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FERTILISATION FOR OPTIMISED YIELD CAN MINIMISE NITRATE LEACHING IN GRAIN PRODUCTION

by

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SUMMARY.

Nitrogen (N) fertilisation does not usually lead to increased N leaching as long as there is a significant yield response. The highest fertilisation rate at which the response of the crop to N uptake is enough to limit N leaching, is in the same range as the economical optimum. Above this optimum 10-50% of the excess fertiliser N is likely to leach with drainage. The optimum N rate is dependent on both potential yield and level of soil N supply. Both these factors vary between sites and years. Predicting the optimum N rate for a specific field and year is therefore a great challenge. There is also a large variation within fields, which increases the challenge even more.

General fertiliser recommendations that consider manure and cropping history, soil organic matter content and expected yield are very good for predicting averages. However, they fail to capture all variation. An accurate average is not good enough, since high levels of leaching in areas where fertilisation is above the optimum cannot be offset by less leaching in areas where the fertilisation is below the optimum level. This just results in lower yields.

In Sweden, one approach to complementing general recommendations is to publish crop N uptake in N fertilisation experiments during the current season. This facilitates discussion about how the weather is affecting crops and soil N regionally in the current year. However this still does not capture the site-specific conditions for every individual field. For this, field observations are necessary. Some fine tuning can be made from local soil analyses. However, the best indicator of crop response is the crop itself.

Some sensors are available that can provide estimates of crop N status. One example is the tractor mounted Yara N-Sensor™. It measures variations within fields, enabling the application of more N to areas with a high yield response, and avoiding or reducing applications in parts of the field which are not N limited. This still needs field calibration. There are several methods available to do this. One is to leave a plot in the field unfertilised, to demonstrate the soil N supply to the crop. By measuring this unfertilised crop at flag leaf emergence with a hand held version of the Yara N-Sensor, good predictions of soil N supply can be made. From this, more accurate optimum N rates can be calculated. The improvement and implementation of such methods could decrease leaching.

CONTENTS

Keywords: nitrogen leaching, optimum nitrogen fertilisation, N-Sensor, precision agriculture.

1. INTRODUCTION.

In most European countries, farmers are encouraged by the authorities to fertilise at no more than the economic optimum, in order to minimise nitrogen (N) leaching and subsequent pressure on the environment. In some countries there are efforts to reduce the level of N fertilisation even more, on the assumption that leaching is already increased at sub-optimal N rates, or that the optimum level of N fertilisation is too difficult to predict. Limiting fertilisation rates will have consequences for both yield levels and the protein content of the grain. An interesting question is whether or not a combination of high yield and protein together with minimised leaching, can be achieved. To answer this we need to explore the relationship between levels of N fertilisation above and below the economic optimum, and the possibility of predicting this optimum. This paper will present results both on leaching and yield response to mineral nitrogen fertilisation and methods for predicting optimum N fertilisation rates. The possibilities for minimising leaching by optimising fertilisation rates within and between fields in cereal production will be discussed. The focus will be mainly on results from Swedish field trials during the last 15 years.

2. GRAIN YIELD RESPONSE TO FERTILISER NITROGEN.

2.1. Yield response and optimum nitrogen fertilisation.

Yield responds positively to N fertilisation up to a certain limit, at which point some other factor, e.g. water, begins to limit crop growth. Too much N may reduce yield due to lodging or more severe fungal infections, which may result in a negative response at higher N levels. The effect of N on yield can be described by response curves expressed as mathematical functions (Wood, 1980), such as second and third degree polynomials (Delin, 2005). The optimum N fertilisation rate is the highest fertilisation rate where the yield response is still enough to cover the cost of the extra amount of fertiliser applied. So it will depend on the prices on fertilisers and grain, and may therefore vary between crops, countries and years. In the Swedish studies presented here, the price ratio between 1 kg of grain and 1 kg of fertiliser N has been set to 1:8 or 1:10, according to Swedish prices of fertilisers and grains during this period.

2.2. Relationship between grain yield and plant available soil nitrogen.

The optimum application rate of N is dependent on the potential yield level. The higher the yield, the more N is needed by the crop. The optimum N rate is also dependent on the amounts of mineral N supplied to the crop by the soil. The more N the soil supplies to the crop, the less fertiliser N is needed to reach a certain yield level. The relationship between the optimum N rate, potential yield and soil N supply can be derived from the results of fertiliser experiments designed to make models for fertiliser recommendations.

In this paper we will present relationships based on the results from 61 field experiments with winter wheat conducted during 2007-2012. They were conducted on mineral soils at various sites in south and central Sweden with various cropping histories and usage of manure. The experiments had seven N fertilisation rates from 0 to 240 kg N/ha, with a 40 kg N application in early spring followed by a main application just before stem elongation (GS30). Other nutrients were applied in sufficient amounts to ensure that only N was limiting. Weeds and diseases were controlled.

The optimum N rate in these experiments and the yield at this optimum were positively correlated, but with a rather low coefficient of determination (r^2) (Figure 1).

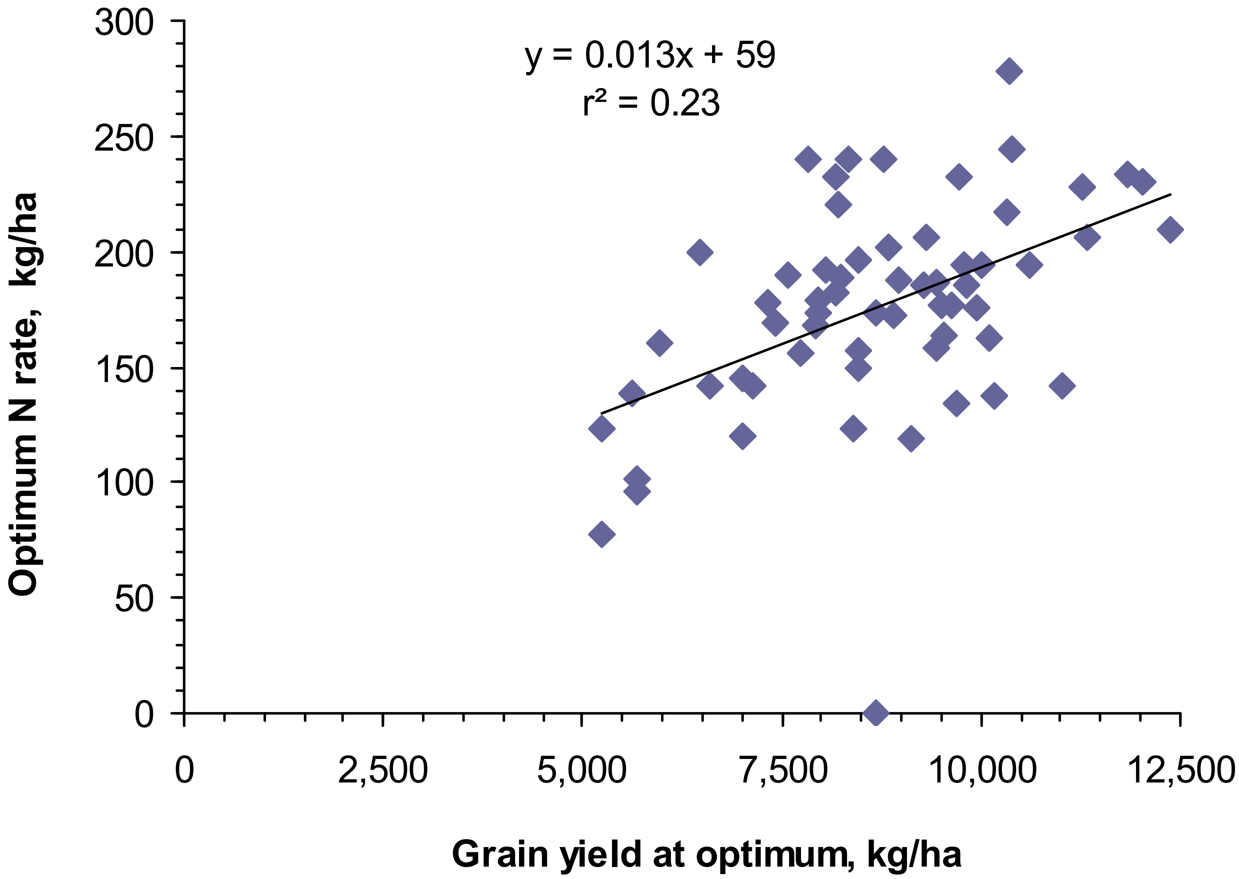

Figure 1: *Relationship between grain yield and optimum nitrogen rate, based on 61 field experiments.*

The low r^2 can be explained by the variation in soil N supply. Soil N supply should be closely related to the grain N offtake in unfertilised plots, which is negatively correlated to optimum N rate (Figure 2).

