Optical Sensors Applied in Agricultural Crops

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Additional information is available at the end of the chapter

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1. Introduction

There is a very wide range of optical sensors applied in agriculture, which goes from sensors used to analyze soil attributes to sensors installed in combines to measure protein content in wheat grains while they are being harvested. But in this chapter we are going to discuss about optical sensors that, from a short distance are able to measure the agricultural crop's reflectance using specific wavelengths, and how can we use this information.

This kind of optical sensors began to be studied in 1991 with the development of sensors focused in weed detection at the Oklahoma State University. Just based on the simple fact that soil and plants (weeds) have a different interaction with the light emitted from the sensors, allowing identifying what is soil and what is a plant.

In 1992 there was the first discussion between the Departments of Plant and Soil Sciences and Biosystems and Agricultural Engineering concerning the possibility of sensing biomass in wheat and bermudagrass. The objective was to use biomass as an indicator of nutrient need (based on removal). In 1993 Dr. John Solie, Dr. Marvin Stone and Shannon Osbourne collected sensor readings at ongoing bermudagrass, with nitrogen rates versus nitrogen timing experiments with the Noble Foundation in Ardmore, Oklahoma. Initial results were promising enough to continue this work in wheat. And in fall of 1993 the first variable application of nitrogen was done across a 70 meter transect. In 1994 John Ringer and Shannon Osbourne collected sensor readings and later applied variable N fertilizer rates based on the first bermudagrass algorithm developed by TEAM-VRT.

In the subsequence years the research advanced creating algorithms for nitrogen application in many different crops. And nowadays we have commercial sensors being sold to farmers to make real-time application of nitrogen, growth-regulators and desiccants. The objective of this chapter is to show different applications of optical sensors in agricultural crops. At the ABC

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Foundation (A private research institution maintained by farmers created in 1984) located in south Brazil, the studies began in 2006 with commercial sensors. Making applied research, the results can be delivered immediately to the agronomists of five cooperatives (Capal, Batavo, Castrolanda, Coopagrícola and Holambra).

The topics to be discussed in this chapter are:

1. The types of sensors used;
2. The range in the spectrum used by sensors and response on crops;
3. Aspects of use in the field and what could affect the measurements;
4. Experiments and the results obtained with sensors;
5. Use of optical sensors combined with a GPS receiver to create maps;
6. Nitrogen application based on sensor's measurements;

2. The types of sensors used

The sensors to measure crops reflectance can be classified according to the platform, like satellites, aerial (airplanes, UAV's - unmanned aerial vehicles, balloon) and ground based. For satellites, airplanes and UAV's it is most common to use cameras to collect images, and ground based optical sensors can collect reflectance data and storage in a text file. The ground sensors can also be classified into active or passive. The basic difference is that the passive sensors need an external source of light, like the sun. The active sensors have its own source of light, which can be a wide range light or a specific wavelength.

There are available a few brands on the market, each one with its own construction characteristics like internal batteries, GPS antenna, data logger and log frequency. The Table 1 has some examples:

Manufacturer	Sensor	Country
AgLeader	OptRx	United States
Falker	ClorofiLOG	Brazil
Force A	Dualex and Multiplex	France
Fritzmeier	ISARIA	Germany
Holland Scientific	CropCircle	United States
Konica Minolta	SPAD	Japan
Topcon	CropSpec	Japan
Trimble	GreenSeeker	United States
Yara	N-Sensor	Germany

Table 1. Optical sensors and manufacturers.

There are also some differences about the distance from the sensor to the crops. For example, the SPAD and the ClorofiLOG sensors need to make static measurements, touching the sensors on crop's leaves. The other sensors make the measurements from centimeters to meters, but do not need to have contact with the leaves.

Figure 1. Crop Circle optical sensor.

Let's use one of the available sensors as an example, the Crop Circle® ACS-210 sensor, manufactured by the Holland Scientific Inc., Lincoln, Nebraska. As show in the picture (Figure 1) this sensor has one LED (Light Emitting Diode) that emits active radiation simultaneously in visible and near infrared light with a system called PolySource™ and two silicon photodiodes with a spectral range of 320 to 1,100 nm to detect light. One detector works between 400 and 680 nm and the other between 800 and 1,100 nm. Using a filter on each detector, the wavelengths used are the amber light (590 ± 5 nm) and near infrared (880 ± 10 nm). The sensor must be placed between 0.25 and 2.13 m from the target, and then the light reaches the target and reflects part of the energy, which is received by the detectors. This sensor needs external batteries (12 V) and GPS antenna, but has its own data logger, that saves the data in a SD card. Also in Figure 1 there is an example on how to install the sensors in a motorcycle to collect data on-the-go.

The Figure 2 has two other examples, one is the Hand held GreenSeeker, from Trimble, and the other one is a prototype from Oklahoma State University, which now is also being commercialized by Trimble. The Pocket Sensor was designed for small farmers, made to be a low cost sensor, it does not use GPS signal or a data logger, and you can just position the sensor over the crop, press the trigger and see the value of NDVI (Normalized Difference Vegetation Index).

Figure 2. GreenSeeker sensor collecting NDVI values for weed (a) and (b); detailed pictures from GreenSeeker Hand Held (c) and Pocket Sensor (d); and GreenSeeker mounted on a sprayer (e) and on a motorcycle (f) collecting NDVI values in sugarcane.

