen content as monitored for 06 June. At the moment when these measurements were taken no additional fertilization was applied. That could be one of the reasons why we did not found higher aboveground plant nitrogen content in the strip which received a sensor based fertilization. Moreover we even found a lower AGN content in this strip. This could be caused by the low organic matter concentrations we found in this area of the map as can be seen in figure 10. The spatial distribution of the organic matter concentrations could also be the reason why we found lower AGN values at the left upper corner of the map. Furthermore, since 06 June was early in the growing season (the aboveground potato plant parts just emerged for 2-3 weeks at this time) the relatively low AGN values found for some of the areas in this map could be caused by the low plant coverage, resulting in soil background reflectance

The upper right map in figure 27 shows the spatial variability of the aboveground plant nitrogen content as monitored for 03 July. The majority of the AGN values are lower compared to the map at 06 June because at this time of the growing season the tubers are already developing so N is partly allocated to the tubers. Furthermore the effect of additional fertilization is already clearly visible, due to the fact that the strip which received the sensor based fertilization has clearly higher AGN values than the strip which did not receive any additional fertilization. The AGN values in the strip which did not receive any additional fertilization range now from 25 – 50.0 kg/ha. Besides the effect of additional fertilization, also the effect of the initial fertilization management zones is clearly visible in the map of 03 July. Since plot E and Plot G have clearly lower AGN values than A and C, which are also located in the strip which did not receive any additional fertilization during the growing season. Furthermore another experiment of the farmer, which was outside the scope of this research becomes visible in this map. That is the reason why the strip left of the strip which did not receive any fertilization during the growing season has lower AGN values (indicated by the black arrow in figure 27).

The map in figure 27 at the bottom of the page shows the spatial distribution of the aboveground plant nitrogen for 24 July. The AGN values decrease further compared to the map at 06 June and 24 July because the development in the tubers continued so more N is allocated to the tubers. In this map the effect of the sensor based fertilization becomes even more clear. Since the AGN content in the strip which did not receive any fertilization has decreased to values between 25.0 - 40.0 kg/ha. Furthermore the influence of the high initial N fertilization management zone has decreased as well, since the AGN values for plot A and C decreased as well. The lowest AGN values found in the left upper corner of the map are caused by problems with the irrigation system, which basically destroyed the above ground plant parts of the potato crops in that area.

The temporal variability in the maps of figure 27 showed in general a decrease in AGN content. Furthermore the effect of the different treatments (sensor based fertilization or no fertilization) becomes more clear over time and the effect of the initial fertilization management zones decreases

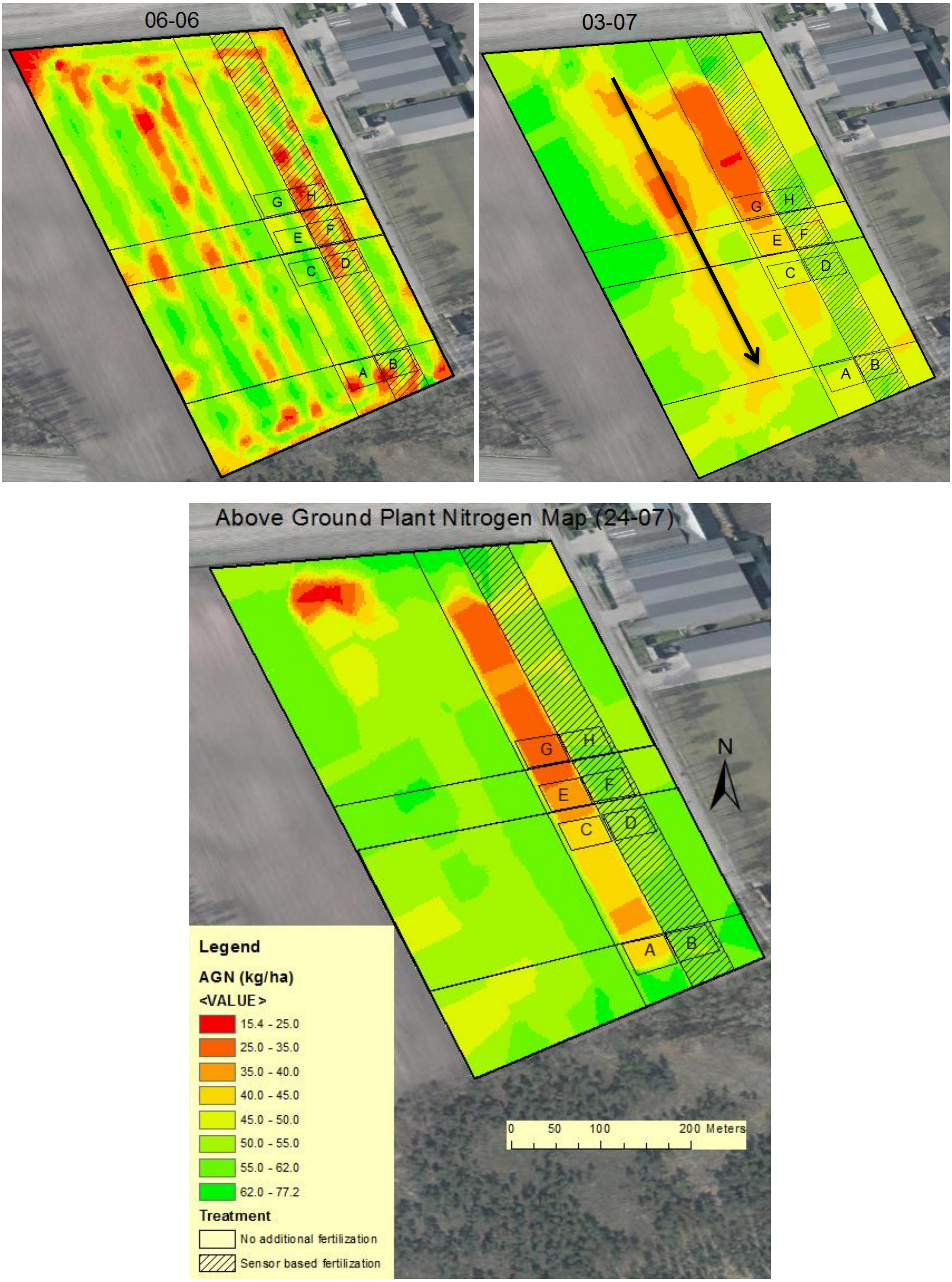

Figure 27. Maps of the aboveground plant nitrogen content for 06 June, 03 July and 24 July.

4.3 N-mass balance over time

In this section we discuss the time course of the components of the N-mass balance over time for some of the selected plots.

Figure 28 shows the cumulative Nitrogen mass balance for plot A. In this balance we made the inputs equal to the outputs, by assuming that the leaching component consists of the leaching losses to the groundwater and gaseous losses via volatilization and denitrification pathways. Since it is a cumulative nitrogen mass balance the inputs and the outputs increase over the growing season. The N-inputs, consisting of fertilizer inputs in combination with $N_{deposition}$ and $N_{mineralisation}$, for this plot are high with values larger than 440 kg N/ha by the end of the growing season. The allocation of nitrogen in the potato plant can be observed in this graph. At the beginning of the growing season the N-content in the aboveground plant parts is larger than in the potato tubers, but from mid-July onwards this changes and the amount of N in the tubers becomes larger than in the aboveground plant parts. We observe in figure 27 that the highest N content in the plant (aboveground plant parts + tubers) has been measured at 03-July and afterwards this N content drops again. This could be caused by the fact that the measurement of the aboveground plant nitrogen content at that day were influenced by the extreme temperatures of above 30°C. Therefore the leaves of the potato plants in especially the high initial fertilization zones droop, which probably influenced the measurements at that day. The last measurement day consists only of measurements of the N content in the tubers, because at that time the aboveground plant parts were destroyed.

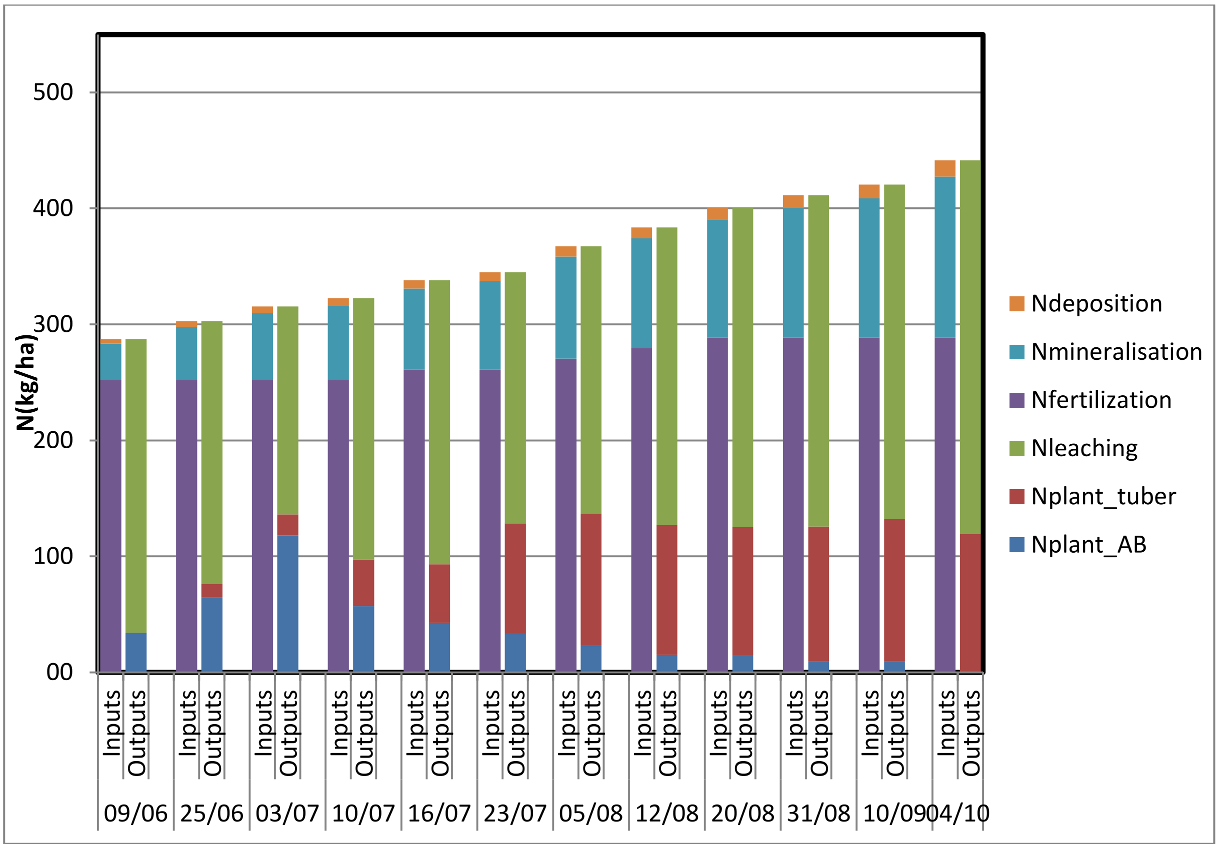

Figure 28. Cumulative nitrogen mass balance for plot A.

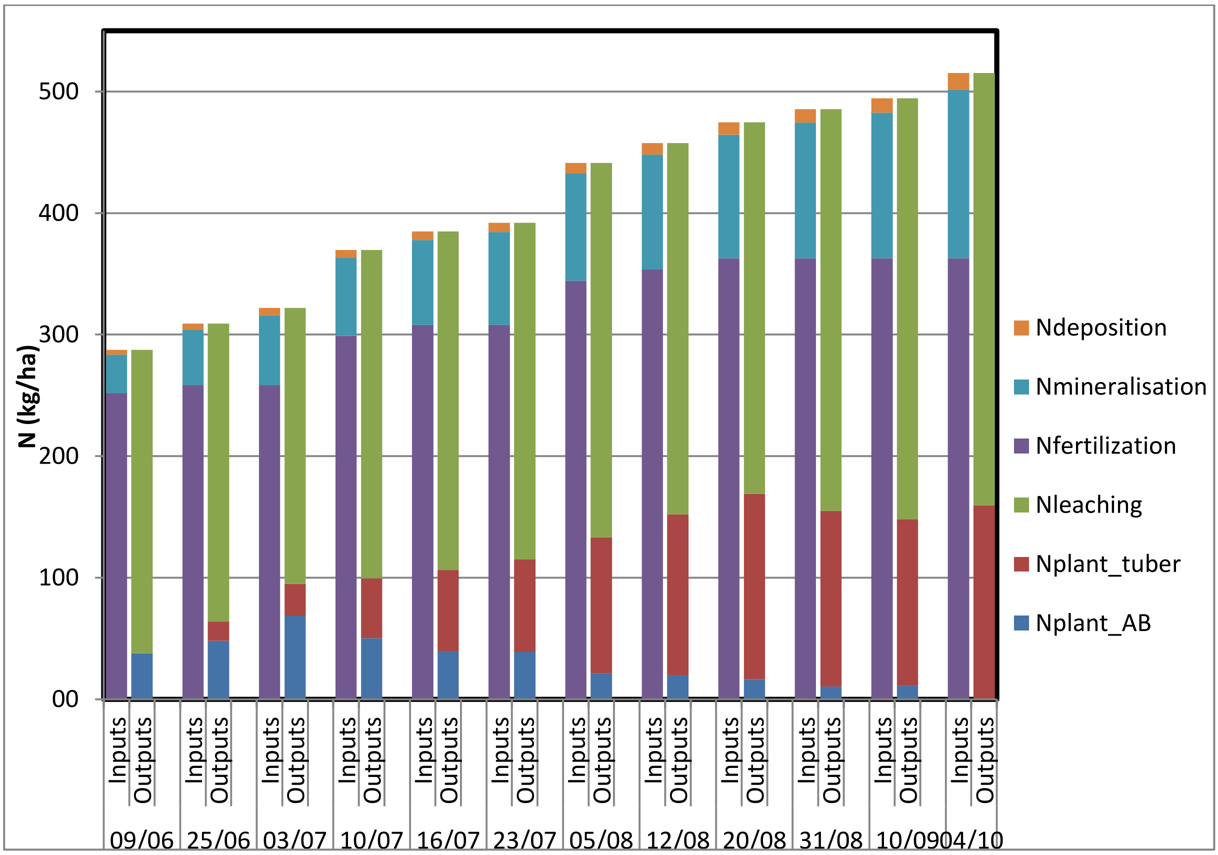

Figure 29. Cumulative nitrogen mass balance for plot B.