To get an accurate estimate of optimum N rate, both yield and soil N supply need to be considered. When this was done, using multiple regression, 75% of the variation in optimum N rate could be explained (Figure 3).

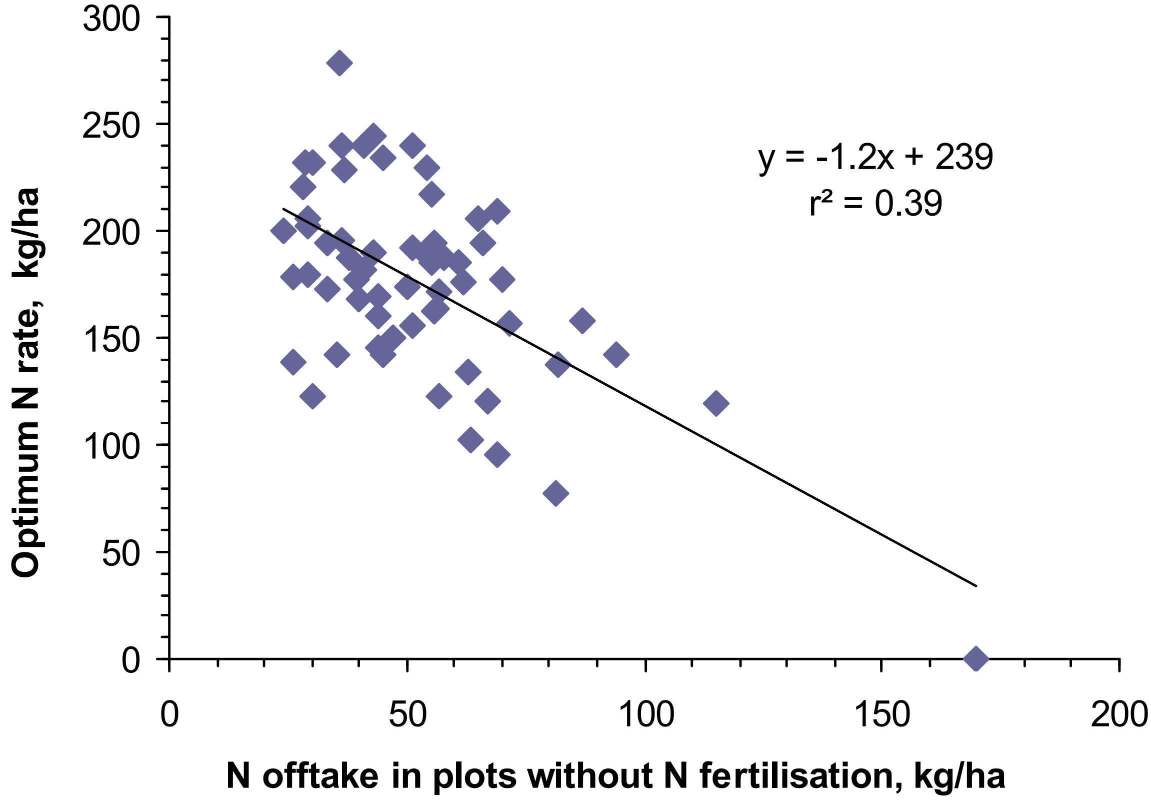

Figure 2: *The relationship between grain nitrogen offtake and the optimum nitrogen rate in unfertilised plots.*

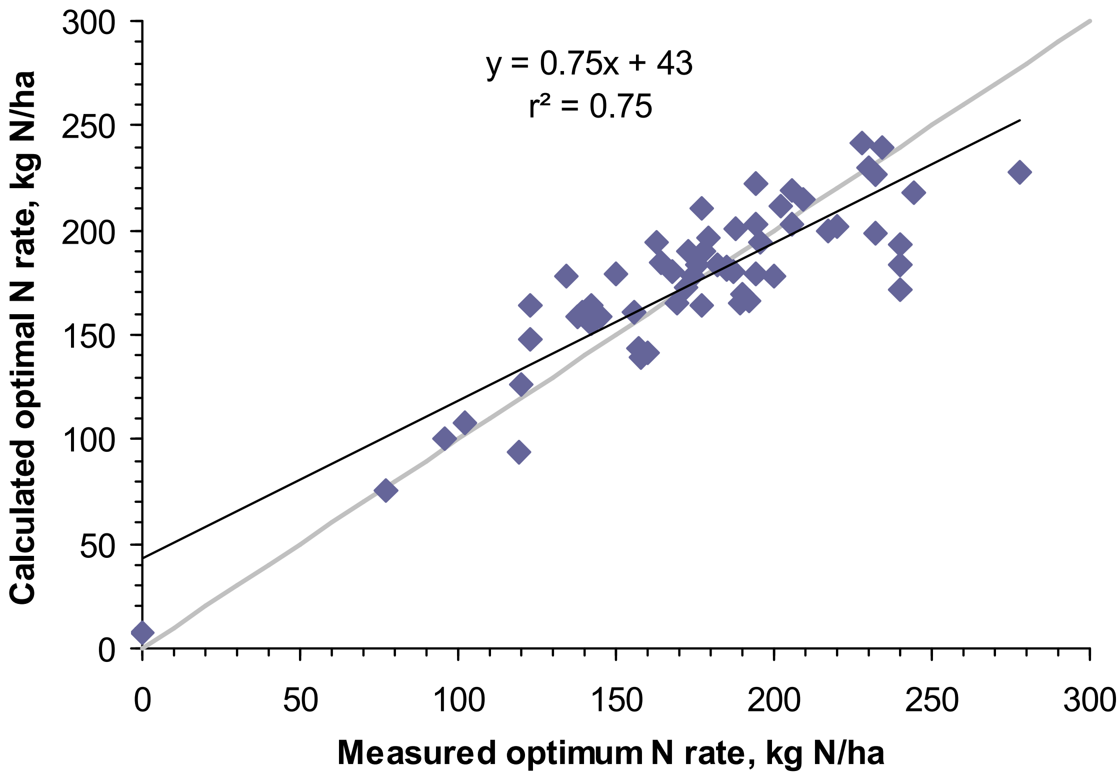

Figure 3: *The relationship between measured optimum nitrogen rate and the calculated optimal nitrogen rate, after variations in yield and soil nitrogen supply have been allowed for.*

3. LEACHING RESPONSE TO FERTILISER NITROGEN.

3.1. The theory of leaching response.

Leaching response to fertilisation with mineral N has often been described as rather low, as long as yield response is high. But the leaching response increases as yield response ceases and the economical optimum is exceeded (Olfs *et al.*, 2005). Such effects have been observed on residual mineral N in soil after harvest (Chaney, 1990), which can be considered as an indicator of risk for N leaching. It is logical that fertilisation where crop uptake has ceased results in higher leaching.

However, even at lower fertilisation rates only a limited proportion of the fertiliser N ends up in the grain yield. According to Macdonald (1997) 32% of the fertiliser N is found in the grain, 20% in straw, 24% in soil and 24% in losses at normal fertilisation rates. Immediate losses of N are likely to depend on in-season precipitation. Where precipitation is heavy and leads to water runoff through drainage during the growing season, fertiliser N may leach before it is taken up by a crop. In Sweden this occurs only very occasionally. If soil gets saturated with water during the same period, denitrification losses may occur, which does happen on poorly drained soils. Otherwise it is reasonable to assume that, as long as the crop responds to more fertiliser N, it will take up the fertiliser N that is not immobilised due to consumption by microorganisms and thereby either incorporated into the organic N pool in the soil or emitted as gaseous nitrogen.

The effect of N fertilisation on leaching has been described in different models. One such model is STANK in MIND or VERA, which is provided by the Swedish Board of Agriculture (Aronsson and Torstensson, 2004). In this model leaching is affected by fertilisation from rates 30% below the optimum. The effect increases to 60% when the optimum is exceeded and then further at higher rates. The effect depends on the clay content of the soil and the climate. The model is mainly used by farmers' advisors within a national advisory program called Focus on Nutrients (Greppa Näringen), which helps farmers to improve their plant nutrient management.