3. The range in the spectrum used by sensors and response on crops

The electromagnetic spectrum goes from gamma rays to radio waves. These sensors used for measure crop reflectance usually work in the visible and near infrared region of the spectrum, and combining at least two wavelengths to calculate vegetation indices. From the agronomic point of view, the visible light has a straight relationship with the chlorophyll content, absorbing the blue and red lights, and reflecting the green light. That's what makes us to see healthy plants as green. The near infrared light, not visible by the human eye, is reflected by the mesophyll cells, which is found in more quantity in a plant than chlorophyll, resulting in a much higher reflectance than visible lights. Using both wavelengths it is possible to evaluate the color and biomass production of a crop. In practice, greener and higher biomass plants have a higher chance to have higher yields.

Remote sensing can be defined as the technique of acquisition and application of information about an object without any physical contact. The information is acquired by the detection and measurement of changes that an object imposes to the environment around it, and this signal may include an electromagnetic field emitted and/or reflected, acoustic waves reflected and/or disturbed by the object or the disturbances of gravitational field or magnetic potential with the presence of the object. Usually the acquisition of information is based on capturing the electromagnetic signals that cover the entire spectrum of electromagnetic waves to radio long waves, passing through microwaves, submillimeter, thermal and near infrared, visible, ultraviolet, X ray and gamma ray [1].

The sensors used by remote sensing are devices capable of detect and register electromagnetic radiation in certain range of electromagnetic spectrum and generate information that may be transformed in a product, which can be interpreted, like an image, graphic or tables. The sensor systems are basically formed by an optical part, constructed with lens or mirrors that have the objective of receiving and directing the energy from the targets to the detectors.

The spectral reflectance measurements are the non-destructive approach most promising for determining nitrogen deficiency in crops [2]. For this purpose, remote sensing has been used to evaluate crop conditions related to nitrogen [3]. Many researchers used remote sensing to estimate crop parameters like LAI (Leaf Area Index) [4], leaf chlorophyll content [2], soil cover [5], dry matter [6], water content [7], yield [8], nitrogen content [9] and many others.

In reference [10] studying spectral signature of green leaves, was found that wavelengths from 400 to 700 nm (visible), the reflectance is low, about 10%, with a smooth increase at 550 nm (green). In the near infrared region (700 to 1,300 nm) there is another increase in the reflectance, close to 50%. For the visible light the low reflectance is related to the absorption associated to leaf pigments, mainly chlorophyll. And the reflectance increase at the near infrared region is due the internal structure of the leaves (size and shape of the cells and empty spaces). Combining both visible and near infrared reflectance there are the vegetation indices, which can be resulted from two or more spectral bands.

First, [11] it was proposed the ratio between the measurements from 800 and 675 nm to determine the leaf area index in forests. The relation between these two wavelengths is known as RVI (Ratio Vegetation Index). The NDVI (Normalized Difference Vegetation Index) appeared just after [12], which was found a relation between two wavelengths that better solved the issues about soil interference on the vegetation measurements, and also reduced the atmosphere influence and sun angle variations.

The normalization proposed guarantees that the values obtained from the NDVI are contained in the same scale of values, between -1 and 1, as shown in the equation (1).

$$NDVI = \frac{(\rho_{IR} - \rho_V)}{(\rho_{IR} + \rho_V)} \tag{1}$$

Which:

ϱ_{IR} = infrared reflectance;

ϱ_V = visible reflectance.

The normalization is produced by the combination of the strong absorption by the chlorophyll in the red region and the strong reflectance in the near infrared, due to the dispersion in the leaf mesophyll and the absence of absorption by the pigments [13]. The peculiarity assigned to the NDVI is the early saturation, what makes it insensible to biomass increase after certain development stage. That means the NDVI stabilizes, showing constant values, even with the biomass increase [10].

4. Aspects of use in the field and what can affect the measurements

Measurements in the field can be affected by the sensor positioning, like the distance from the crop, dependence of a light source, the presence of dew over the leaves and also because of factors that can stress the plants. The light source classifies the sensors in active and passive sensors. The passive sensors are dependent of sunlight, not working at night or might show different readings when there are clouds or shadows. There is a limitation of the distance from the target to the sensor, because if it is too close the sensor may not capture the reflectance, and if it is too far the data may have noise signals. And the presence of dew is just because the presence of water over the leaves can change the reflectance in both visible and near infrared. With the presence of dew the reflectance increases, but as visible light is more affected, consequently reduces the NDVI values.

Other methods can be used instead of on-the-go sensing to indirectly measure nitrogen stress, like chlorophyll content in the leaves using chlorophyll meters [14] like SPAD and ClorofiLOG. In reference [15], analyzing aerial and satellite images it was found lower correlation with wheat crops variables then ground sensors, besides depending on the weather it is not possible to have satellite images due the presence of clouds.

The spectral data that can be obtained from satellite images have low temporal resolution to use in agriculture. The ground acquisition is independent from the weather, the data collection can be done together with other machinery operation and the data are available just after you finish, with no need of complicated processing [16]. Higher correlation was found between the NDVI obtained from the GreenSeeker then the NDVI obtained from the satellite Quickbird II images for the amount of nitrogen applied, nitrogen content on the flag leaf, yield and protein content in wheat grains [15].