Figure 29 shows the time series of the cumulative nitrogen mass balance for plot B. This plot received the same initial fertilization as plot A, however this plot received three times over the growing season a sensor based fertilization amount. Therefore the total N inputs in this plot are larger than in plot A. The dates of the fertilization application (17-June, 04 July and 03 August) do not directly lead to an increase in the N content of the plant as can be seen in this graph. Furthermore, we observe in this plot that the highest total N content in the plant (aboveground plant parts + tubers) has been measured for 20 August. After this moment the quality of the aboveground potato plant parts decrease and there is almost no N left in the aboveground plant parts.

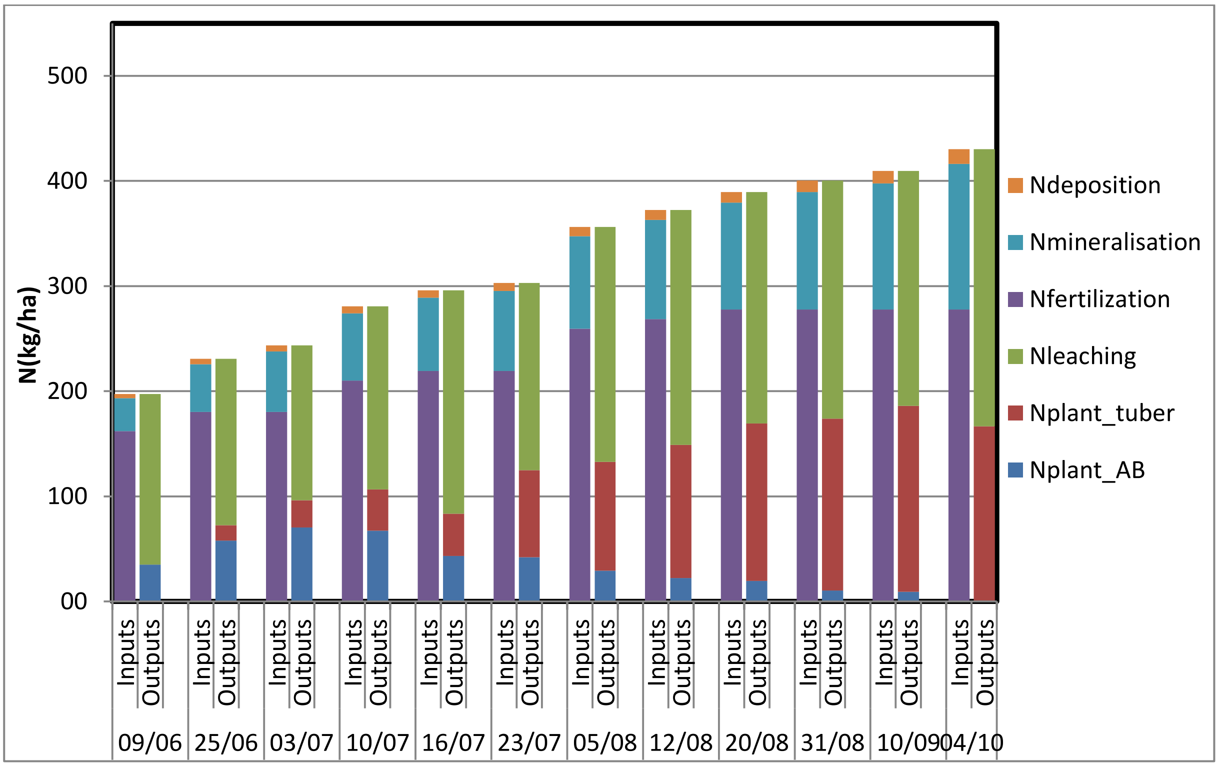

Figure 30. Cumulative nitrogen mass balance for plot D.

Figure 30 shows the time course of the potato plant in plot D. We choose to describe this plot, because plot D is the plot in which the highest yield is obtained. This plot was located in the second highest initial fertilization zone and received sensor based fertilization during the growing season. The total fertilizer N-input for this plot is 277.8 kg N/ha and the total amount of N inputs by the end of the growing season is estimated around 420 kg N/ha.. The graph for this plot also shows clearly the allocation of the N content in the potato plant. From mid-July onwards the measured N concentration in the tuber keep increasing and in the aboveground plant parts keep decreasing. The total leaching amount of N in this plot is estimated around 250 kg N/ha by the end of the growing season.

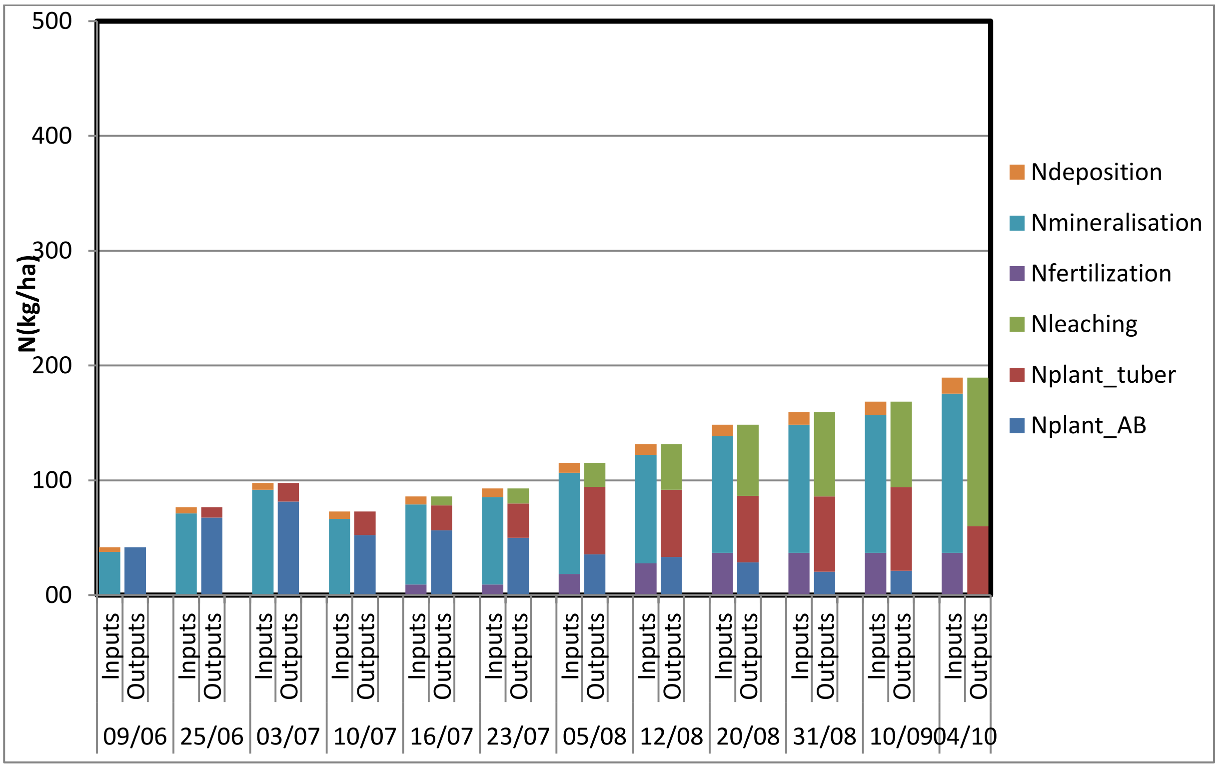

Figure 31. Cumulative nitrogen mass balance for plot E.

Figure 31 shows the cumulative nitrogen mass balance for plot E. This is the zero plot, which did not receive any initial fertilization and also did not receive any sensor based fertilization over the growing season. The only fertilization this plot got is four times a small amount of liquid urea, used as a boost for the crop in a dry period. The total inputs for this plot are around 190 kg N/ha by the end of growing season. Furthermore we observe that the transition between the largest component in the plant (aboveground plant parts or tuber) occurs at a later moment in the growing season than for the other plots. For this plot is the N content in the tuber at 05 August for the first time larger than the N content in the aboveground plant parts. For the other plots this transition occurs at mid-July. However to make the inputs and the outputs at the beginning of the growing season for the N mass balance of plot E equal to each other we needed to cheat a little bit. We did that by assuming that the N mineralisation speed for plot E is faster than for the other plots. If we did not assume a higher N mineralisation speed for this plot, we would get a negative leaching parameter.

The cumulative nitrogen mass balances for Plot C, F, G and H, which have not been discussed in the results chapter can be found in appendix 5

5. DISCUSSION

This chapter reflects on the main results obtained from this study, in which we will link those results to the research questions proposed in section 1.3. The results are discussed in broader context and linked to scientific literature. The order of the discussion chapter is similar to the results chapter, so we will start with the discussion of the parameters influencing the N-content in the soil and continue with the parameters for the plant followed by the N-mass balance in which we will combine the plant and the soil. In the final subchapter we relate the results obtained in this study to the research-questions.

5.1 Soil Nitrogen Parameters

In this subchapter we discuss the spatial variability in the main soil parameters which we analysed and described in section 4.1.1. Furthermore we discuss the results of the development in the N-content for the topsoil (0-20cm), unsaturated zone and the saturated zone over the growing season and we relate these results to results obtained in scientific literature.

5.1.1 Parameters affecting N-content soil

If we look at the organic matter map (figure 10) and relate this map with the map of the A-horizon depth (figure 11), we observe that the locations where a relatively low organic matter content is observed are located in the areas where we found a relatively thick A-horizon and vice versa. Only the area in the north of these maps show an area where both high organic matter contents and relatively thick A-horizons have been found. These maps of the spatial variability of the soil organic matter content and the depth of the A-horizon are essential to estimate the N mineralization potential. Realistic estimates of the N mineralization potential of the soil is essential for determining the rate of N fertilizer application required to optimize crop yield and to minimize the impacts of excessive N on the environment. Furthermore we used the maps of the spatial variability in the electrical conductivity (EC) and the relationship of Koumanov et al., (2001) to determine the NO_3-N content in the soil. If we look at the figure 14 in which the spatial the NO_3-N content in the soil layer 0-0.5m is given we observe large differences between the values presented in this map. The values range from 0.1-93 mg/kg soil. In which the extreme values are found in the upper area of the map, in which the highest EC-values are measured where the wettest zone is located. Within the field these values vary between 0.1 – 6.0 mg/kg soil. If we take an average value of 4.0 mg/kg NO_3-N than this value can be converted to 22.6 kg NO_3-N /ha (by assuming a bulk density of 1.13 g/cm^3; Bakker, 2014). These values are in the range with the values found by BLGG AgroXpertus for the field next to our study area for which values of 28 and 31 kg NO_3-N /ha have been found. However this method is strongly influenced by the wetness of the soil because for the area in the north, containing a high soil moisture content, we found average values for the NO_3-N content of 25 mg/kg resulting in 141.25 kg NO_3-/ha, which is not realistic.

The map showing the spatial variability in the A-horizon depth (figure 11) shows some accordance with the map presenting the spatial variability in the NO_3-N content (figure 13). Especially for the area including the plots E, F, G and H, which are located in an area with a thicker A-horizon we also found a higher NO_3-N content in the map in figure 14. However, for other areas we found opposite patterns in the spatial variability in the A-horizon depth compared with the spatial variability in the NO_3-N content.

If we compare the map of the spatial variability of the NO_3-N content (figure 14) with the map showing the spatial variability in the total soil organic matter content (figure 12), which is closely related to the N content in the soil, we do not observe the same patterns. We even observe opposite patterns for example the for the plots where we found the highest total organic matter contents (Plot A and B) are in the NO_3^- map recognized as the locations where the lowest NO_3-N content has been observed. Only for the areas at the north and south border of this parcel we found both high organic matter contents and high NO_3-N. However, as discussed earlier, the determined values for the NO_3-N content in this area could be considered as less reliable due to the high moisture content of the soil in these areas. Therefore, based on the visual assessment of the spatial variability between the NO_3-N content in the soil and the spatial variability of the soil organic matter measurements, we can conclude that an assessment of the spatial variability in the N content of the soil by using the EC-values does not result in a reliable estimation of the spatial variability in the N-content.