3.2. Experimental results on nitrogen leaching.

The relationship described above, with leaching response mirroring the yield response of N fertilisation in cereal crops, has been observed in leaching experiments (Lord and Mitchell, 1998; Delin and Stenberg, 2014). In both these studies leaching was related to fertilisation above and below the optimum N rate, which was calculated from yield results. In the paper by Delin and Stenberg (2014), three years' data were compiled into one diagram (Figure 4). The results were from three experiments on loamy sand in Sweden, performed in spring oats during the years 2007-2009. Each experiment had six fertilisation rates. There was an additional treatment with a split application and an adjustment to estimated demand at tillering (GS 21-23) in the first year. The subsequent crops were winter wheat or spring barley, which received normal fertilisation rates on all treatments. Soil water was sampled biweekly with ceramic suction cups (Djurhuus and Jacobsen, 1995) installed at a depth of 80 cm. Nitrate N leaching was determined from nitrate concentrations in soil water and drainage. The deviation in leaching from that in the unfertilised treatment was plotted against the deviation in fertilisation from the optimum N rate when the price ratio of grain to fertiliser was 10:1 These results showed <0.04 kg N/ha leached per kg N/ha fertiliser N applied below optimum and 0.1 and 0.5 kg N/kg N when exceeding the optimum N rate by 30 and 100 kg/ha respectively (Figure 4).

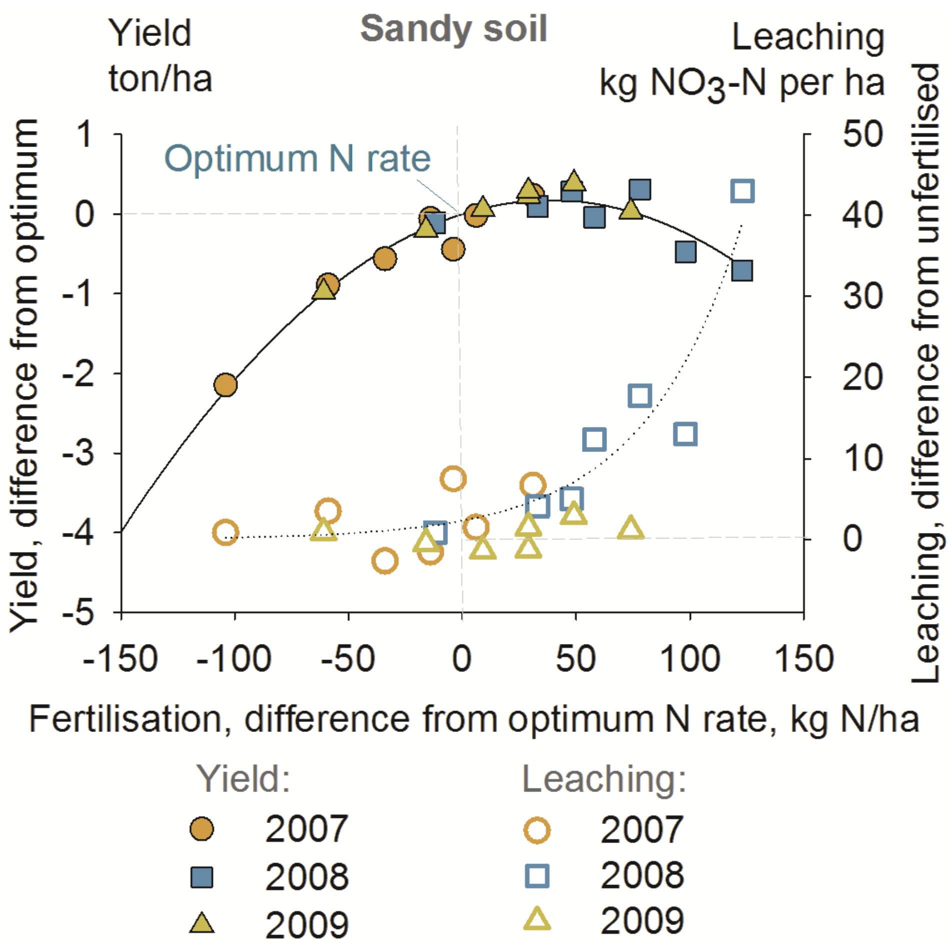

Figure 4: *The impact of nitrogen fertilisation and offtake on nitrogen leaching on loamy sand soils.*

Three additional experiments were performed on silty clay during 2009-2011, in the same region as the experiments on loamy sand. These trials had five N fertilisation treatments between 0-240 kg N/ha. Plots with separate drainage systems were used, with drainage measurements and flow-proportional water samples. Total N leaching was calculated from nitrogen concentrations and measured discharge. The three years were compiled into one diagram as described above. On this soil, the leaching response above optimum was very low (0.04 kg N/kg N) in two of the three years, but higher than on the loamy sand both below (0.1 kg N/kg N) and above (0.15 kg N/kg N) optimum in the third year (Figure 5). This third year was very dry at the time of fertilisation, meaning there were large cracks in the clay soil. Shortly after fertilisation there was very heavy rainfall with 170 mm within 10 days.

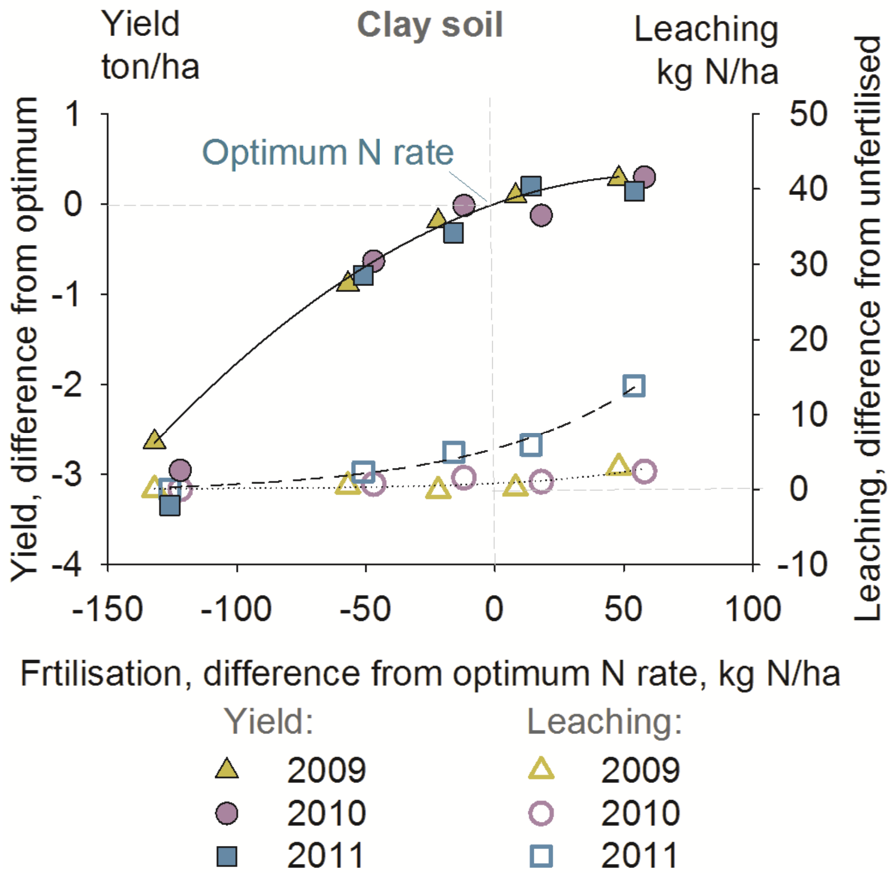

Figure 5: *The impact of nitrogen fertilisation and offtake on nitrogen leaching on clay soils.*

Lord and Mitchell (1998) presented similar results from the UK on N leaching at different N inputs to different cereal crops (mainly winter wheat). They found that leaching was only affected very slightly (<0.05 kg N/kg N applied) at rates below the economic optimum, but on average by 0.52 kg N/kg N above economic optimum rates. These results are based on 21 experiments on sandy soils performed during 1990-1994. Nitrogen fertiliser inputs ranged from 0 to 240 or 300 kg N/ha in six steps. All sites were well drained loamy sands or sandy loams over sandstone and each experiment was carried out on a different site.

3.3. Long term effects of repeated fertilisation.

The results presented above are from annual experiments and do not consider long term effects on leaching after several years of repeated fertilisation. As mentioned above, only about a third of N input is removed from the field with the grain and large quantities ends up in soil and straw. This means that there is an accumulation of N in the field that may become available for crops or for leaching later on. Bergström and Brink (1986) performed a 10-year study which indicates that there are accumulated effects in treatments with very high fertilisation rates. Due to the experimental setup it is not possible to relate the effects to the economic optimum, but at rates below 100 kg N/ha, the leaching effect of the fertilisation remained low (0-0.1 kg N/kg N) throughout the experimental period.