In reference [17] the author used a sensor installed in the front of a tractor to acquire spectral data in wheat. The tractor was at the speed of 0.8 m/s, and the sensor was set to register data with the frequency of 10 measurements per second. The authors found good relationship between the reflectance and nitrogen absorption by the wheat crop. The same configuration was used to collect data in pasture and also found good relationship between the NDVI and the nitrogen removal by the crop [18]. But depending on the sensor used, the speed can also affect the NDVI, increasing the coefficient of variation of the measurements.

An experiment conducted along the day, collecting NDVI values at the same spot but in different times of the day showed that the presence of dew on the leaves reduced the NDVI values of 12% for GreenSeeker and 27% for Crop Circle, from the first (7:30 am) to the last reading (11:30 am). Near infrared showed small differences in the readings, not significant, unlike the results of the visible data, but they both increased. These results lead to conclude that the visible wavelength is more affected by the presence of dew than the near infrared. Then, the presence of dew should be considered for nitrogen recommendation based on active optical sensors.

Stressed plants can show a decrease in the absorption by the chlorophyll, also decreasing the reflectance in the near infrared due to changes in the cells structure [19]. And that is what makes the sensors to be promising while evaluating nitrogen stress. Many studies were realized to estimate nitrogen deficiency in corn [3], wheat [20], edible beans [21], cotton [22], citrus [23], barley [24] and sugarcane [25]. These authors showed great potential to use sensors to estimate nitrogen content in crops.

5. Experiments and results obtained with sensors

As discussed previously, the sensors are able to measure differences in color and biomass production. In the field when nitrogen is applied and the plant absorbs it, the result is a plant greener and with more biomass. The Figure 3 shows the first experiment realized by ABC Foundation in Brazil in the winter of 2006 with the result of nitrogen application in wheat and the effect on the NDVI measured by the GreenSeeker sensor in two different soils.

The graphic in Figure 3 is a typical result of nutrient application in agricultural crops, with a quadratic model. There is always a limit, technical or economic, which beyond that there is no gain in yield. If linear models explained fertilizers application, where more fertilizer applied should result in more yield, it would be much easier, but there is also a physiological response, when higher nutrients rates become toxic to the plant. This result shows that applying more nitrogen we could find a response from the NDVI measured with a GreenSeeker sensor. In

Table 2 it is possible to see other variables that had significant correlation with the NDVI in the same experiment.

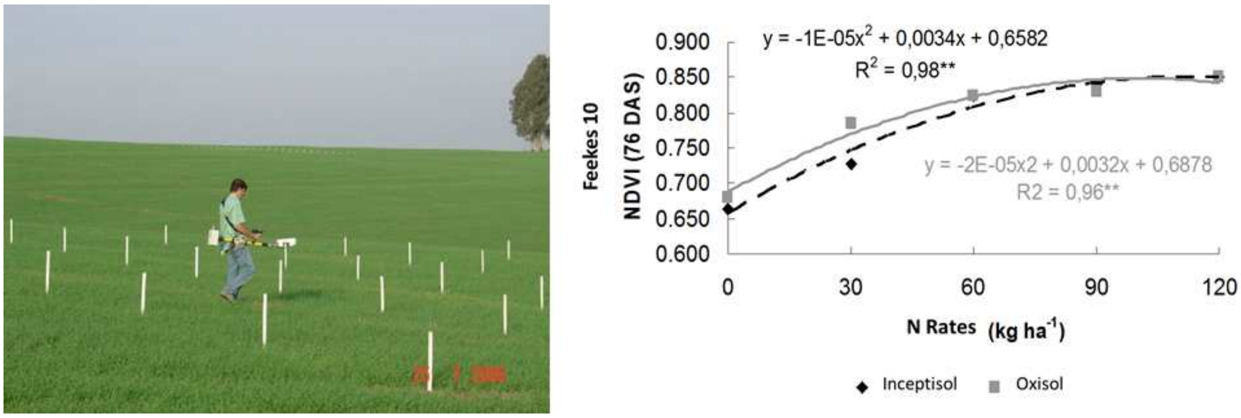

Figure 3. First experiment and NDVI response with nitrogen rates in wheat.

Variables	Inceptsol	Oxisol
	(r)	
Leaf N x Yield	0,99**	0,95**
Dry Matter x Yield	0,98**	0,97**
NDVI x Leaf N	0,95**	0,88*
NDVI x Dry Matter	0,97**	0,99**
NDVI x Yield	0,95**	0,98**

Table 2. Coefficients of correlation (r) between the evaluated variables in a wheat experiment in two different soil types. Leaf nitrogen content, dry matter and NDVI were evaluated 76 days after sowing, at the Feekes 10 stage of development.

6. Use of optical sensors combined with a GPS receiver to create maps

Maybe one of the most interesting applications for optical sensors in agriculture is to be able to use geographical coordinates to create maps from reflectance measurements. But why do that? Precision Agriculture is based on the fact that all fields have variability. Understanding this variability is first step to make decisions about investments in Precision Agriculture. Many procedures may be used to characterize and treat spatial variability on yield aiming profit for the farmers, but a wide and safe vision about the impact of the variability in a production system requires an accurate measurement of this variability.