5.1.2 Dynamics of N in the topsoil, unsaturated zone and groundwater

In figure 15, the development of the N content in the topsoil (0-20 cm) is shown. The N-content in the topsoil for plot B, D, F and H is strongly influenced by the in-season sensor based N-fertilization, resulting in the peak values as shown in the graph. Overall we observe a decrease in the N-content over the growing season. After the potatoes were harvested the N-content in the topsoil increases due to ongoing mineralisation and N deposition. The results of our study correspond with the results of study of Ikerra et al., (1999) in which also peak values in the N-content of the topsoil (0-20cm) have been measured after application of N-fertilizer in combination with an overall decrease in the N-content over the growing season. The results in the study by Liu et al., (2003) showed that in a system with winter wheat, N-concentrations in the topsoil (0–20 cm layer) peaked 6 days after N-fertilizer application was added to the soil, and then the N-levels dropped to the level of the control within the next 14–21 days. This pattern is similar to the pattern we observed in the graphs for the plots D, F and H in figure 15.

Figure 16 shows the development of the N content in the unsaturated zone at three different depths. In the study by Liu et., (2003) N-levels in the unsaturated zone at depths between 20-60cm and 60-100cm remained constant and low even when N-fertilizer was applied. However when excessive N-fertilizer was applied the N-levels in the plots increased and showed peak levels after application, suggesting that a large amount of N moved into the deeper soil layers after fertilizer application. Different than the results published in the study by Shahnazari et al., (2008) we do not observe lower N contents in the deeper soil layers. In the study by Shahnazari et al., (2008) the N content decreases from the topsoil layer to the deeper layers in the unsaturated zone for all different N treatments. In our study we did not find any pattern based on the measurements at the three different depths of the N content in unsaturated zone. Even the measured N-content in the topsoil is often lower than the N-content measured in the unsaturated zone. The reason for the absence of a pattern for the N measurements in the unsaturated zone has mainly to do with the functioning of rhizons for sandy soils. Especially in dry periods the rhizons extracted barely no water from the unsaturated zone. Sometimes a very small amount just enough for diluting it a couple of times was extracted. However the accuracy of diluting a very small sample unit is small and therefore the uncertainty for those samples was large. The peak values observed in the N-content as shown in figure 16 occur mainly after application of in-season N-fertilization in combination with irrigation. Furthermore, we did not have experience with placing rhizons in sandy soils and the tubes used for collecting the samples lost their vacuum needed to extract water from the unsaturated zone already after a couple of days. Therefore, we can conclude that the measurements of the N-content obtained by extracting water from the unsaturated zone do not have a high accuracy.

The nitrogen content (kg/ha) or the nitrate concentration (mg/L) in the groundwater as can be found in figure 17 and 18 respectively show the general pattern of a decrease of the N-content at the beginning of the growing season and an increase after the potatoes were harvested. Furthermore the peaks in these graphs could be caused by fertilization directly followed by irrigation. Figure 18 shows that the nitrate concentration in the groundwater for some of the monitoring wells continuously exceeded the legislation limit of 50 mg NO_3^- /L. In appendix 3 the time course of the NO_3^- concentration as measured by RIVM for the closest monitoring well in Bladel is presented. To determine this time series, once a year (generally in autumn) a sample of the nitrate concentration in this well is analysed. As can be seen in the time course in appendix 3, since 2007 no values exceeding the legislation limit have been measured. However, in the last years an increasing trend is observed and for the last year (2014) NO_3^- concentration of 41 mg/L has been measured. Therefore, compared with this value the NO_3^- concentrations measured in this study are higher and especially the concentrations in autumn after the crop was harvested. For which the all the NO_3^- concentrations exceed the legislation limit. What is also striking is the variability of the NO_3^- concentrations of the groundwater within the field. For some moments the concentrations measured at the same day for two monitoring wells in the same initial fertilization zone are twice as large. This variability is not caused by the initial fertilization levels since there is a large difference observed in the NO_3^- concentrations within areas that received the same initial fertilizer input. Another possible reason could be the flow direction of groundwater in the field. The groundwater in this field flows from monitoring well 4 in the direction of monitoring well 1, which could lead that the NO_3^- concentrations in monitoring well 1 are higher than 2, 3 and 4. However this possible explanation is often rejected, since the concentrations in monitoring 3 are often the highest. Another possible explanation for the variability between the monitoring wells could be the in-season fertilization. Since, in the strip in which the monitoring wells were located another experiment has been performed, which could be the cause of the variability in the measured NO_3^- concentrations.

5.2 Plant Nitrogen Parameters

In this section we discuss the main results presented in section 4.1. In which we will relate those results to previous studies found in scientific literature.

5.2.1 Vegetation indices related to aboveground plant N-content and petiole plant NO_3-N concentrations

In this study we tested the relationship between VI's and the aboveground plant nitrogen content. This correlation has been made to develop a relation in which we were able to convert spectral reflectances obtained with the CropScan Multispectral Radiometer into aboveground plant nitrogen contents (AGN). The results of this study show that the Red – Edge Chlorophyll Index ($CI_{red\ edge}$) is the best vegetation index for describing this relation as can be seen in table 8. This correlation can be described with an exponential relation, with a coefficient of determination (R^2) of 0.62. The results for this relation correspond with the relation of previous studies. In which was shown that the Red – Edge Chlorophyll Index ($CI_{red\ edge}$) is the most appropriate hyperspectral vegetation index for assessing potato AGN with a high N sensitivity (Clevers and Kooistra, 2012; Mourier et al., 2015; Kooistra et al., 2015). This indicates that the $CI_{red\ edge}$ is suitable for detecting potato crop N stress and performs well in discriminating nitrogen status patterns (Cambouris et al., 2014). The relation between the Red – Edge Chlorophyll Index and the AGN is used to estimate the N-content in the aboveground plant parts, which was one of the output parameters of the nitrogen balance used in this study.

Cohen et al., (2007) figured out that TCARI values were inversely correlated to NO_3-N concentrations in the petiole plant sap. Therefore, TCARI values increase with decreasing N levels. They found both linear and exponential relationships with high correlations between TCARI and petiole N content. Those results have not been found in this study. In this study both a linear and an exponential relation have been investigated, however we observed coefficient of determinations of 0.24 and 0.17 respectively. We investigated for all VI's as given in table 1 the correlation with the NO_3-N concentrations in the Petiole Plant Sap. The results of this assessment can be found in table 8. The TCARI/OSAVI vegetation index showed the highest coefficient of determination for the relation with the NO_3-N concentrations in the petiole plant sap for which we found a linear correlation with a coefficient of determination of 0.44. Kooistra et al., (2015) performed a similar analysis for four successive years of potato cultivation and they found a best fit coefficient of determination of 0.28 for a linear relation between TCARI/OSAVI and NO_3-N concentrations in the petiole plant sap. The goal of these analyses was to check whether CropScan reflectances can be used for the assessment of the NO_3-N concentrations in the Petiole Plant Sap. Based on the results of this study and the study of Kooistra et al., (2015), we can conclude that we did found a negative correlation between TCARI or TCARI/OSAVI values and NO_3-N concentrations in the petiole plant sap, however it is not a strong correlation.

5.2.2 Plant status assessment

Vitosh and Silva (1996) stated that there are many factors affecting the nitrate-nitrogen (NO_3-N) concentration in the petiole plant sap of potatoes. They stated that the following factors are the most important factors influencing the nitrate-nitrogen concentration: N-fertilizer applications, the amount of mineralizable soil N, time of sampling, position of the petiole on the plant, age of the plant, potato cultivar, time of the day when plants are sampled, and the environmental conditions prior to sampling. However, the results of this study showed that the development of the nitrate-nitrogen in the petiole plant sap is mainly influenced by the different N-treatments as can be seen in figure 21. The graph in this figure clearly shows the effect of sensor based fertilization with a peak in the NO_3-N concentration one week after the application of additional fertilizer for plot B, D, F and H. In which an increase in the level of nitrogen fertilization was followed with increase in the NO_3-N concentration. The results of our study show similar results than the study by Majic et al., (2009) in which one of the conclusions was that petiole plant sap for the leaves is highly responsive to N treatment in terms of measured nitrate concentrations, because leaves accumulate nitrates more than other parts of plants. Similar to our study, the results of Majic et al., (2009) and Vitosh and Silva (1996) showed that over the growing season the concentration of nitrate-nitrogen in the leaf petiole plant sap, declined with plant ageing, due to allocation and binding into organic compounds took place. As can be seen in figure 21 this decline of the NO_3-N concentration over time can be interrupted or delayed by in-season N applications.

The spatial and temporal variability of the aboveground plant nitrogen content (AGN) will be discussed in section 5.2.4. In this section we focus on the development over time of the AGN for the different plots as an indicator of the plant status and to show the effect of different N-inputs. As can be seen in figure 22 the aboveground nitrogen content is highly related to the N-inputs in which plot B which received the highest initial N fertilization in combination with sensor based fertilization has the highest AGN contents over the whole growing season. Those results are supported by the study of Ros et al., (2008) in which was shown that aboveground biomass, chlorophyll concentration and N content were significantly higher for potato plants cultivated with higher N inputs. Furthermore, we observe that the effect of the sensor based in-season fertilization is larger on the AGN content in the second half of the growing season than the initial fertilization rates. This can be observed due to the fact that the AGN content for all plots who received sensor based fertilization (Plot B, D, F and H) has larger values than the plots who only received a specific initial fertilization rate (Plot A, C, E and F)

The N-content in the tuber is determined differently from the other parameters discussed in this section, because it is not completely based on actual measurements. N_{tuber} is estimated based on actual lab measurements in combination with interpolation and extrapolation for the time period between and before those actual measurements. This interpolation is based on the study of Brown et al., (2011). Based on the extrapolations we observed that for this type of potatoes, Fontane, and under this particular field conditions, the nitrogen the tubers started to develop 7-8 weeks after they were planted.

5.2.3 Yield assessment

In table 9 an overview is given of the yield, the N content in the tuber when the potatoes were harvested, the N-fertilizer inputs and N-footprint per plot in kg/ha. In this table we observe that plot D has the highest yield and the highest N content in the tuber, with lower N fertilizer inputs than plot A and B. We observe that the effect of sensor based fertilization after application of high initial N-inputs does not lead to a large difference in the yield anymore as can be seen in the yield for plot A and B. However it is reflected in the N content in the tuber at the end of the growing season. The N-footprint as shown in table 9 is estimated with a model developed in the study of Leip et al., (2014) and is mainly based on the yield. In which the N-footprint can be calculated as 2 g N/kg harvested potato for food production in the European Union. So based on this study the N-footprint for plot D would be higher than for plot A and B. However, as can be seen in table 9, the N-inputs for plot A and B are higher than for plot D. Based on our N mass balance in which the outputs equals the inputs, the amount of N which leaches to the environment, the N-footprint, for plot A and B should be larger than for plot D. The results of our study are not in line with the results of the study of Leip et al., (2014) in which the N footprint for potato cultivation in the European Union can be directly calculated by taking 2 g N/kg harvested potato.

The efficiency of nitrogen fertilization is most commonly assessed by the magnitude of either quantitative or qualitative parameters of the yield (Kolodziejcyk, 2014). The N uptake efficiency (NUpE) is such a parameter and defined as the plant N accumulation per unit of N supply to the crop (Zebarth et al., 2008). Based on the N-uptake efficiency we have the following order for the plot: G>D>F>H>C>E>B>A, as can be found in table 10. These results show that a high initial N fertilization does not lead to an efficient N-uptake, since plot A and B have the lowest N-uptake efficiency. In the study of Kolodziejcyk (2014) nitrogen uptake efficiencies between 0.53 and 0.67 kg/ha kg/ha^{-1} have been found. These values are higher than the values found in this study ranging between 0.28 – 0.45 kg/ha kg/ha^{-1}. A possible reason for the higher NUpE is the lower N supply in the study of Kolodziejcyk, 2014, compared to our study. In the study of Kolodziejcyk, 2014 the N-supply ranges from 0 to 180 kg N/ha, for which the highest NUpE is found for a N-supply of 60 kg N/ha, with a corresponding yield of 18.6 to 44.2 ton/ha. In our study the N-supply ranges from 175 – 500 kg N/ha, for which the highest NUpE is found for a N supply of 254.4 kg N/ha. However, in our study the yield is ranging from 46.3 ton/ha to 96.1 ton/ha. The NUpE values found in our research correspond to the general nitrogen uptake efficiency values for potatoes which are ranging between 0.33 to 0.55 kg/ha kg/ha^{-1} (Errehbi et al., 1998; Alva et al., 2011).

Finally, we are also interested in the N-use efficiency (NUE). For the N-use efficiency we observe the following order for the plots: D>G>E>C>F>H>A>B. In the study of Kolodziejcyk (2014) the values for the NUE range from 33 – 43 kg/ha kg/ha^{-1}, in which the lowest fertilization rate resulted in the highest NUE. In our study the NUE values range from 192 - 346 kg/ha kg/ha^{-1}, in which the plot with the highest yield (plot D) resulted in the highest NUE.