3.4. Leaching and recommended fertilisation.

According to the results presented above the leaching response to fertilisation depends on the yield response, and is therefore significantly higher above the economical optimum than it is below this. However, if leaching is instead related to recommended fertiliser application rates, the result may appear different, depending on the accuracy with which the recommendations match the economic optimum. Simmelsgaard and Djurhuus (1998) compiled such data from Denmark and found an exponential relationship between fertilisation and leaching, where leaching was already responding at very low fertilisation rates and without any distinct change in response when 'recommended normal fertilisation' was exceeded. This could be partly due to high precipitation after fertilisation, but is more likely to be because the recommended N rate failed to agree with the optimum. It is necessary to find and implement methods of accurately predicting the optimum N rate if optimised yields are to be combined with reduced leaching.

4. DIFFERENCES IN OPTIMUM NITROGEN FERTILISATION BETWEEN AND WITHIN FIELDS.

4.1. Between-field trials variations.

The optimum N rate may vary considerable between different sites. Wetterlind (2010) summarised the first three years from 36 of the 61 winter wheat experiments described above. There were large variations observed between trials, both in optimum N rate and the contribution of N from the soil (Table 1).

Table 1: *Variations in nitrogen offtake in plots without nitrogen fertilisation and optimum nitrogen rate between 36 winter wheat field experiments in Sweden in 2007-2009.*

	N offtake in grain from plots without N fertilisation (kg N/ha)				**N offtake in grain with optimum N fertilisation** (kg N/ha)			
	Mean	Min.	Max.	SD	Mean	Min.	Max.	SD
2007	58	21	83	18	155	95	213	44
2008	47	24	72	15	172	147	188	14
2009	49	26	82	18	159	71	224	41

The soil N supply was measured as N offtake in the grain in plots without N fertilisation. The difference between the lowest and the highest N offtake in these plots within a single year was 50-60 kg N/ha (Table 1), which would mean around 90 kg N/ha if N in straw were also included. The difference between the lowest and the highest optimum N rate was up to 150 kg N/ha (Table 1).

4.2. Within-field variations.

Optimum N fertilisation does not only vary between fields, but also within fields. Both N supply from the soil and yield potential may vary within fields. To study this variation, two projects were performed in Sweden during 1998-2000 (Delin and Lindén, 2002; Delin *et al.*, 2005) and 2003-2005 (Wetterlind *et al.*, 2008).

Table 2: *Nitrogen in the above-ground crop (kg N/ha) in plots without nitrogen fertilisation (Delin and Lindén, 2002; Wetterlind et al., 2008).*

Site	Year	Crop	n	N offtake, kg N/ha			
				Mean	Min.	Max.	SD
Ribbingsberg 1	1998	Winter wheat	34	83	30	137	26
	1999	Spring barley	34	45	12	74	16
	2000	Winter wheat	34	92	55	139	21
Ribbingsberg 2	2003	Winter wheat	20	91	41	167	41
	2004	Oats	13	94	37	150	37
	2005	Winter wheat	12	68	32	122	26
Nybble	2003	Oats	20	53	20	134	30
	2004	Oats	20	51	21	106	29
	2005	Spring barley	12	53	18	111	31
Hacksta	2004	Winter wheat	21	67	33	105	19

For these studies, fields that could be expected to have some variation in yield and soil N supply were selected, but can still be considered to represent a common type of field. To study soil N supply, 60 m^2 large plots were left without N fertilisation and the crop was sampled before harvest to measure

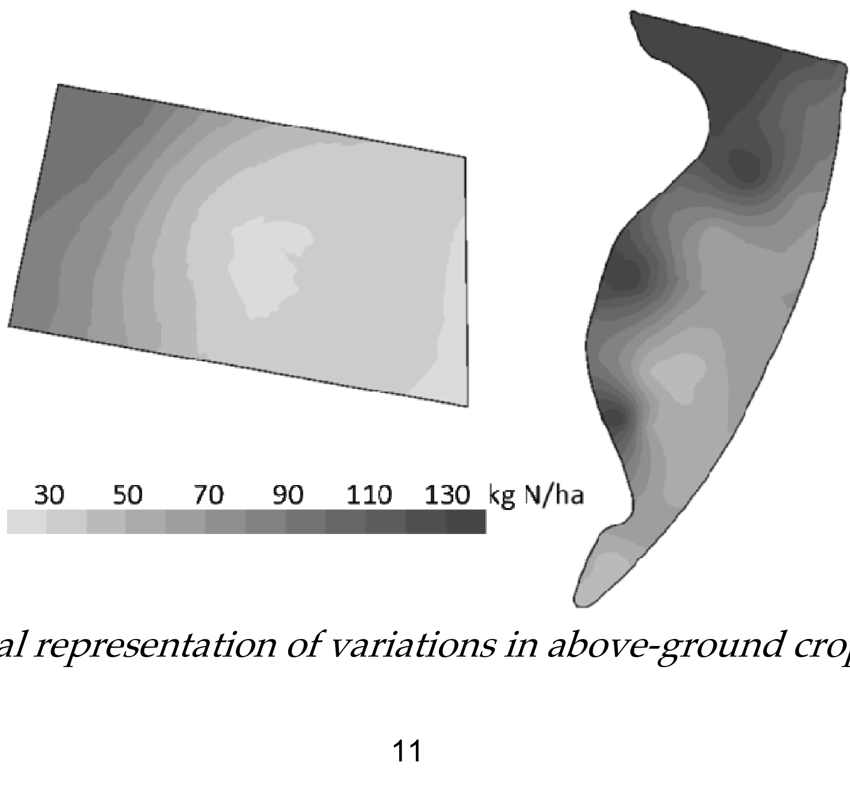

Figure 6: *Visual representation of variations in above-ground crop nitrogen.*

above-ground crop N. The difference between the highest and the lowest area was typically 100 kg N/ha and the standard deviation was around 30 kg N/ha (Table 2; Figure 6). In other words the within-field variation can be just as large as the variation between fields.

5. HOW CAN OPTIMUM NITROGEN FERTILISATION BE ESTIMATED?

5.1. Standard recommendations.

The Swedish Board of Agriculture gives official recommendations on how N fertilisation rates should be calculated. It is based on estimated yield potential, previous crop, soil organic matter content and historical use of manure. The correspondence between this recommendation and the actual optimum N rate has been studied by calculating both the recommendation for the yield achieved and the actual optimum N fertilisation rate for each of the 61 experiments described above (Figure 7).

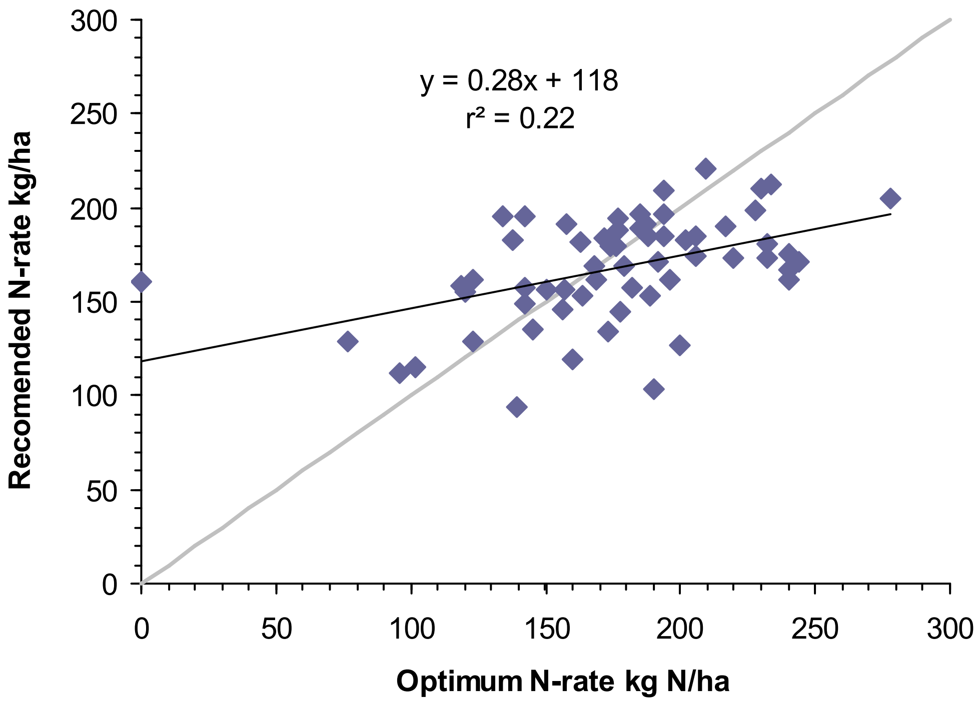

Figure 7: *Relationship between actual optimum N rates and Swedish Board of Agriculture recommended N fertilisation rates.*

On average, the recommendation was correct, but in individual situations the difference between the two can be large, with a tendency to underestimate the fertilisation requirements at sites with a high optimum rate, and overestimate them where optimum levels are low.