Soil variability is caused by climate, topography, vegetation, soil forming processes and also management. These factors can influence the variability in different scales and cause great variability on nutrient availability in the soil. Then, when using uniform rates of fertilizers it is almost certain that excessive rates will be applied to some parts of the field and inadequate rates in others.

Precision Agriculture can be defined as a management system that considers spatial variability that is present in a production field, independently of the size and treats locally this variability. It is well proved that quality and yield are spatially variable and systems are being developed to explore these variations and increase profit [26]. The variable rate application of fertilizers is one of the options to manage variability, and creating maps from optical sensors can help to realize variable applications with nitrogen.

An optical sensor connected to a GNSS (Global Navigation Satellite System) receiver is able to register reflectance values with a pair of coordinates (latitude and longitude), and when the file is imported to a GIS software (Geographic Information System) it is possible to represent the measurements and its distribution in a field with maps (Figure 4).

Depending on sensor system used, that information can be stored in different ways and types of files. Some systems installed in agricultural machinery allow using a laptop with software that will store the sensor readings and coordinates. Other systems use their own data logger or a pocket pc. The Figure 4 is an example of a raw data collected in a field. Each strip is around 24 meters from each other, but what looks like a line, actually are many dots very close to each other due the frequency used to collect the data in the field. If we look closer, we see as in Figure 5.

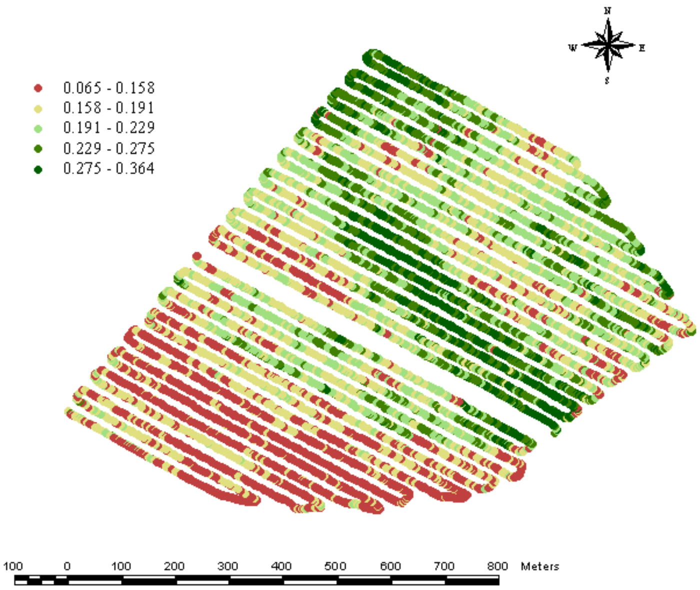

Figure 4. NDVI raw data.

As showed before in the picture of the motorcycle with one sensor on each side, when looking closer at the data we can see that in every coordinate we have a NDVI value from each sensor.

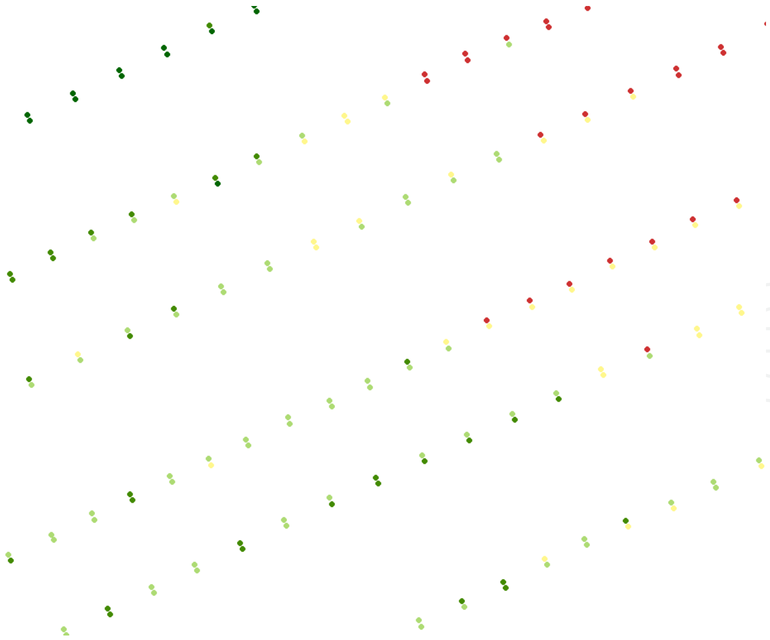

Figure 5. NDVI raw data (zoom in).

As the frequency is very high, lets say 5 Hz or 5 measurements per second, if the motorcycle moves at 5 m/s (18 km/h) with 24 m distant from the next pass, the sensor registers two NDVI values every meter and more than 800 measurements per hectare. But the raw data may have noise, so after applying some statistical filters to remove outliers and using some kind of interpolation method, for example the inverse distance, it is possible to create a surface map with a regular grid that will look like a raster image. The Figure 6 is a NDVI map after interpolating the raw data from a corn field.