5.2.4 Sensor based N-assessment at field scale

A previous study by Kooistra (2011) showed a good relation of the Fritzmeier instrument in determining the REP compared with the REP CropScan. Figure 25 shows that REP values measured by the Fritzmeier Isaria Sensor are underestimated compared with the REP measured with CropScan. This might be caused by the fact that for the calculation of the REP measured with the Fritzmeier a reflection band close to 820nm is used instead of a reflection band in the NIR. Another possible reason why the correlation we found this year is not very high is the effect of the time of the day at which the Fritzmeier Isaria Sensor has been used to measure the REP values compared with the time when the CropScan measurement took place. For some days the Fritzmeier data is obtained early in the morning (around 7 am) when the position of the sun was still low. For those early morning measurements a large part of the light reflected by the canopy comes from the light source the sensor has. This could lead to lower REP values. Furthermore we also observed that if the measurement day of the Fritzmeier was not similar than the measurement day of the CropScan larger deviations between the measured REP values were observed.

To be able to map the spatial variability in the aboveground nitrogen content for the potato crops we related the REP values to the laboratory measured aboveground nitrogen content. For this relationship we found a linear correlation equation with a coefficient of determination of 0.49 (figure 26). Kooistra (2011) found in a previous study for the relationship between the REP measured with the Fritzmeier sensor and the aboveground plant nitrogen content an exponential relationship with a coefficient of determination of 0.75. The lower coefficient of determination for the relation of this year can be caused by the relatively low REP measured this year with the Fritzmeier sensor. The relationship for this year has been used to map the spatial variability in the AGN for this field. However, if we compare the correlation of the REP CropScan to the AGN with the correlation between REP Fritzmeier to the AGN we observe that the REP Fritzmeier has a higher coefficient of determination than the REP CropScan (0.49 vs 0.10). So, based on these results we can conclude that the Fritzmeier sensor can be used to determine the Aboveground plant nitrogen content. However, if the Fritzmeier determines the reflectances at more and/or different spectral bands than it does now, e.g. also at 780nm and 710nm than other vegetation indices could be calculated like the CIre for which a higher correlation can be expected, as seen in table 8.

In the maps of the aboveground plant nitrogen content we can observe the allocation of N over the growing season (figure 27). This allocation becomes clear due to a decrease in the N content in the aboveground plant parts if the growing season proceeds. This N allocation can also be observed in the plots of the cumulative N mass balance (figures 28-31), for which the N content in the aboveground plant parts decreases when the N content in the tubers increases. Brown et al., (2011) stated that N is allocated to the plant parts based on the highest priority plant organ. If the minimum N demand of the highest priority organ is fulfilled than N will be allocated to the second highest priority organ. For potato the order of priority is tuber > root > leaf > stem. Furthermore Brown et al., (2011) stated that the potato plant prefers to use the amount of N, which has already been taken up by the plant and converts this amount into useful organic forms necessary for a specific organ instead of taking up additional mineral N. Hence, the plant will only take up the amount of N it directly needs, if the total N demand is less than the uptake supply the crop will leave the surplus mineral N in the soil. For plot E, the 0-plot, the development of the N-content in the tubers and therefore the transition between the largest component in the plant (aboveground plant parts or tuber) occurs at a later moment in the growing season than for the other plots. This is mainly caused by N-shortage.

The maps of the aboveground plant N-content (figure 27) clearly show the influence of sensor based N-fertilization. Even after applying only once a sensor based fertilization amount the effect becomes clearly visible in the aboveground plant nitrogen content.

Besides the Fritzmeier, we also tested the use of the S::can Spectrometer Probe (nitrate sensor) in monitoring the nitrate concentration in the groundwater. The results of the assessment can be found in Appendix 6. As can be seen in this figure, we have only limited data available to make the comparison. As discussed in section 3.4.1. It took us a while to get the S::can Spectrometer Probe operating and store useful data from the data logger. One of the reasons was that the S::can Spectrometer Probe, which is normally used to measure concentrations of substances in rivers, was never used before to measure substances in groundwater. Furthermore, the groundwater in our study area is turbid and therefore we needed to order a special casing. This casing was used to shorten the path of the light beam, so we were still able to sense the nitrate concentration. Another disadvantage due to turbid groundwater was that the emitter and the receiver of the light beam needed to be cleaned with acid regularly, because after a couple of days the emitter and receiver were too dirty to measure. Therefore we have only for three weeks nitrate concentrations measured by the S::can Spectrometer Probe available (24/07 – 30/07, 19/08 – 25/08, 23/09 - 27/09) as can be seen in Appendix 6. The only assessment we could perform is to check whether the measurements with the S::can Spectrometer Probe are in the same measurement range than the measurements of the nitrate content in the groundwater determined with the Spectroquant Nova 60 – Nitrate cell test. However, in those three weeks mentioned above we have only 4 measurement days in which we determined the nitrate content in the groundwater. Since the sample size is too small we decided not to perform a statistical analysis for the S::can Spectrometer Probe. As can be seen in Appendix 6 for some days the values are closely related, however for other days the difference is with 5.0 mg/L relatively large. This can be solved by calibrating the sensor with more than one sample, since now it is only calibrated for one sample. Therefore, we cannot really conclude whether or not the S::can Spectrometer Probe is able to determine the nitrate content in the groundwater. However, due to the limitations as mentioned earlier caused by the turbid groundwater in this study area, it is not feasible to use this sensor to sense the nitrate concentration for this agricultural field.

5.3 N-mass balance over time

As can be seen in the cumulative nitrogen balance for the different plots (figure 28-31, 39-42) the total leaching term for the different plots ranges from 129 - 356 kg N/ha. Other studies reported that for potato grown on sandy soils, nitrate leaching values were ranging between 100 - 200 kg N/ ha (Meisinger, 1976), 135–215 kg N/ ha (Saffigna et al., 1977), and 78–220 kg N/ ha (Hill, 1986). In the study by Kraft and Stites (2003), the N loading under potato cultivation at the Wisconsin Central Sand Plain was measured as 228 kg N/ ha per year. The losses we presented are calculated for the period between planting and harvesting. The average daily loss ranges between 0.80 - 2.20 kg N/ha. By assuming an equal N leaching rate for the whole year this leads to values ranging from 292 – 803 kg N/ha per year. Therefore we can conclude that the absolute leaching amounts as found in this study are larger than the amounts measured in other studies.

Of the total N input, the contribution of $N_{fertilizer}$ ranged between 19% for 0-plot E and 70% for plot B. These values are lower than the $N_{fertilizer}$ inputs estimated in the study of Prasad et al., (2015) in which the contribution of $N_{fertilizer}$ ranged between 79 to 82%. The second highest nitrogen input parameter is the N from mineralization of soil organic matter and previous crop residues. In this balance the contribution of $N_{mineralization}$ is ranged between 27% for plot B to 73% for plot E. These values are higher compared to the values found in the study by Prasad et al., (2015) in which $N_{mineralisation}$ contributed only for 13-16%. In this study we used for the estimation of $N_{mineralisation}$ the results published in the studies by van Dijk and van Geel (2012) in combination with the study by Van Haecke (2010). Van Dijk and van Geel (2012) estimated a N mineralisation input for potatoes of 1 (±0,2) kg N per ha per day over the whole growing season and based on the study by Van Haecke (2010) a mineralisation of 140 kg N/ha was estimated for similar soils in "De Kempen", however not for potato cultivation, but for Floriculture. We used these values and estimated the total $N_{mineralisation}$ in our study as 138 kg N/ha. This could be an overestimation, especially compared with the $N_{mineralisation}$

values found in the study by Prasad et al., (2015) of 43 to 51 kg N/ha for sandy soils in Florida.

In the study of Prasad et al., (2015), the environmental N loading via leaching was 25 to 38% of the total N input. Giletto and Echeverria (2015) reported mean N leaching losses of 12 to 57% to the groundwater and Verhagen (1997) found N leaching losses of 38% of the applied N for potato production on clay and loamy soils in the Netherlands. Whereas, in our study $N_{leaching}$ ranges from 57% (Plot G) to 73% (Plot A) of the amount of N supplied. In which we observe the same order than for the N-uptake efficiency between the different plots: $G<D<F<H<C<E<B<A$. However, in our study $N_{leaching}$ consists of the losses due to leaching to the groundwater and gaseous losses via volatilization and denitrification pathways. As stated in section 3.1.2 gaseous losses of N via denitrification and volatilization have been assumed to be small in magnitude in well drained soils for potato production, in which the organic manure was applied by injection. To be able to quantify these gaseous N losses by volatilization we follow the approach as mentioned in the study by Prasad et al., (2015), in which the results of the study of Liu et al., (2003) have been used to quantify the percentage of N-losses by denitrification and volatilization. In this study by Liu et al., (2003), the measured gaseous N losses during a 2-year rotation with winter wheat and maize grown were found to be between 4 to 7% of the fertilizer N-inputs. By taking into account these values we observe that the leaching losses to the groundwater as found in this study are still higher than the values found in other studies. Furthermore, the amount of N which leaches to the groundwater is also overestimated, due to residual plant parts destroyed 2-3 weeks before harvesting, but still partly present in the soil. The aboveground plant nitrogen content, determined 4 weeks before harvesting, still accounted for 2 to 13% of the total amount of N outputs, with an average of 5%. After destroying the aboveground potato plants this amount of N becomes available in the soil and is still partly present in the soil at our last measuring date. However in the final N-mass balance this amount is included in the N leaching losses. Even though taking into account this parameter the $N_{leaching}$ is still the major loss parameter in our N mass balance. A possible explanation for these high N leaching losses found in this study compared with the study of Verhagen (1997) is the poor N and water holding capacity of sandy soils found in this study area compared with the clay and loamy soils in the study of Verhagen (1997). The results of this study are in accordance with Levallois et al., (1998) in which was stated that areas with sandy soils, which are intensively cultivated with potatoes or other crops, demand higher N fertilizer inputs and have therefore higher N leaching losses than clay or loamy soils.

As mentioned earlier leaching is a major loss parameter for the different N mass balances of this study. The source of the N leaching losses found in this study could originate from direct sources, such as fertilizer N inputs (considered as direct leaching), or from indirect sources, such as mineralization of soil organic matter or left over plant residues (considered as indirect leaching). In this study, fertilizer N inputs contributed for 19 to 70% towards the total input of N, with an average value of 55% for the contribution of $N_{fertilizer}$ to the total N-inputs. Whereas for mineralization of soil organic matter and crop residue contributed for 27 to 73% of the total N inputs, with an average value 41% for the contribution of $N_{mineralization}$ to the total N-inputs. Therefore, we can conclude that the contribution of direct sources towards N leaching is higher than the indirect causes. However, in the study of Prasad et al., (2015) direct sources towards N leaching play a more important role than in our study. This might be caused by the poor N and water holding capacity of the sandy soils found in Florida Prasad et al., (2015).

5.4 Reflection based on research questions

In this subchapter we reflect on the results obtained in this study by looking at the research questions defined in subchapter 1.3.

The first research question is about which parameters in the soil and crop influence the nitrogen balance. In section 3.1 we have discussed a theoretical N-mass balance (formula 15, 16 and 17) and how based on the assumptions we simplified this theoretical N-mass balance into the final N-mass balance used in this study (formula 18, 19 and 20). This N-mass balance is used to design the graphs as given in figure (28-31 and 39-42). The results of this thesis showed that nitrate leaching to the groundwater is recognized as a major loss parameter, with higher N leaching values compared with the values found in previous studies in which a N-mass balance was designed. However, this could be partly caused by the overestimation of the mineralization input pool. Since, leaching is the closing parameter of this N-mass balance, an overestimation of $N_{mineralization}$ will automatically result in an overestimation of the amount of N leaching. Reflecting to research question 1, the N-mass balance as recognized in this study is mainly influenced by the N inputs due to N fertilization amount in combination with N mineralization. The outputs are mainly influenced by the N content which is taken up by the plant (N_{tuber} and N_{aerial}) and the N content what leaches to the losses due to leaching to the groundwater and gaseous losses via volatilization and denitrification pathways. In which leaching losses to the groundwater are the main leaching losses.

For the second research question we related the spatial variability of soil properties (e.g., thickness and SOM content of the A-horizon) to the variation in the nitrogen content of the topsoil. We calculated based on the EC-values, determined with the Dualem 21-s sensor, and the relationship of Koumanov et al., (2001) the NO_3-N content in the soil. The values found were strongly influenced by the moisture content in the soil. This resulted into an overestimation of the NO_3-N content in the soil in the upper area of our study field. The NO_3-N content found for the other areas in this field were in accordance with the lab analysis by BLGG AgroXpertus for the field next to our study area. However, comparing the map of the organic matter content with the map showing the spatial variability of the NO_3-N content in soil, which is closely related to each other, shows us a different spatial distribution. For example a higher organic matter content does not lead to a higher NO_3-N content in soil. The map of the organic matter content in the topsoil is based on actual measurements. Therefore based on the visual assessment of the spatial variability between the NO_3-N content in the soil and the spatial variability of the soil organic matter measurements we could conclude that an assessment of the spatial variability in the N content of the soil by using the EC-values does not result in a reliable estimation of the spatial variability in the N-content.