The recommendations are based on the average effects of parameters such as the residual effects of N-rich crops such as rapeseed and peas. However Engström and Lindén (2009) reported a great variation in the effects of previous crops on the N fertiliser rate between sites. The optimum N rate for winter wheat grown after winter oilseed rape could vary from 55 kg/ha lower to 18 kg N/ha higher than that after spring oats. The optimum N rate for winter wheat grown after peas could vary from the recommended rate by between 46 kg lower and 26 kg N/ha higher than that after spring oats. There are probably similar variations in the effects of other parameters.

5.2. Mineral nitrogen in spring.

In many countries mineral N levels in soil in spring are measured and used to adjust fertilisation rates. In 54 of the 61 experiments in winter wheat described above, the soil mineral N in the 0-60 cm level was measured at the beginning of crop growth in spring. If this could describe not only the variation in N supply at that time, but also what will be available during the rest of the growing season, it could give useful information for how to adjust the fertilisation. Unfortunately it does not explain much of the variation in either N offtake in unfertilised plots (r^2 = 0.08) or the optimum N rate (Figure 8). At one time this method was used by some advisors in Sweden, but due to the very low correlation with optimum N rate and the inconvenience it brings, it is hardly used anymore.

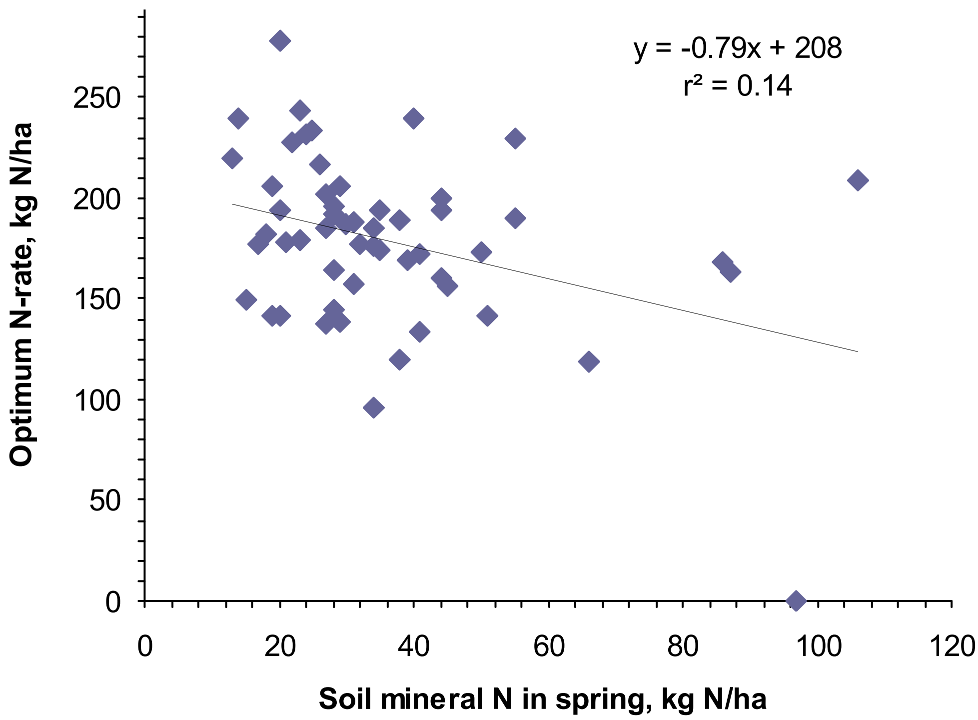

Figure 8: *Relationship between levels of soil mineral nitrogen in spring and optimum nitrogen rate.*

5.3. Soil analysis.

Since soil organic matter content constitutes the source of N supply from the soil, it could be expected to be a potential predictor of mineralisation capacity. However, this relationship can be rather weak, even within a single field (Delin and Lindén, 2002). A number of other soil parameters have therefore been tested to identify better predictors of soil N supply. One example is to use near infrared (NIR) spectroscopy. NIR spectra are not only affected by soil organic matter (SOM) content but also by its quality, and even more so, by the soil texture, which also influences the mineralisation (Stenberg *et al.*, 2010).

There are studies that have shown the possibility of estimating plant N uptake in plots without N fertilisation using NIR measured in the topsoil of fields with a large range in SOM content (Wetterlind *et al.*, 2008; Stenberg *et al.*, 2005; Dunn *et al.*, 2000). In the study by Wetterlind *et al.* (2008) NIR predicted plant N uptake within years and fields with r^2-values between 0.75 and 0.85 and with a root mean squared error of cross validation between 11 and 16 kg N/ha for two fields in Sweden. In the same study, predictions between years resulted in almost equally good r^2-values but with higher errors (12-26 kg N/ha).

The better estimations using NIR compared with SOM as a predictor can be explained by the information about soil texture incorporated in the NIR spectra. However, there is a possible limitation for fields with a pronounced correlation between plant N uptake and variation in SOM and clay content (Wetterlind *et al.*, 2008). Another limitation of this type of technique is the need for field or possibly farm calibrations.

Another parameter that has been tested for the prediction of soil N supply is water extractable carbon (Körschens *et al.*, 1998). However, when tested in 21 of the 61 winter wheat experiments presented here, no such relationship could be found. One of the problems with both using mineral N in spring and other measurements of soil parameters is that they are all static: at best they give an idea of the potential soil N supply. But they cannot provide information related to the weather conditions during the specific growing season. For that, it is necessary to look at the crop.

5.4. Chlorophyll meter.

Since there is a strong correlation between chlorophyll concentration and N concentration in plants (Olfs *et al.*, 2005), chlorophyll meters can be used to estimate crop N status. The Yara N-Tester™ is a handheld chlorophyll meter, which can be used in several crops as an aid to determining whether there is a need for complementary fertilisation with N. The N-Tester will then recommend an amount in kg N/ha. For this, the relationship between the chlorophyll and leaf N concentrations is used.

Larsson (2012) compared readings from the N-Tester in winter wheat (GS 37) with actual fertilisation deficits to reach N optimum fertilisation. In total, 49 experiments were used during the years 2008-2011. He found that the relationship between the recommended value from the N-Tester and the amount of N missing to reach optimum N fertilisation calculated from yield results was highly affected by weather. Nitrogen recommendations were overestimated in dry years and in fields with high N mineralisation capacity. This can be explained by a lower N demand than expected in dry weather and a lower requirement for N input with fertiliser when large amounts of N are supplied by soil. The best correlation was in 2010 ($r^2 = 0.68$) and the weakest in 2011 ($r^2 = 0.26$). Larsson (2012) also undertook interviews with farmers and advisors. Farmers were generally satisfied with the N-Tester even though some found it to overestimate the N fertilisation requirements. Advisers' attitudes were more negative and many questioned the relationship between measurement value and actual fertiliser demand.

5.5. Yara N-Sensor(TM).

The chlorophyll meter described above only relates to the N concentration in the leaf, irrespective of biomass. Other sensors that make measurements on a surface area, relate instead to kg N/ha. One example is the Yara N-Sensor. It measures the reflectance from different wave-length bands, and estimates the N content in the aboveground crop using an algorithm. The value achieved is called the SN value. There is a tractor mounted version, which is used for measuring variations within fields, to adjust the N fertiliser rate in real time for a better distribution of fertiliser N between areas with different fertiliser N requirements. This method still needs field calibration. Another version of the Yara N-Sensor is hand held and can be used to take measurements in smaller plots. In the 61 winter wheat experiments described above, measurements with a hand held N-Sensor were made at flag leaf emergence (GS 37). The SN value from plots without N fertilisation has shown a good correlation with the level of N in the harvested grain (Figure 9).