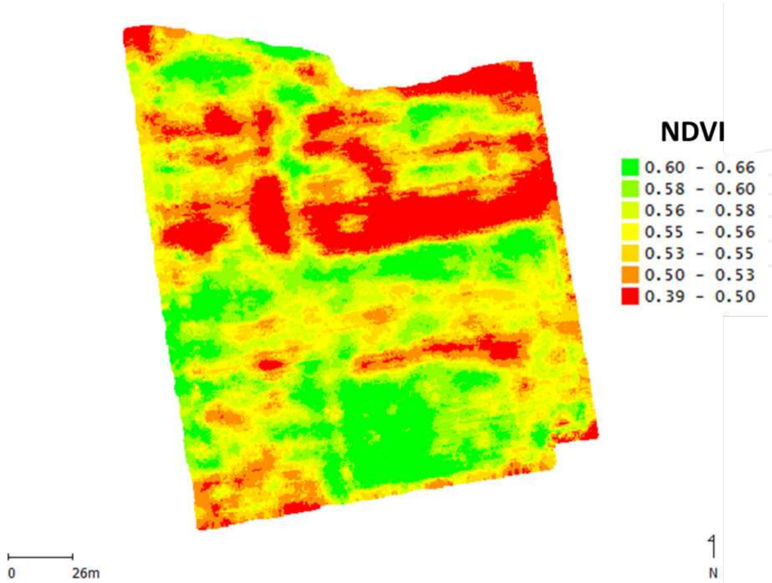

Figure 6. Interpolated NDVI map of a 2.86 ha field with a corn crop.

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Figure 7. Picture of corn plants with low NDVI values.

This maps shows that in the red areas the corn plants had a low development and because of that will have lower yields (less than 10 tons/ha), while the green areas had yields over 12 tons/ha. This information is important for precision agriculture users that are interested in finding the specific problem for that particular location. Looking at plants in the field, right in middle of the map in the red area, we can see the plants as showed in Figure 7.

The NDVI map created while the corn crop is still at the V6 stage of development, allow the farmers and agronomists to go back in the field and see what is causing this slower growth of the plants. And as the information is stored, it is possible to go back every year at the same spot for comparison, collect soil and plant samples, send to the lab and try to understand what the problem is. That means the farmer can treat each part of the field accordingly with its own characteristics.

7. Nitrogen application based on sensor's measurements

Why manage nitrogen in agricultural crops? Because some crops do not have the ability to fix atmospheric nitrogen like soybeans do, so nitrogen is applied to crops from mineral fertilizers.

Among the nutrients, nitrogen (N) is the most important and essential for crop development and is also important from an environmental perspective. Nitrogen is a constituent of chlorophyll, the first pigment to absorb the light energy necessary for photosynthesis. Plants usually have 1 to 5% nitrogen in their tissues, and if used appropriately with the other nutrients, N addition can accelerate the development of corn and other grains [27]. And unlike other important nutrients as phosphorus or potassium that are measured in the soil with chemical analyses of soil samples, nitrogen is recommended based on historical response curves.

Plants with N deficiency have yellow leaves and reduced growth. Not only does the absence of N limit yield, but so can excess N. In most cases, N application recommendations are based on average conditions, and farmers do not use the most advantageous fertilizer combinations, even when there is no financial limitation [28].

The absorption of N by crops is variable among and between seasons, as well as between locations in the same field, even when the N supplies are high [29]. The N supply from soil to crop varies spatially. Consequently, the demand for N by the crop also varies. As a result, the crop's nutritional status is a good indicator of the necessary N rate application [30].

Traditional N management around the world is generally inefficient, creates environmental contamination and is controversial. To provide appropriate recommendations of spatial N applications, it is necessary to use several tools simultaneously, such as crop and soil sensors, to achieve reliable measurements of N availability from soil and crops needs [31].

The evaluation of nitrogen use efficiency (NUE) in agriculture is an important way to evaluate the density of N applied and its role in yield [32]. Because crop responses to N application depend on the organic matter in the soil, strategies of N management in cereal crops that include reliable predictions of the response index in each season could increase NUE [33].

In this scenario, sensors are becoming more prevalent in agricultural lands. Using variable rate equipment, it is possible to detect variability in crops and make rapid decisions in the field. Some sensors allow real time changes in agricultural practices by detecting variability and responding to that variability [34].

In reference [20] they developed a methodology to apply nitrogen based on crops reflectance, using a yield parameter sensible to local conditions, intrinsic and that could reflect yield potential, possible to be used in season. Unlike other models that need several parameters to predict plant growth, the optical sensors use the plant as an indicator. Later [35] they created an index called INSEY (in-season estimated yield), which is calculated dividing the NDVI value by the number of days from sowing to sensing. The relation between the INSEY and Yield generate an exponential model using plot experiments, which can be used to estimate yield just based on the sensor measurements. Estimating yield where there is and where there is not nitrogen, by the difference in yield it is possible to calculate the nitrogen rate to make them to have the same yield.

This method considers the spatial variability of yield potential, the absorption of nitrogen applied at sowing and the crop's response to an additional N rate. NUE were increase in 15%

and showed that the measurement of crop's reflectance can be used to calculate more efficient and profitable N rates [35]. The ability to identify areas where the crop will respond to the fertilizer applied is important, if the response to N is expected, then management strategies can be modified [36].

Many field experiments were realized in order to create the algorithms that convert the sensor readings in nitrogen rates and to validate the results. Depending on the year, savings of none to 75% of nitrogen were found. For example the Figure 8 shows the NDVI and yield response to nitrogen rates. Using the 120 kg of nitrogen per hectare as the standard rate, the NDVI measured 50 days before the harvest indicates that the wheat crop won't respond to rates over than 60 kg of nitrogen per hectare. And the wheat yield obtained after the harvest shows that rates over than 60 kg/ha will affect yield negatively. Therefore, in this example, the nitrogen rate was 50% lower than the commonly recommended rate.