In the third research question we focus on how accurate the nitrogen concentration in the soil and crop can be measured over the growing season by using remote and proximal sensing based methods. From the parameters recognized in the nitrogen mass balance as given in formula 18, 19 and 20, we have measurements available for the nitrogen content in the aboveground plant parts and the potato tubers. Furthermore, we know the exact amount of the N fertilizer added and we have measurements available of the nitrogen content in the topsoil, groundwater and the unsaturated zone. The development of the nitrogen content in the aboveground plant parts within the plots is determined by the relationships between the VI's based on CropScan reflectances and the AGN lab-analysis by TTW. For which the highest coefficient of determination (R^2 = 0.62) is found for the correlation by using the Chlrophyll Red Edge Index (Clre). In this study we used the correlation relation belonging to this relationship to determine the aboveground plant nitrogen content used as one of the output parameters in the nitrogen mass balance. To evaluate the use of remote and proximal sensing we evaluated the use of the Fritzmeier Isaria Sensor in determining the aboveground plant nitrogen content and the S::can Spectrometer Probe (nitrate sensor) in monitoring the nitrate concentration in the groundwater. As discussed in section 5.2.4 the Fritzmeier Isaria Sensor can be used for determining the aboveground plant nitrogen content at field scale with a corresponding coefficient of determination of 0.49. Furthermore as is discussed as well in section 5.4.2 we evaluated the use Spectrometer Probe (nitrate sensor) in monitoring the nitrate concentration in the groundwater. However, due to practical problems we cannot really conclude whether the S::can Spectrometer Probe is able to determine the nitrate content in the groundwater. Furthermore as discussed earlier we showed that Dualem 21-s sensor, in combination with the relationship of Koumanov et al., (2001) does not lead to reliable estimates of the NO_3-N content in the soil.

To determine how the nitrogen balance is influenced by the different treatments of N-inputs we evaluated several parameters. We determined the parameters influencing the current aboveground plant status (AGN, Petiole NO_3-N plant sap, Leaf Chlorophyll Concentration, Leaf Area Index, Canopy Chlorophyll Concentration), the potato N-tuber concentration and the N-content in the topsoil. In addition we evaluated the yield for the different treatments and based on the yield in combination with the final N-content in the tuber we evaluated the N-footprint, N-uptake efficiency and N use efficiency. In general we observe the effect of in-season fertilization of N in the nitrogen content in the aboveground plant nitrogen content in the plant, but also in the other parameters determining the plant status. The fertilizer effect is generally visible 1-2 weeks after application. The plots which received a high initial fertilization rate in combination with in-season sensor based fertilization have higher N and chlorophyll concentrations than the plots which received a low initial fertilization and/or no in-season N fertilization. This effect is also visible in the N-mass balances. The time series of the N content in the potato tubers show that for the concentrations at the beginning of the growing season the amount of N present is mainly determined by the initial fertilization and later on in the growing season the N content in the tubers is more based on in-season sensor fertilization. For the N-content in the topsoil we observe similar patterns than for the N-content in the plant. In which the additional sensor based fertilization leads to a peak value, however 2-3 after the application the concentrations in the soil drop to concentration slightly higher than the concentrations found in the plots that did not get in-season fertilization. For the yield and for the NUE we observed that plot D, the plot with the second highest initial fertilization zone (162 kg N/ha) in combination with in-season sensor based fertilization scored the best. However, for this plot we also determined that 61% of the N leaches. The NUpE was highest for the plot G, this plot received the second lowest initial fertilization rate (90 kg N/ha) and no additional sensor based fertilization. However for this plot we found also the second lowest yield.

6. CONCLUSIONS & RECOMMENDATIONS

In this section, an overview of conclusions about the main findings related to the nitrogen mass balance for an agricultural parcel of potato crops by using sensing based methods is given. Furthermore, in the recommendations we discuss how to reduce the uncertainties based on the methodology of this study and we provide some strategies related to the reduction of nitrate leaching into the groundwater.

The first research question, which parameters influence the nitrogen balance for an agricultural field of potatoes is presented by formula 15, 16 and 17. This N mass balance equation, which is based on literature studies, has been modified to the balance presented in formula 18, 19 and 20. This equation is adopted for the soil-cropping system as found in our study area. In this balance the following input parameters are recognized: $N_{fertilizer}$, $N_{mineralisation}$ and $N_{deposition}$. The outputs as identified in this simplified N-mass balance are N_{aerial}, N_{tuber} and $N_{leaching}$. In which $N_{leaching}$ is the closing parameter, comprising the leaching losses to the groundwater and gaseous losses via volatilization and denitrification pathways. Based on the results of our study we can conclude that $N_{fertilizer}$ and $N_{mineralisation}$ are the largest input-parameters and N leaching losses are quantified as the largest output parameters with values between 57 and 73%. The highest uncertainty is found for the estimation of $N_{mineralisation}$, which therefore influences $N_{leaching}$.

It is important to know the spatial variability of N in the soil before application of N-fertilizer. In this study we used the spatial variability of some soil properties (Electrical Conductivity, SOM content and thickness of the A-horizon) to determine the variation in nitrogen in the soil. We used the EC-values to determine the NO_3-N-content in the soil. Validation of the NO_3-N-content in the soil, based on the lab-analyses for the neighbouring field, showed promising results. However, visual assessment of the NO_3-N content map (figure 14) with the map showing the spatial variability in the total soil organic matter content (figure 12), which is closely related to the N content in the soil, showed large differences. Based on this we can conclude that determining the spatial variability in the N content of the soil by using the EC-values does not result in a reliable estimation of the spatial variability in the N-content.

In this study we evaluated the use and accuracy of the CropScan Multispectral Radiometer, the Fritzmeier Isaria Sensor and the S::can Spectrometer Probe for sensing the aboveground plant nitrogen concentration at canopy scale, at field scale and the nitrate concentration in the groundwater, respectively. The results for the years 2012, 2013 and 2015 showed that the best vegetation index related to the aboveground plant nitrogen content is the Chlorophyll Red Edge Index (Clre), described with an exponential correlation equation and a corresponding R^2 of 0.62. For the relationship between the red-edge position (REP) as sensed with the Fritzmeier Isaria sensor and the aboveground plant nitrogen content, we found a linear expression with a R^2 of 0.49. Both relationships have been used in this study to determine the aboveground plant nitrogen content at canopy scale (CropScan) and at field scale (Fritzmeier). Due to practical limitations caused by the turbid groundwater in this study area, in combination with the difficulties in getting the S::can Spectrometer Probe operating we have to conclude that this nitrate sensor is not yet feasible to sense the nitrate concentration in the groundwater for this agricultural field.

The results of this study clearly have shown that the nitrogen balance is influenced by different treatments of N fertilizer. This effect is mainly present in the aboveground nitrogen content and the N content in the potato tubers, but also in the leaching to the groundwater. The different plots showed that the highest yield in combination with the highest N use efficiency is obtained for the plot D. This plot received the second highest initial N fertilization (162 kg N/ha) rate in combination with in-season sensor based N fertilization. The highest N-uptake efficiency, in combination with the lowest N-leaching percentage, is found for plot G. Which received the second lowest initial fertilization level, without any sensor based fertilization. Therefore, by only looking at N leaching, the management practices of plot G would be advised. However, by also taking into account the yield, the management practices of plot D are preferred. Moreover, plot D resulted in the second lowest N leaching fraction.

The overall results of this study have shown that leaching losses have been recognized as a major loss parameter in the nitrogen balance. The leaching losses found in this thesis exceed the leaching values found for cultivation of potatoes in other studies. Even though these values could be partly caused by an overestimation of the amount of N which becomes available for the plant by mineralisation, these values are still substantial high. Nitrate leaching is recognized as one of the major environmental concerns for agriculture within the European Union and therefore we present in the recommendations several strategies which, based on the results of this study, might be implemented to protect ground and surface water against pollution with nitrate (NO_3^-) in Europe.

Recommendations

The parameters of the nitrogen balance, as presented in this study, consist of actual measurements in combination with estimations and assumptions based on literature studies. The results of this study have shown that especially these estimations results in uncertainties and possible overestimations. To reduce these uncertainties measurements of the actual N loading to the groundwater are necessary. Kraft and Stites (2003) presented in their study a way to estimate nitrate loading to the groundwater based on a novel “water year” method in which N-concentrations in the groundwater were measured over 4 consecutive years in combination with a N-budget approach. Furthermore, as the results of this study showed the uncertainty in the estimation of N mineralisation lead to an overestimation of the leaching parameter. As discussed in section 3.1.2, the amount of nitrogen which becomes available by mineralisation of organic matter can be calculated by multiplying the total amount of soil organic matter with the nitrogen fraction in the soil and the specific N mineralisation rate for this soil. Actual measurements of the nitrogen fraction in combination with a reliable determination of the N mineralisation rate could provide a more accurate estimation of $N_{mineralisation}$ and therefore a lower uncertainty in the N leaching losses.

One of the outcomes of this thesis is that nitrate leaching to the groundwater is recognized as a major loss parameter in this thesis. The paper of Shrestha et al., (2010) presents several strategies to reduce nitrate leaching into the groundwater from potato production in sandy soils. These strategies can be summarized into five categories: 1) Nitrogen Management, 2) Irrigation Management, 3) Cover Crops and Residue Management, 4) Soil Amendments and 5) Site-Specific N management.

Nitrogen management is considered as applying the right source of N at the right time and place, and matching the N fertilizer application rate with the crop needs. In which the goal is to increase N use efficiency, N uptake efficiency and therefore reduce NO_3^- leaching.

Especially the N-uptake efficiency could be increased, since these values are in this study ranging between 28 and 45%. The plots for which we determined the highest uptake efficiency were those plots which had the second lowest initial fertilization rate (90 kg N/ha). For which in-season additional sensor-based nitrogen fertilization could lead to both an increase in the N-uptake efficiency as in the yield, as shown by the results of plot D. Especially the plots with the highest initial fertilization rate of (252 kg N/ha) were recognized as plots with a low N-uptake efficiency.

Irrigation management is considered as management of the irrigation water amount and timing by taking into account the water-holding capacity of soil, evaporation, precipitation and the current crop growth stage to reduce NO_3^- leaching (Shrestha et al., 2010). The results of this study showed that N-fertilization directly followed by irrigation resulted in higher nitrate concentrations in the groundwater and in the unsaturated zone (figure 16 and 17). In the current management practices irrigation is performed by applying a relatively large amount of water (25mm) in a short period of the time to soil. The NO_3^- leaching rate could be reduced by applying a smaller amount of water to the soil, but increase the frequency of irrigation over the growing season.

Cover crops and residue management increases the N-content in the soil and capture more NO_3^-, especially if they have a deep rooting system. The farmer in this study already applies cover crops and the effect of the different cover crops is outside the scope of this study.

Increasing soil amendments by increasing the soil organic matter (SOM) content could lead to an increase in the water and nutrient retention, in combination with an increase of the N use efficiencies. However, excessive addition of organic matter in a short time period might enhance NO_3^- leaching when OM is mineralized. The results of this study with an estimated average N mineralization nitrogen pool of 41% showed that the amount of soil organic matter in this study is already relatively high and therefore causes indirect leaching losses of NO_3^-. However, as discussed earlier this estimated mineralisation pool, might by an overestimation of the actual mineralisation in this field.

Site-specific N management by variable rate nitrogen application could lead to a reduction in the leaching losses of NO_3^-. The farmer for who we performed this study already applies variable rate in-season sensor-based nitrogen application by using the Fritzmeier Isaria Sensor. The results of this study showed that the plots receiving in-season sensor based fertilization have a higher yield than the plots located in the same initial fertilization zone, without getting in-season sensor based fertilization. Until now the spatial variability in soil characteristics is not considered when applying variable rate in-season nitrogen application. By taking into account this spatial variability in soil properties when applying variable rate nitrogen fertilizer the N use efficiency and N uptake efficiency could be increased and NO_3^- leaching could be reduced.

These measures are generally focussing on increasing the N use efficiency in combination with improving water management. Some of these measures might be applied for this field to reduce nitrate leaching into the groundwater from potato production in sandy soils. Furthermore these measures could be used to further optimise the N management in agriculture and reduce nutrient losses and eutrophication by nutrients from agricultural sources, which is still a major environmental concern in Europe.

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APPENDICES

Appendix I Assumptions location Wells and Rhizons

In this appendix we describe how we made the assumption to determine the N- content in the groundwater and in unsaturated zone.

To determine $N_{leaching}$, the amount of nitrogen which leaches from the topsoil (0-20cm) to the deeper soil layers and even to the groundwater, we performed several measurements, however we also needed to make some assumptions. We have weekly measurements of the Nitrate concentration in the groundwater available. This was possible since four wells have been placed in the field. The experimental set-up, with the locations of the wells is described in section 3.2.2 and visualized in figure 5. However, due to miscommunication two wells were located in the 0.5 (90 kg N/ha) initial fertilization zone and two wells are located in the 1 (162 kg N/ha) initial fertilization zone. Instead of one well for every distinct initial nitrogen fertilization rate (0, 90, 162 and 252 kg N/ha). Therefore, we made the assumption that the values for the 0 initial nitrogen fertilization rate are represented by the wells in the 0.5 (90 kg N/ha) initial fertilization zone. The same is true for the 2 (252 kg N/ha) initial nitrogen fertilization zone, which is represented by the wells in the 1 (162 kg N/ha) initial fertilization zone. Another assumption that we needed to make is about the location of the wells compared to the plots. The wells were not located in the same fertilizations strips as the plots. Therefore, the potato plants in these fertilization strips got a different fertilization scheme as the potato plants in the plots studied in this study. We assume that the influence of this different fertilization scheme is not too strong on the nitrate measurements in the groundwater.