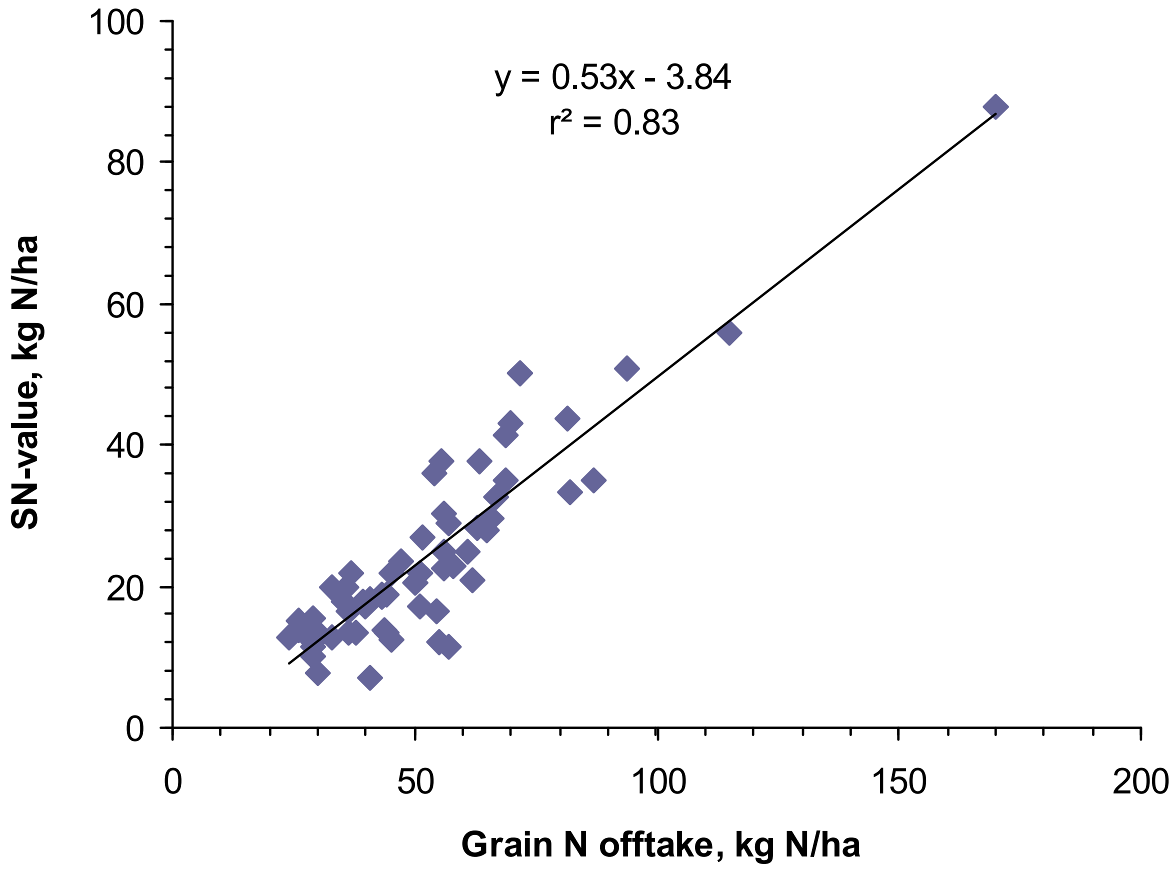

Figure 9: *Relationship between grain nitrogen offtake and SN values from the N-sensor in unfertilised plots.*

Using N-Sensor measurements from unfertilised plots can therefore be useful for predicting optimum N fertilisation rates. The equation from Figure 3 ($y = 0.75x + 43$) should then be modified to:

Optimum N rate = 0.016 * expected yield potential – 2.25 * SN-value in unfertilised plot at GS 37 + 90 (Figure 10).

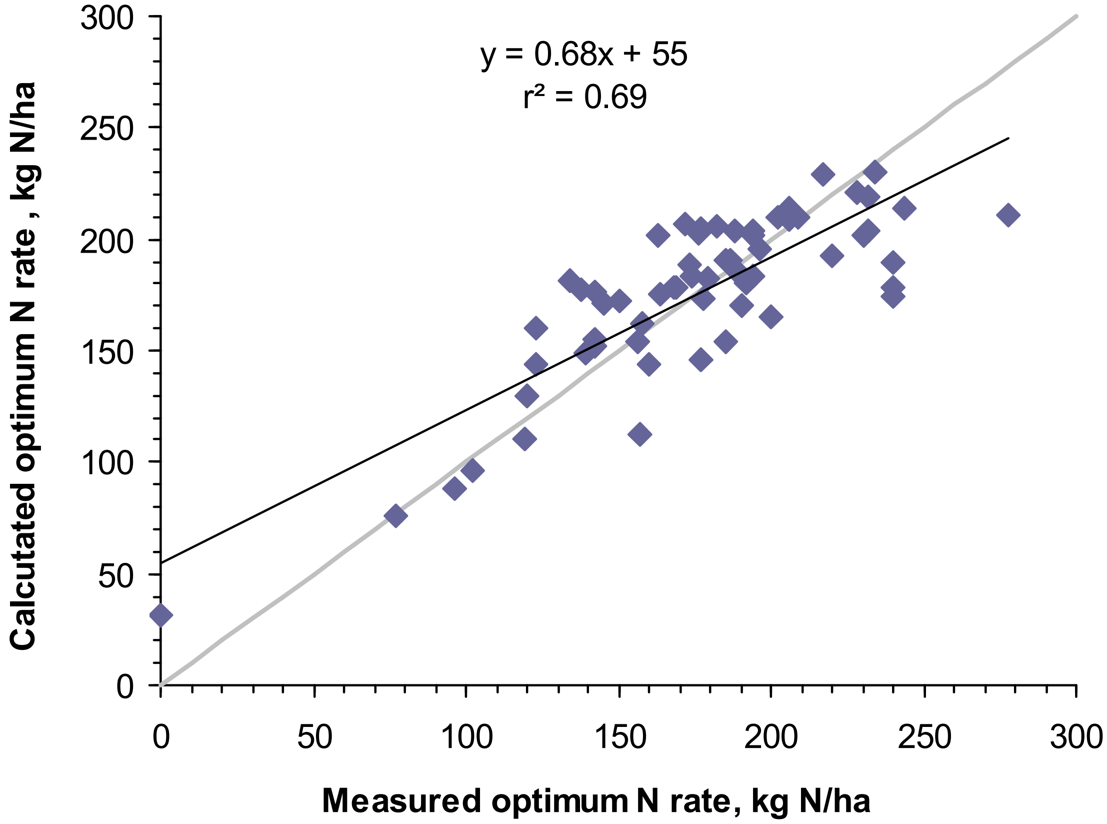

Figure 10: *Correlation between measured optimum nitrogen rate and optimum nitrogen rate calculated from yield at optimum and N-sensor measurements in plots without nitrogen fertilisation.*

To leave an unfertilised plot in the field is easy on farms that use fertiliser applicators with a boom. For those who use centrifugal fertiliser spreaders, a tarpaulin can be used to cover the area during application. However, to use the proposed method still means that the yield at optimum has to be estimated. That is still difficult, but easier to do from crop status and weather parameters known in GS 37, than earlier in the growing season. Also yield has the potential to be predicted with remote sensors (Overgaard *et al.*, 2013). For the N-Sensor an absolute calibration without the requirement for local calibration is under development.

5.6. Crop height.

Not everybody has access to the N-Sensor or other similar spectrometers. An alternative way to utilise unfertilised plots, is to compare crop growth between the fertilised and unfertilised crop. In 48 of the 61 winter wheat experiments crop height in the different treatments was measured one month before harvest. The relative crop height in unfertilised plots, i.e. height in plots without N divided by height in plots with no N limitation, was compared with optimum N rate. There was a weak negative linear relationship (r^2=0.33).

5.7. Nitrogen forecast.

The yearly weather conditions affect both potential yield and soil N supply. In Sweden Yara has introduced a system to highlight how the individual year affects nitrogen supply and crop growth. Every year a number of official N fertilisation experiments are conducted with joint funding from the Swedish Board of Agriculture, Yara and the Farmers Foundation for Agricultural Research. The experiments have different N fertilisation levels from 0 to 280 kg N/ha. Weekly measurements with the handheld N-Sensor are presented in a newsletter (Figure 11).