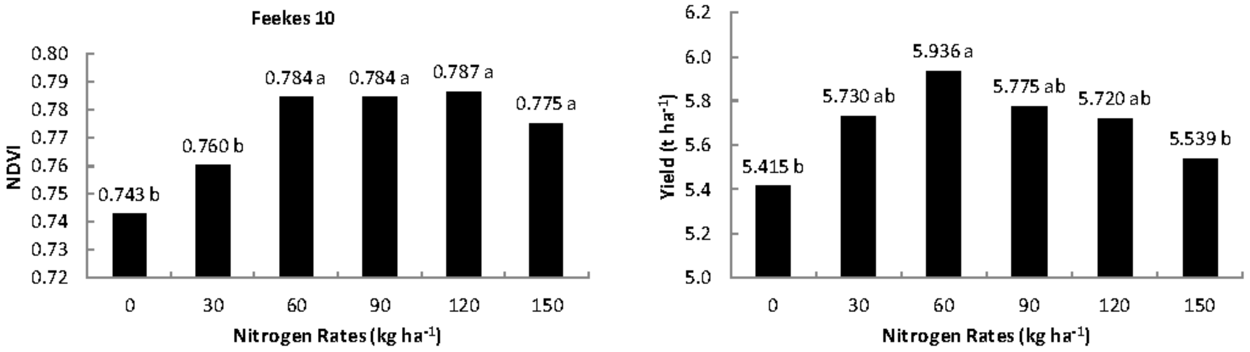

Figure 8. NDVI and wheat yield response with nitrogen rates applied.

The yield goal, often used for nitrogen recommendations, is the yield that the farmer expects to produce. But what you expect to produce and what really is going to be produced are usually different. In [20] they exemplify that the North Dakota State University recommend using the maximum yield obtained in the last 5 years as yield goal, because it is usually 30% higher than the average. The yield goal can also be calculated adding 5 to 10% to the average yield from the last 5 to 7 years [37]. One example is to use 25 kg of nitrogen per ton of corn expected. But management practices and the weather have a huge influence on yield. Climate can vary significantly from one year to another, what may cause great differences in yield potential [31].

Now let's use an experiment as an example of how to realize a nitrogen recommendation using variable rate across a field. The experiment was realized in South Brazil, Paraná State, farm Manzanilha (25° 28′ 55″ S, 50° 21′ 07″ W), during 2007 winter. The sensor used was the GreenSeeker Hand Held^{TM} measuring the NDVI. The treatments (Table 3) were disposed in strips with fixed rate of nitrogen (6 x 600 m) and variable rate of nitrogen (11 x 600 m), with four treatments and four replications. The wheat was sowed in May 28th. The Sketch is presented in Figure 9.

Treatments	N Sowing	N Feekes 1	N Feekes 5	N Feekes 10	Total N
1	18,4	0	0	Sensor	18,4
2	18,4	34	0	Sensor	52,4
3	18,4	0	102	0	120
4	18,4	34	68	0	120

Table 3. Treatments with nitrogen rates (kg/ha)

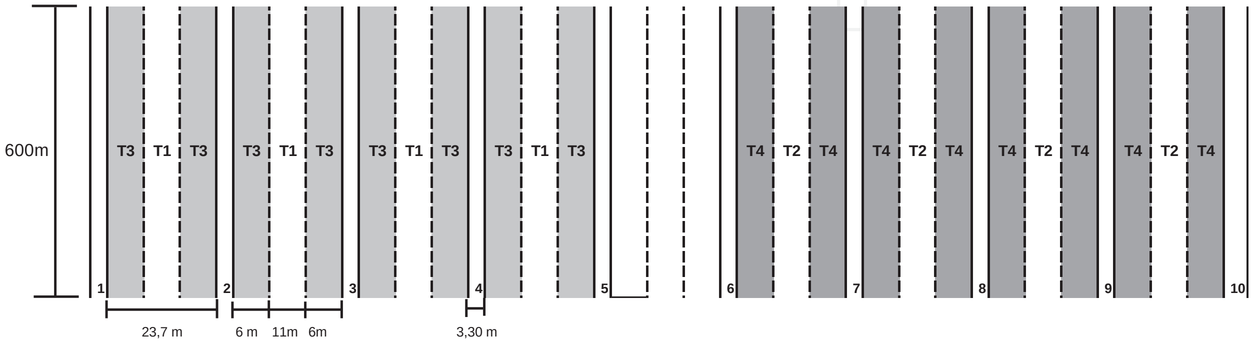

Figure 9. Experiment sketch.

All treatments received 18.4 kg/ha of nitrogen at the sowing; treatments 2 and 4 had an extra 34 kg/ha just after sowing and treatments 3 and 4 received more 102 and 68 kg/ha of N, respectively, on Feekes 5 to complete the 120 kg/ha of N, recommended based on historical response curves. Treatments 3 and 4 were used as control, and treatments 1 and 2 received variable rates of nitrogen at Feekes 10 based on the sensor readings.

The measurements were realized with the GreenSeeker sensor mounted on a motorcycle 79 days after sowing (Feekes 10). The pictures of the field and data collection can be seen in Figure 10.