We also measured the amount of nitrogen/nitrate which leaches to the unsaturated zone. This is the zone between the topsoil and the groundwater level (saturated zone). To determine the N content in this zone rhizons have been placed. Close to all four wells three rhizons are located to determine the N content at three different depths, namely at 25 cm, 50 cm and 75 cm. Like for the nitrate concentration in the groundwater we have also weekly measurements of the nitrate concentration in the rhizons available. However, since we did not have a lot of experience with placing rhizons in a sandy soil, this experiment could be considered as a test case. This experiment showed that especially during dry periods and when no irrigation took place the rhizons did not succeed in subtracting water from the unsaturated zone. Therefore, we need to make assumptions for the moments when we do not have any measurements available. The assumption we made is that for that specific moment the nitrogen content in that zone is the average of the nitrogen content in that zone one week earlier and one week later. In addition we needed to make the same assumption as for the nitrogen content in the groundwater. Since the rhizons are located close to the wells. So the values for the 0 initial nitrogen fertilization rate are represented by the rhizons in the 0.5 (90 kg N/ha) initial fertilization zone. The same is true for the 2 (252 kg N/ha) initial nitrogen fertilization zone, which is represented by the rhizons in the 1 (162 kg N/ha) initial fertilization zone.

Appendix 2 Electrical Conductivity Maps

Figure 32. Map of the spatial variability in the electrical conductivity for the soil layer 0-1.0m in mS

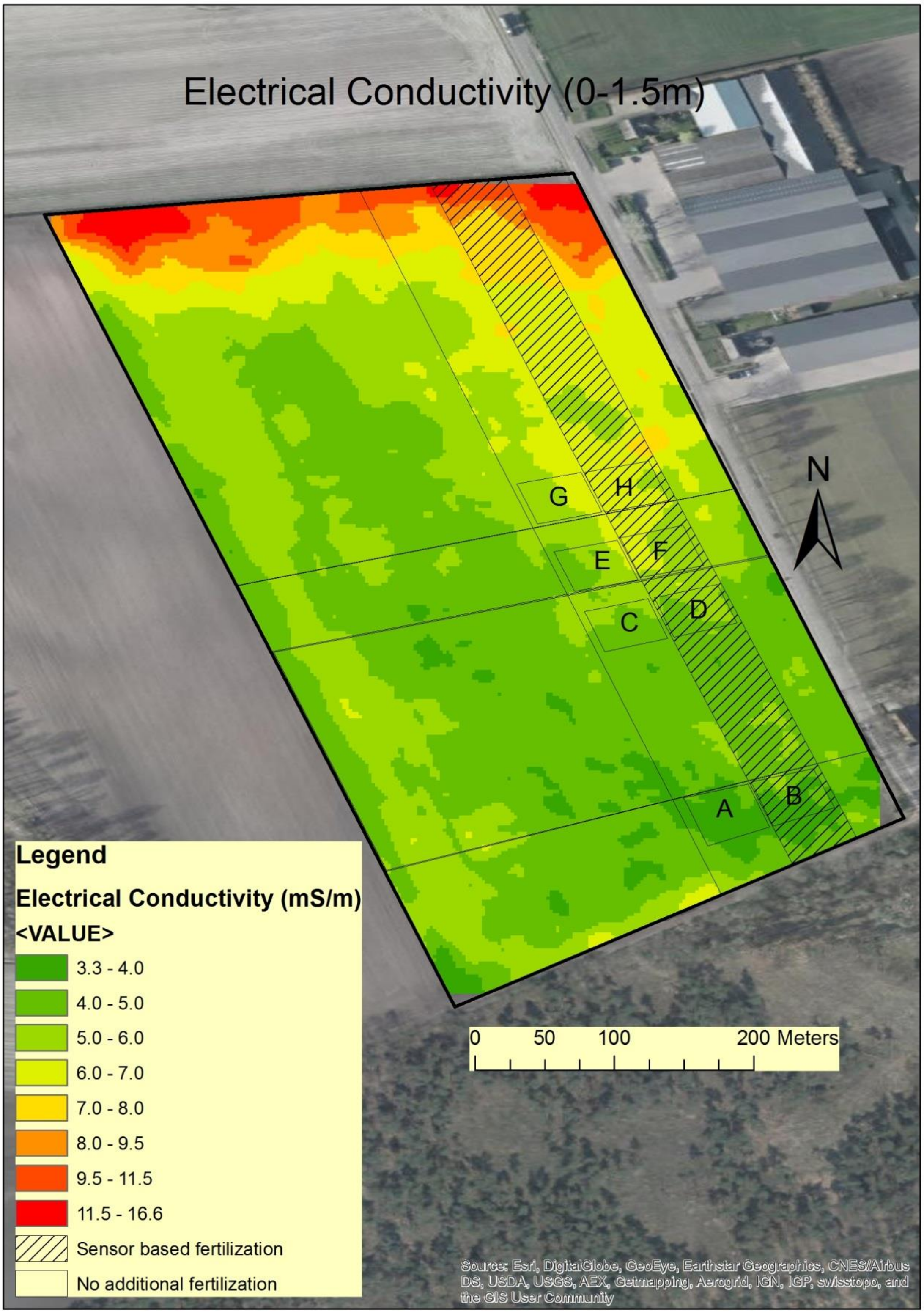

Figure 33. Map of the spatial variability in the electrical conductivity for the soil layer 0-1.5m in mS

Figure 34. Map of the spatial variability in the electrical conductivity for the soil layer 0-3.0m in mS

Appendix 3 Groundwater nitrate reference value Bladel

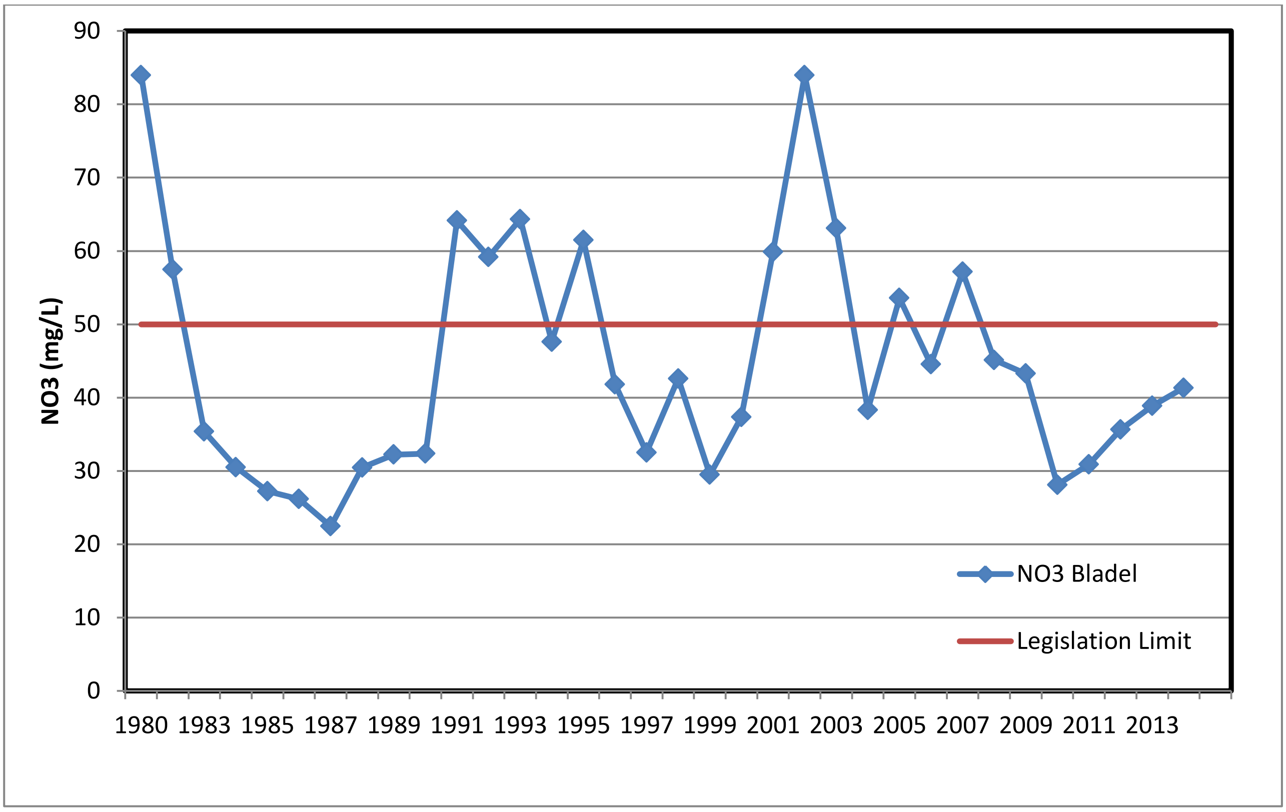

Figure 35. Time course of the NO_3^- concentration as measured by RIVM for the closest monitoring well in Bladel.

Appendix 4 Parameters determining Plant Status

In this appendix we describe the dynamics of some parameters which are not directly related to the N content in the plant, however they give us more information about the development of the vegetation status over the growing season.

One such a parameter, which can be used to determine the current plant status is the leaf chlorophyll concentration (LCC). In figure 36 the development of the leaf chlorophyll concentration over the growing season is given. In this figure we observe more or less the same pattern as in the graph for the NO_3-N concentrations in the petiole plant sap. In which the plants which do not receive any additional fertilizer input during the growing season decrease after the general peak concentration which was measured at 15 June. Therefore, the plots A, C, E and G have the lowest leaf chlorophyll concentrations at the end of the growing season. In the plots B, D, F and H, which did receive additional fertilizer amounts based on the crop demands determined with the Fritzmeier sensor, we observe some peaks later on in the growing season as well. Different than the peaks observed in the NO_3-N concentrations in the petiole plant sap occur those peaks not directly the first time we sampled after fertilizer application, but more or less two weeks later.

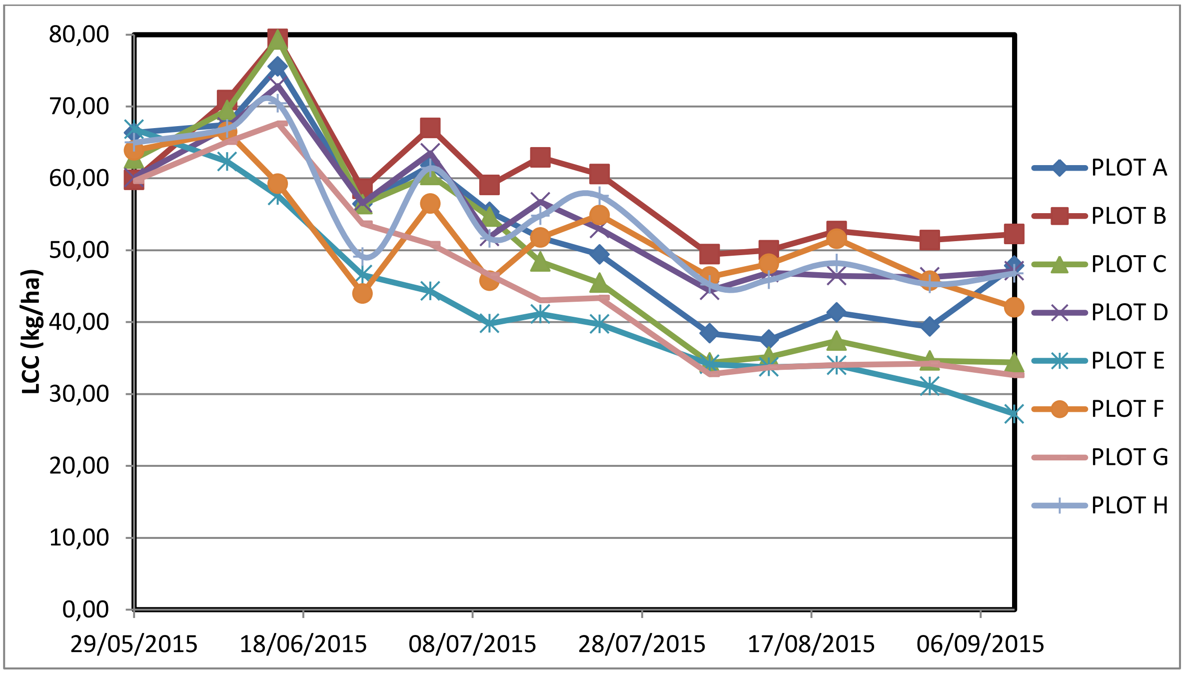

Figure 36. Development of the leaf chlorophyll concentration over time for the different plots.

Figure 37 shows the development of the leaf area index (LAI) over time. In this graph we observe that in the beginning of the growing season the LAI is mainly determined by the initial fertilization management zones, but later on the application of the sensor based additional fertilization becomes more important for the LAI, which leads to higher LAI values for the plots which received the sensor based additional fertilization and lower LAI values for the plots which did not receive additional fertilization. This pattern becomes especially clear if we look at the development in plot F over time. In the beginning of the growing season we found in this plot the lowest LAI values because it is in the 0 initial fertilization zone. However later on in the growing season when for the first time sensor based fertilization took place (17 June) the LAI in this plot starts increasing. Afterwards the LAI in this plot kept increasing until a specific maximum is reached and then it slowly decreases. For plot A which was in the highest initial fertilization we found a different curve. The LAI for the plants in this plot increases strongly in the beginning of the growing season in which it reaches a maximum of 9 at 25 June. However after this peak value is measured the LAI also decreases rapidly to LAI values close to the values measured for the other plots which did not receive any additional fertilization during the growing season.