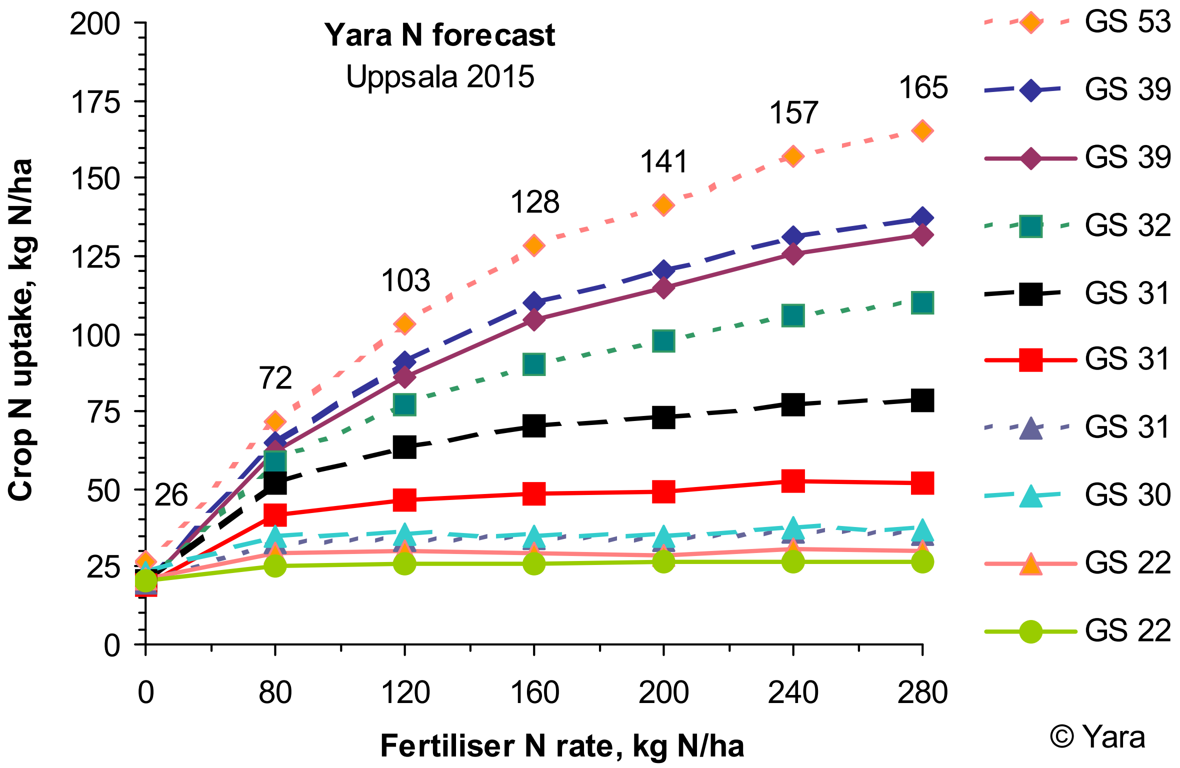

Figure 11: *Variations in the impact of fertiliser nitrogen rate on crop N uptake.*

Measurements are started when crop growth begins in spring and are finished after ear emergence. By following the N uptake in plots without N fertilisation, the soil N supply can be estimated. Increasing uptake with time indicates a net mineralisation and the amount can be compared to the results from past years to indicate if this is less or more than usual. The amount of N in fertilised plots indicates the effect of fertiliser. If there is a great difference between the different rates, the crop will probably respond to more N before the optimum is reached. With small differences there is probably N left in soil, which often happens under dry conditions.

In addition to the official experiments, a number of farms in the most intensively cultivated regions in Sweden use a tarpaulin to cover a small plot in the field during fertiliser application. The Swedish project 'Focus on Nutrients' then measures N uptake with a handheld Yara N-Sensor on a weekly basis, both in the unfertilised plot and in the field surrounding the plot. The fields are chosen to represent different soil types, climatic conditions and preceding crops. Nitrogen uptake in the unfertilised plots and in the fields is presented in a newsletter once a week. This provides the ability to follow the N mineralisation in the soil and uptake of fertiliser N throughout the season and to compare these with previous years. In this way farmers can adjust the fertilisation rate according to the actual conditions (Figure 12).

The newsletters from Yara and 'Focus on Nutrients' reach a large number of farmers and advisors. They result in an increased awareness about variation between sites and years, and an encouragement to adjust fertilisation to current conditions. The newsletters do not give site-specific information for the individual farmer. It is a complement to other more site-specific methods.

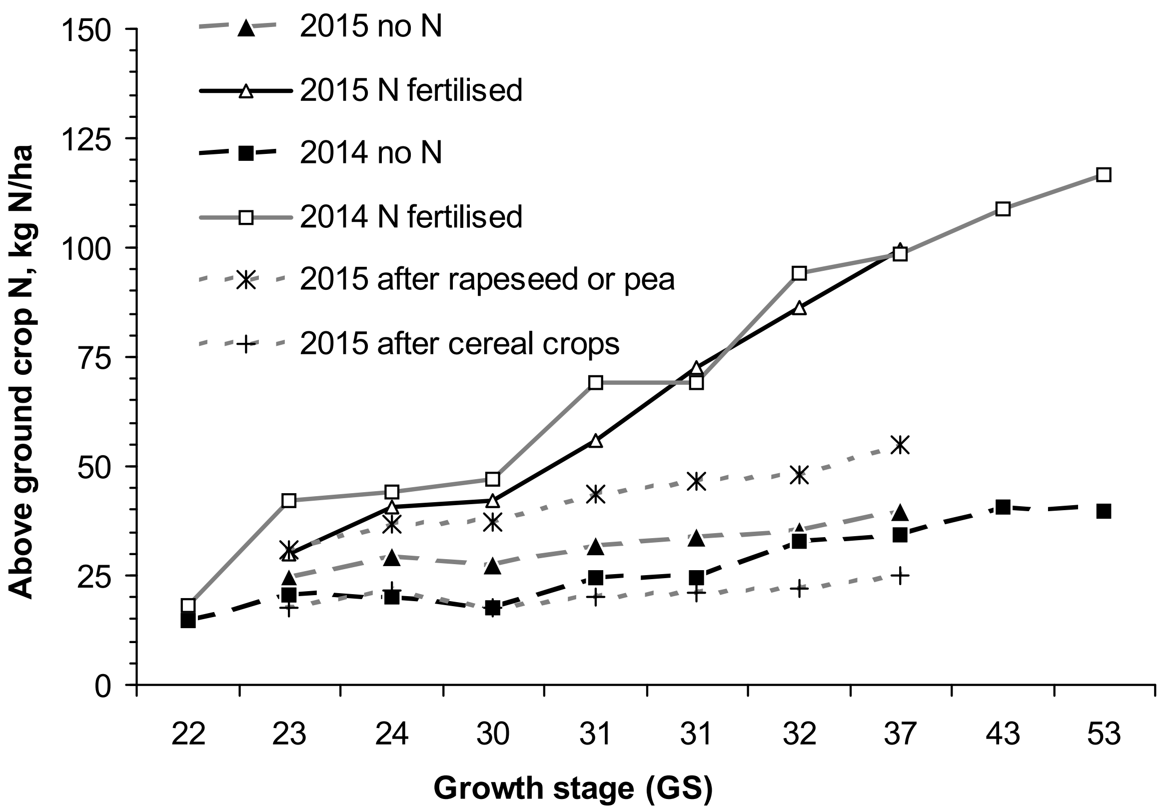

Figure 12: *Variations in above ground crop N at successive growth stages.*

5.8. Satellite images.

As well as using sensors to determine within-field variable rate N application there are also services based on satellite images. A Swedish system, CropSAT, is a web based, freely available system developed by the Swedish University of Agricultural Sciences, together with partners from advisory services, government agencies and the trade[1]. The system is based on vegetation indexes from satellite images and users are guided through a simple step-by-step procedure resulting in a downloadable variable rate application file. There are no absolute fertilisation recommendations, but the users have to decide what very high, high, medium, low and very low vegetation index values should represent in terms of N fertiliser application. The system was tested during 2014 and has been fully operational during 2015, with 1,500 downloaded application files. Though not operating in real-time (the system uses two images per field during the period April to June) and with lower resolution (22m x 22m) compared with having a ground-based sensor, the advantage with the system is that it is available for almost all farmers in Sweden (it covers about 95% of all farmland).