(a) (b)

Figure 10. Details of the sensor mounted on the motorcycle (a) and data collection (b).

After the measurements, the data were imported to a GIS software (SSToolBox) to create a map with the NDVI raw data (Figure 11).

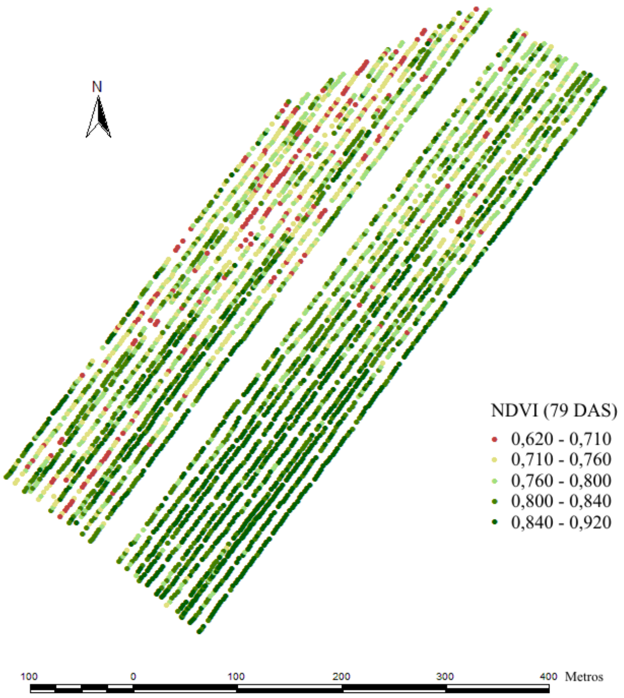

Figure 11. NDVI raw data in wheat.

Looking at the NDVI map it is possible to notice that even at the 120 kg/ha of N strips there was spatial variability, so it was decided to adapt the methodology proposed in [35], and do not use the average of the strip as a control, but divide the strip in three levels according with the topography. The elevation map (Figure 12) was created from the data collected by the GPS receiver. It was used three NDVI averages for treatment 3 and more three averages for treatment 4, with a total of six NDVI values to be used as a reference and estimate yield.

After dividing the elevation in three ranges it was calculated the average of the NDVI values for the 6 regions. Then the response index (RI) was calculated (eq. 2) with the ratio between the average NDVI from strips with 120 kg/ha of N and the NDVI from every point in the map. That means that every point has an NDVI value and a RI value.

$$RI = NDVI_{\text{rich strip}} / NDVI_{\text{field}} \tag{2}$$

Which:

$NDVI_{\text{rich strip}}$ = NDVI from 120 kg/ha of N strips;

$NDVI_{\text{field}}$ = NDVI from all points in the field that will be applied N;

RI = response index.

The response index means that if the number is higher than 1, the NDVI from the strip with more N is higher than the NDVI from the parts of the field that will be applied, so the plants are using the N. And if RI = 1 means that where there is N and where there is no N the NDVI is the same, so there is no need to apply more N. Using RI it is possible to identify the parts of the field that will need more nitrogen, and save where there is no response, because it will not have increase in yield.

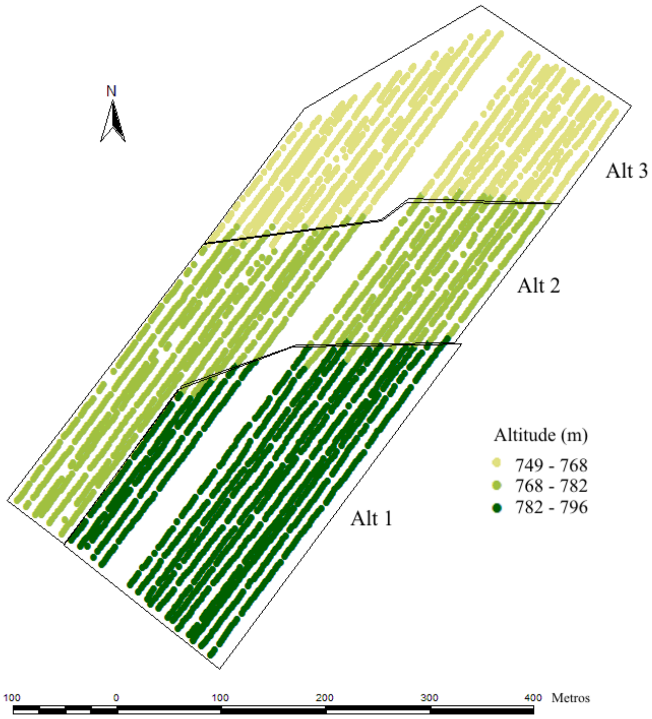

Figure 12. Elevation map divided in three levels.

To calculate the N rate was used the methodology from [35], identifying the difference of yield between the N rich strip and the rest of the field, and then applying the correct N rate to reach the same yield. That means the objective is to save nitrogen and not increase yield. The N rates calculated were used to create a nitrogen application map (Figure 13).