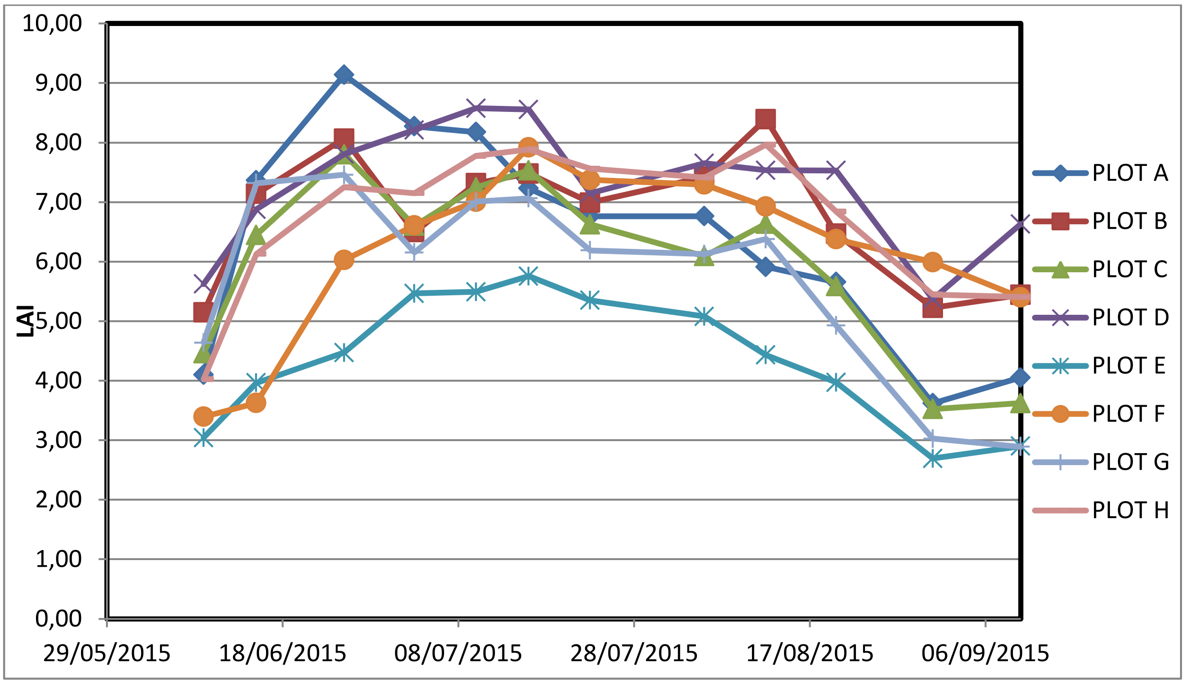

Figure 37. Development of the leaf area index over time for the different plots.

Another parameter which is closely related the leaf chlorophyll concentration and the leaf area index is the canopy chlorophyll concentration. Figure 38 shows the development of the canopy chlorophyll concentration over time. Since this parameter is calculated as a combination of the leaf chlorophyll concentration and the leaf area index it follows also the patterns of these parameters. It has the same peak value at 17 June as the leaf chlorophyll concentration. After reaching this peak value the canopy chlorophyll concentration decreases until the end of the growing season. Furthermore also the same peaks are observed 1-2 weeks after application of the sensor based fertilization application for plot B, D, F and H.

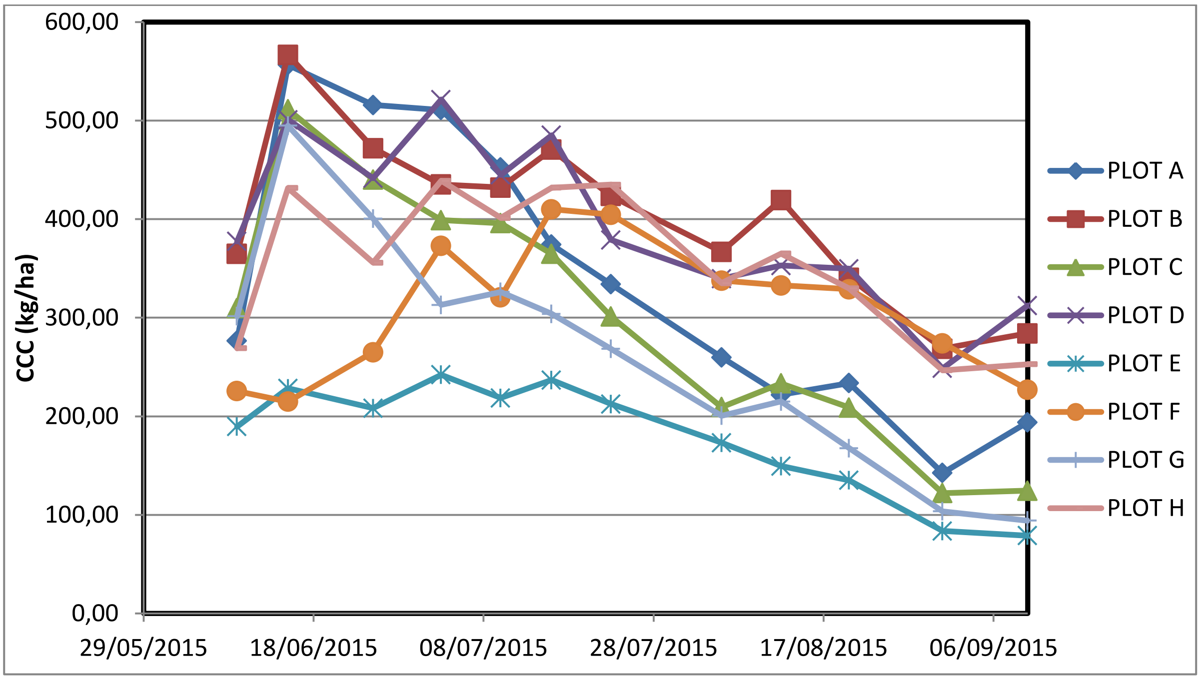

Figure 38. Development of the canopy chlorophyll concentration (kg/ha) over time for the different plots.

Discussion

The leaf chlorophyll content and the canopy chlorophyll content are closely related to N fertilizer inputs as can be seen in figure 36 and 38. Herrmann et al., (2010) stated that the chlorophyll content is physiologically linked to the amount of N, as the chlorophyll content is mainly determined by the N-availability. The results of our study correspond with the results obtained in the studies of Mauromicale et al., (2006) and Ros et al., (2008), in which the chlorophyll content increased significantly with increasing nitrogen fertilizer rates, but decreased significantly with plant ageing. This pattern can also be seen in figure 36 and 38 in which we observe that the chlorophyll content increases significantly when sensor based fertilization was applied, however over the growing season the general trend in the chlorophyll content shows a decrease in the leaf chlorophyll content and the canopy chlorophyll content caused by plant ageing. In which the plots which received a higher total N-input have the highest final chlorophyll concentration.

Appendix 5 Cumulative Nitrogen Balance

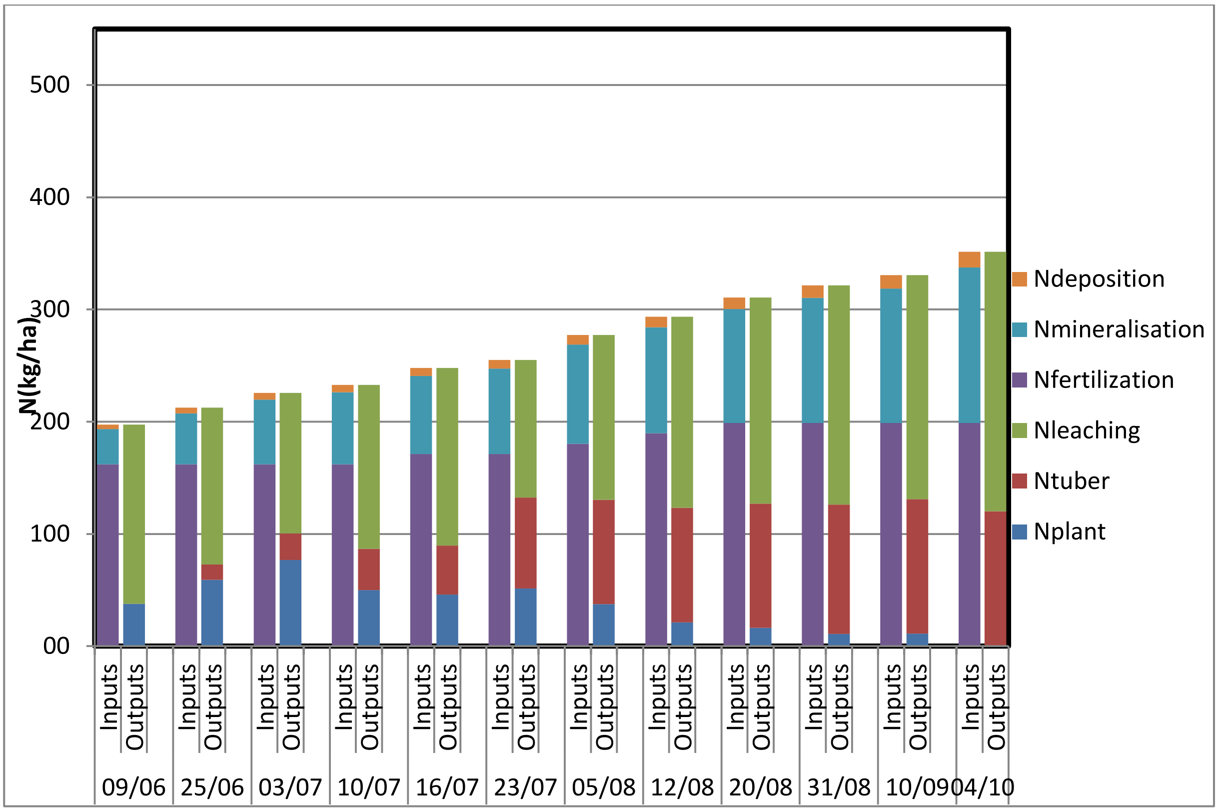

Figure 39. Cumulative nitrogen mass balance for plot C.

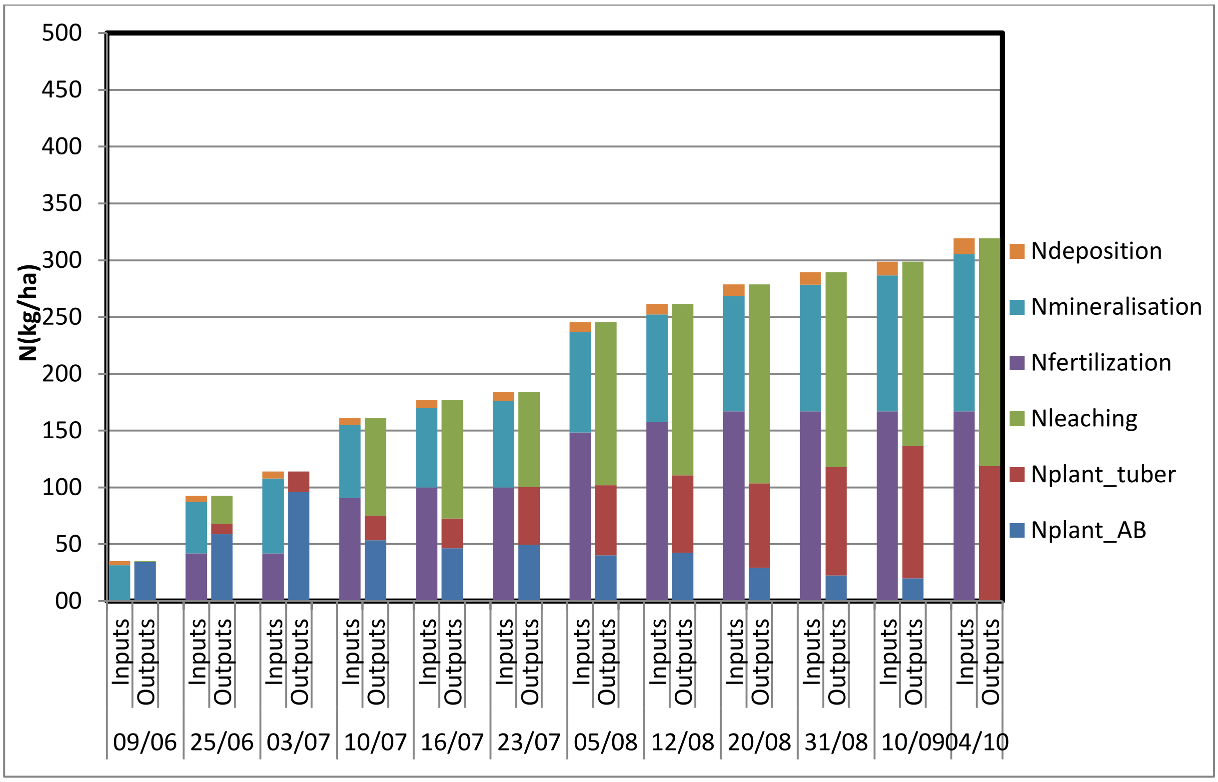

Figure 40. Cumulative nitrogen mass balance for plot F.