[1] http://CropSAT.se

6. LEACHING WITH SITE-SPECIFIC FERTILISATION.

6.1. Potential reduction with using unfertilised plots.

As previously mentioned, N fertilisation does not usually lead to increased N leaching as long as the fertiliser rate does not exceed the optimum level. Among the 61 winter wheat experiments presented here, the sites would on average have been fertilised at, or slightly below, the economic optimum if general recommendations were followed (Figure 7). However, about 15% of the sites would have been fertilised with more than 25 kg and about 6% more than 50 kg above the economic optimum (Figure 6). According to the numbers presented here on leaching effects at different levels above optimum, that means that leaching due to excess fertilisation could be approximated to 3-25 kg N/ha in those areas. The corresponding area that would instead have been fertilised at more than 25 kg N/ha below the optimum reduces the average rate, but unfortunately only leads to yield loss without any leaching reduction. However such a yield loss does in fact represent a higher leaching loss per kg grain produced. Therefore using more precise methods, instead of a general recommendation, has the potential to reduce leaching. Using hand held Yara N-Sensor measurements in unfertilised plots has the potential to reduce the fertilisation error. Based on the data presented here, this reduction could be about half, or more, compared to using general recommendations.

6.2. Leaching with site-specific fertilisation within fields.

As previously mentioned, the optimum N rate varies as much within fields as between them. Site-specific adjustments within fields should therefore also affect leaching. Nilsson (2010) calculated the potential to reduce leaching by adjusting the N fertiliser rates according to variations within fields cropped with cereals. Leaching was estimated with the leaching model used in the application STANK in MIND (now called VERA) developed for advisors by the Swedish Board of Agriculture, described by Aronsson and Torstensson (2004). The degree of variation in optimum N rate within fields varies. In fields with larger variation, site-specific variation of fertilisation is more worthwhile, and the effect on leaching is expected to be higher. Nilsson (2010) selected a number of examples of how the optimum N rate can vary within fields in the context of leaching. Some of these distributions are presented in Figure 13. Site-specific fertilisation was compared to uniform application within fields for different soil types (i.e. clay content) and degrees of variation within fields (Figure 13).

The results showed that the reduction in leaching by using site-specific N fertilisation varied between 0.5-3.8 kg N/ha for a sandy soil (<5% clay) and 0.2-1.6 kg N/ha for a soil with high clay content (>40% clay) depending on the degree of within-field variation (Table 3).

This is in addition to the reduction that may have been already implemented by adjusting application rates to the field average demand. Many farmers who have tried the Yara N-Sensor claim that they often reduce their total fertiliser use when using the N-Sensor. This could be due to them looking at the more

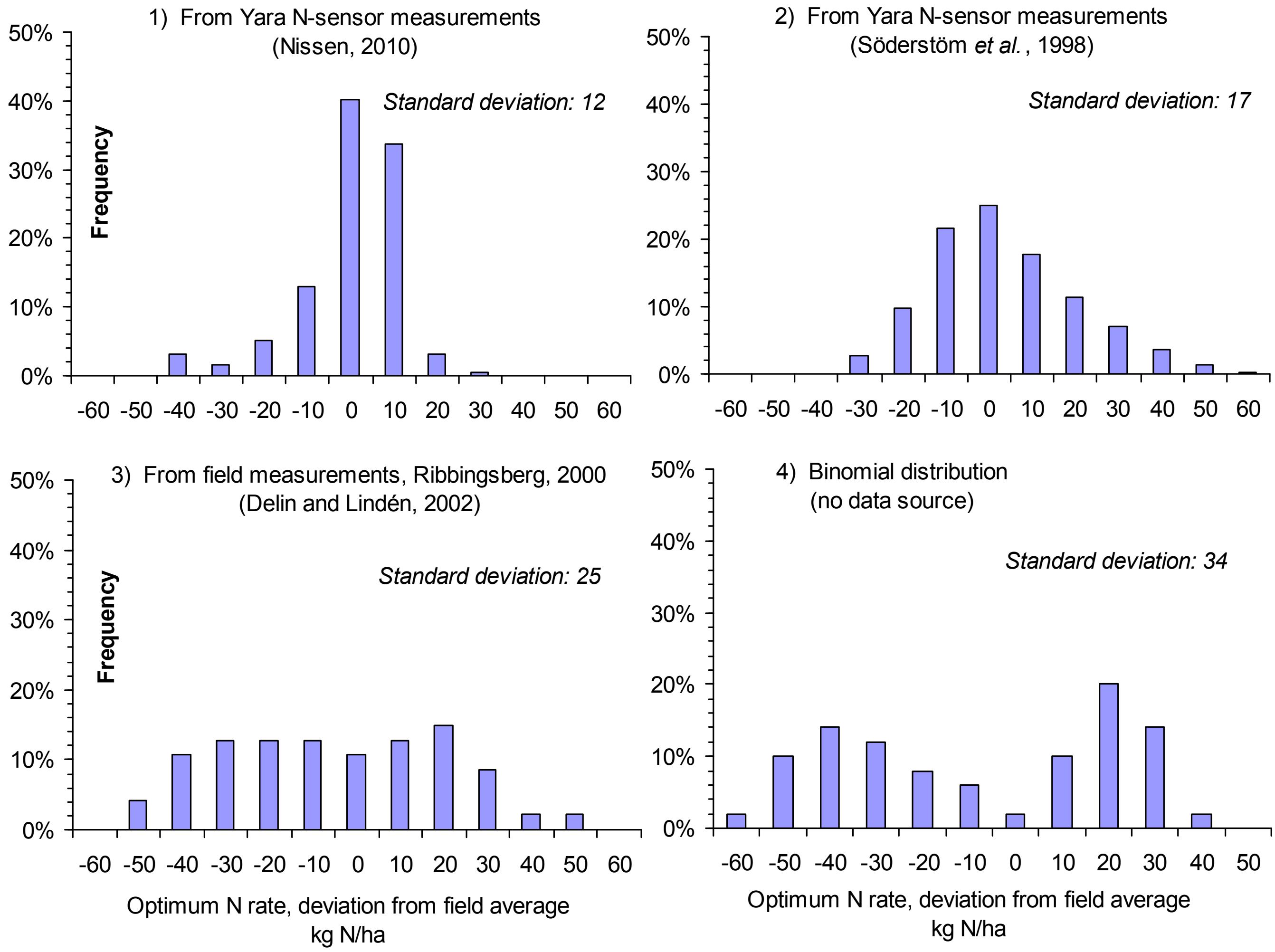

Figure 13: *Examples of how optimum nitrogen rate can vary within individual fields.*

Table 3: *Potential yearly net reduction in nitrogen leaching (kg N/ha) in fields with different variations in optimum N rate (as indicated by distribution) and clay content, when N fertilisation is applied at the optimum N fertilisation rate in each part of the field compared to the application of the average optimum N rate for the field.*

Distribution (Figure 13)	Standard deviation	<5% clay	5-15% clay	15-25% clay	25-40% clay	>40% clay
1	12	0.5	0.5	0.4	0.3	0.2
2	17	1.7	1.6	1.4	1.0	0.7
3	25	2.4	2.2	2.1	1.4	1.0
4	34	3.8	3.5	3.3	2.3	1.6

productive part of the field when assessing the average fertiliser requirement, and then applying this to the whole field despite the fact that a large part of it is less productive. Therefore the estimation of fertiliser requirements for all individual parts of the field will not only generate better estimates for each single part, but also a better estimate of the average. Nilsson (2010) assumed that looking at all parts of the field could improve the estimation of the average by at least 10 kg/ha. She also estimated the decrease in leaching due to a reduction from a level of 10 kg/ha above the average optimum to actually achieving the optimum level for all parts of the field. The resulting reduction was 3.2--6.8 kg N/ha for a sandy soil and 1.4-3.0 kg N/ha for a soil with high clay content.

7. CONCLUSIONS.

The highest fertilisation rate, at which the response of the crop to N uptake is enough to limit N leaching, is in the same range as the economical optimum. Above this optimum 10-50% of the excess fertiliser N is likely to leach with drainage. Fertilisation adjusted to the economic optimum could therefore also minimise leaching. Since the optimum fertilisation level varies between sites and years, fertilisation must be site-specifically adjusted. An accurate average is not good enough, since high levels of leaching in areas where fertilisation is above the optimum cannot be offset by less leaching in areas where the fertilisation is below the optimum level. This just results in lower yields. To predict optimum fertilisation rate for each site and year is a great challenge. Using general recommendations does not capture all variation. Local field measurements can improve this. One promising method is to leave a plot in the field unfertilised, to demonstrate the soil N supply to the crop. By measuring this unfertilised crop with the Yara N-Sensor, good predictions of soil N supply can be made. From this, more accurate optimum N rates can be calculated. The improvement and implementation of such methods could decrease leaching.

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