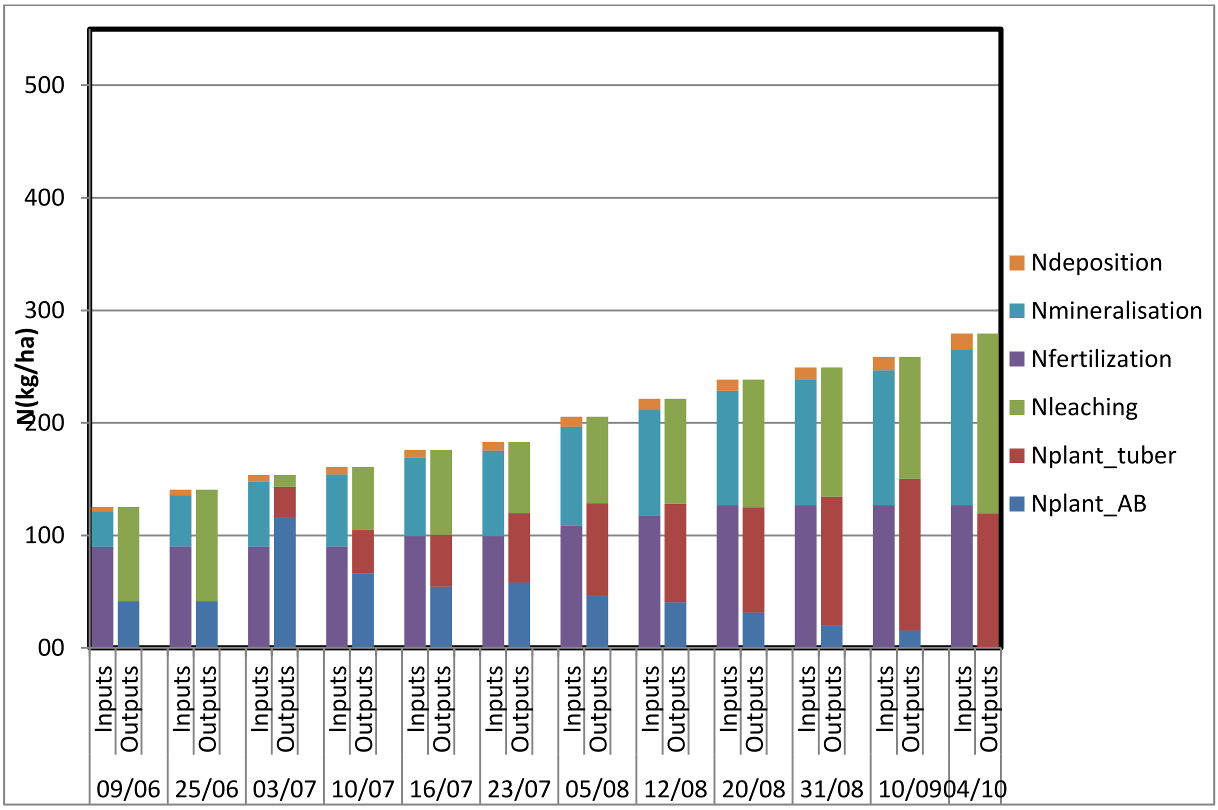

Figure 41. Cumulative nitrogen mass balance for plot G.

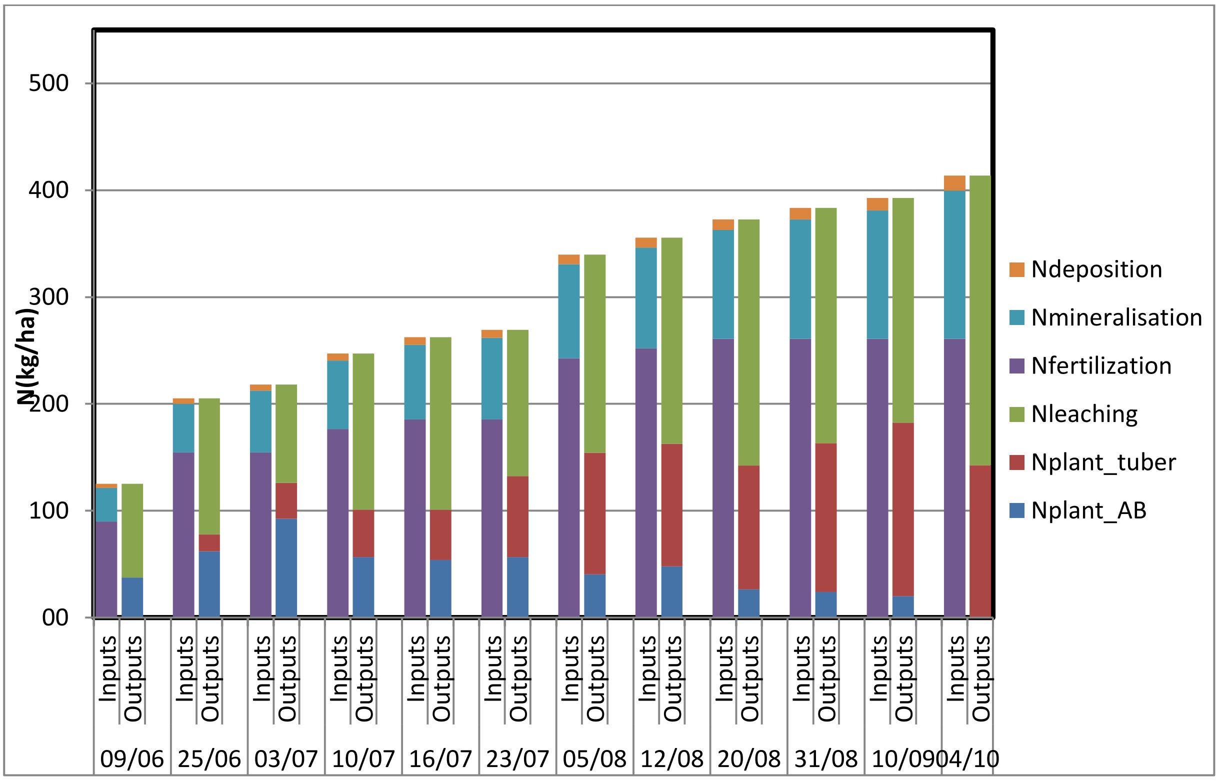

Figure 42. Cumulative nitrogen mass balance for plot H.

Appendix 6 Sensor based monitoring nitrate groundwater

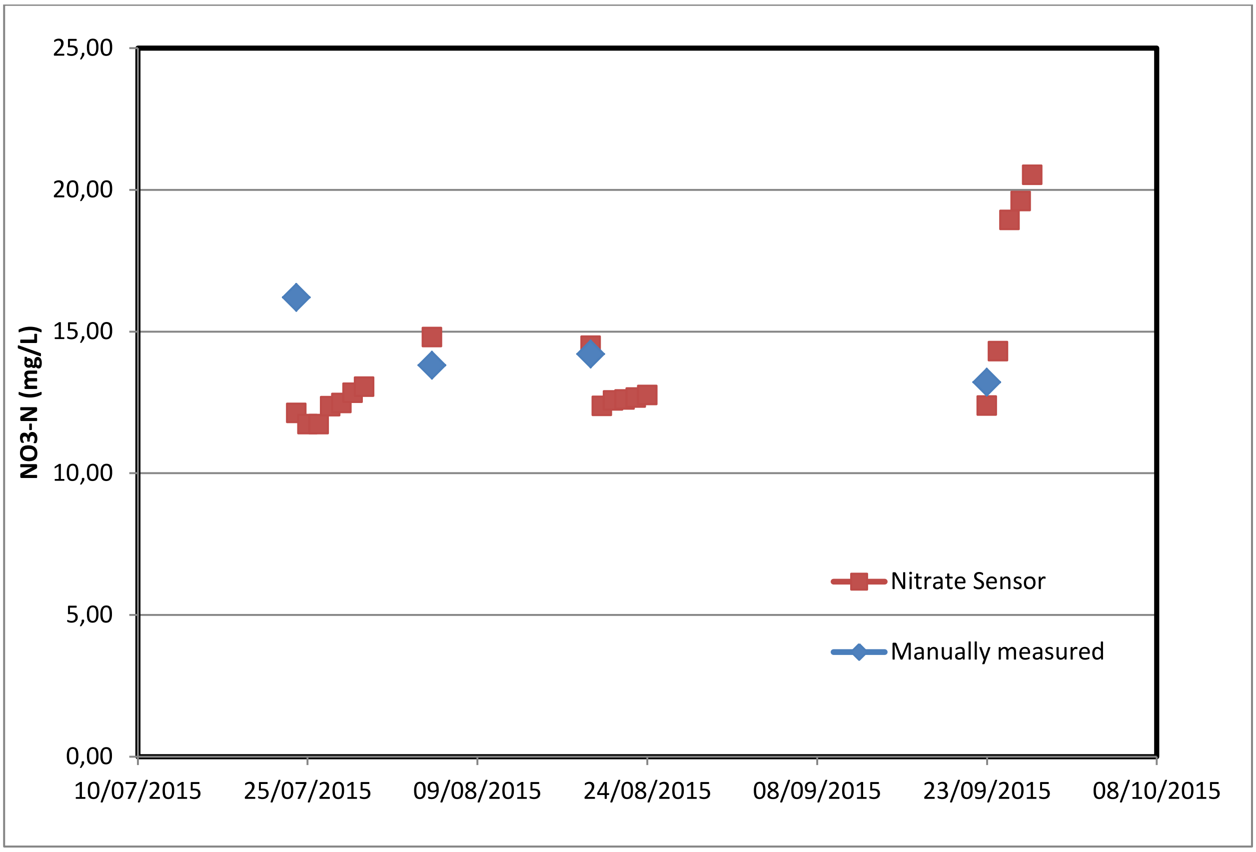

Figure 43. Nitrate concentration in the groundwater determined with the S::can Spectrometer Probe vs the Spectroquant Nova 60 – Nitrate cell test.

Appendix 7 Time course Chlorophyll Red-edge

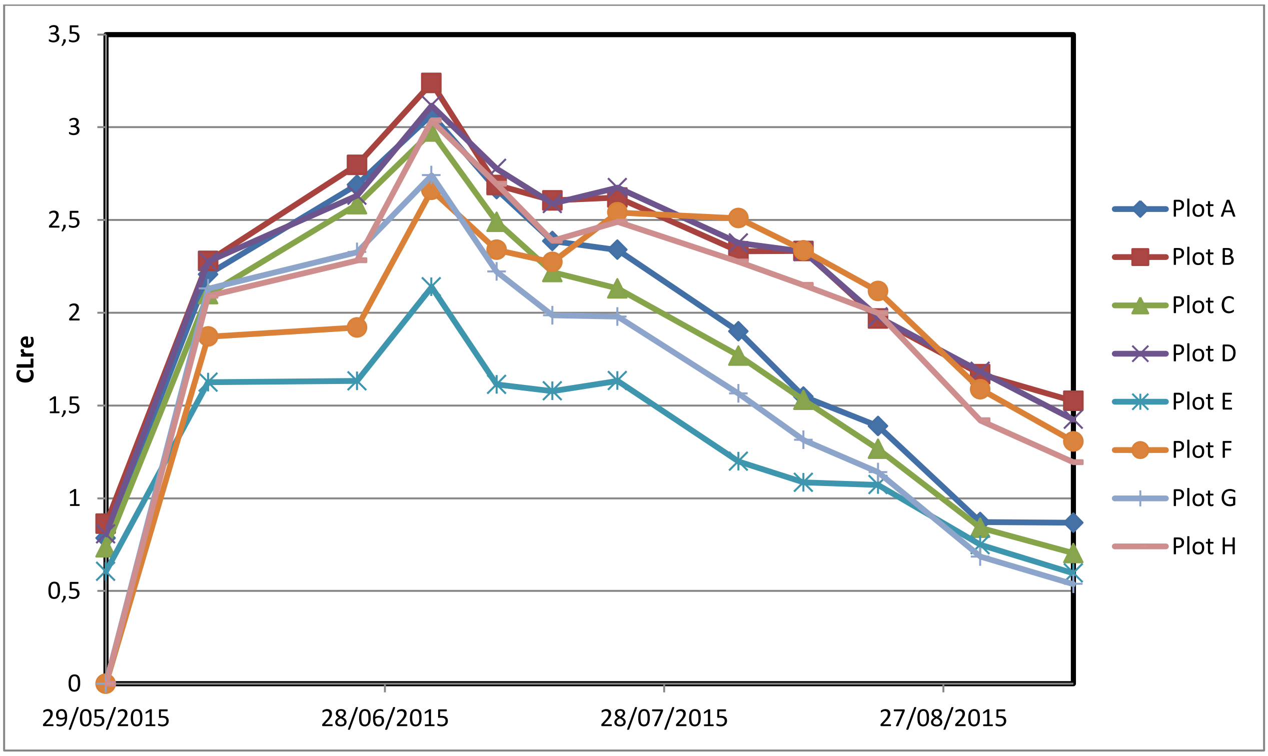

Figure 44. Time course of the Chlorophyll Red-edge (Clre).