The calculated rates varied from 0 to 60 kg/ha of N, but they were simplified into three ranges and applied the maximum of each range. For example, the rate 20 kg/ha represents the rates from 0 to 20 kg/ha and so on. This simplification was done to make the application easier. To apply the nitrogen it was used a sprayer mounted on a tractor for liquid nitrogen application (Figure 14). To vary the rates along the field the tractor changed the speed, for each one of the rates was determined a specific gear of the tractor and a specific engine rotation. The sprayer was calibrated to apply 20 kg/ha (2.5 m/s), 40 kg/ha (1.25 m/s) and 60 kg/ha (0.8 m/s). The gears and the engine rotation for tractor were determined with a 50 m space measuring the time that the tractor took to move the 50 m. The sketch of the application is in Figure 15.

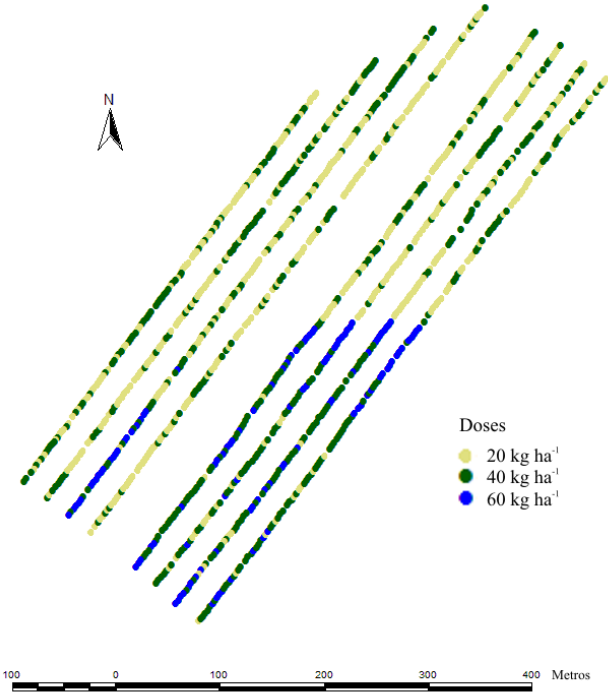

Figure 13. Nitrogen map from the calculated rates.

Figure 14. Pictures of the liquid nitrogen fertilizer application.

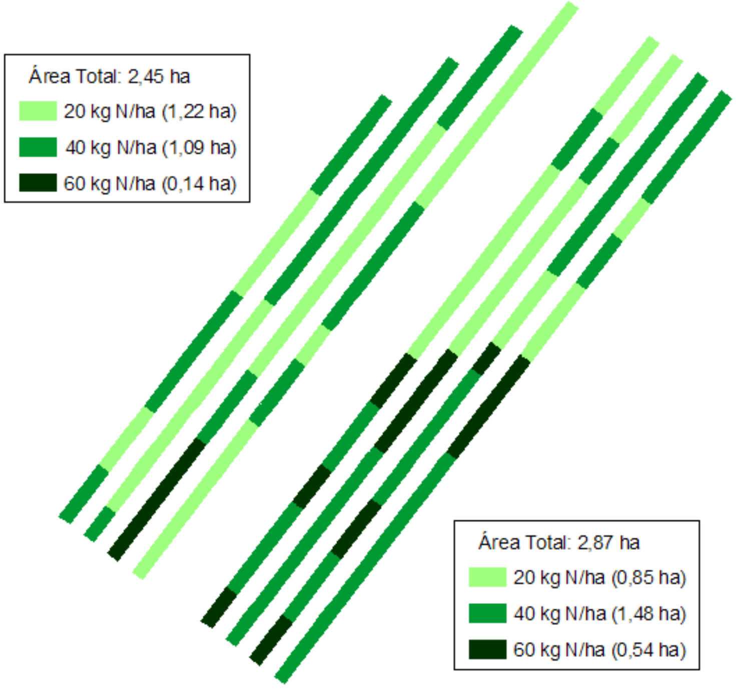

Figure 15. Sketch of the nitrogen application.

The harvest of the strips was realized using a combine John Deere 9650 STS with a 30 feet header and equipped with a yield monitor AgLeader PF3000 Advantage, what made possible to generate the yield map. The Figure 16 shows the yield map that was similar to the NDVI map. We can see in the map that each strip has a pair, because one strip is the 120 kg/ha of N and the other is the variable rate application. The yield varied from 1,500 to 5,500 kg/ha of wheat. But even the strips with 120 kg/ha of N had some parts of the field with lower yields, which means that these regions of low yield have some other problem and not nitrogen deficiency. Comparing with the application sketch the region of higher rates are same regions of high yields.

The left side of the experiment (first 4 pair of strips) had an average yield of 3,053 kg/ha using variable rate application, with 69.3% of saving in nitrogen, and 3,026 kg/ha using 120 kg/ha of N. The right side of the experiment had an average yield of 3,568 kg/ha using variable rate, with 42.5% of saving in nitrogen, and 3,546 kg/ha using 120 kg/ha of N. There was no statistical difference between the yield of fixed rate and variable rate, but the savings were high. The saving of nitrogen was higher in the region with lower yield potential.

As high is the yield goal just with the nitrogen supplied by the soil, with no additional N (low RI), in general, lower will be the N rates to reach maximum yields. If the RI for a field is low (RI < 1.1), that means the places with no N applied are similar with the places with N, and probably the response to an additional application will also be low. But if the RI is high (RI > 1.1), probably the crop will respond to the fertilization, so complementary rates should be applied [36].

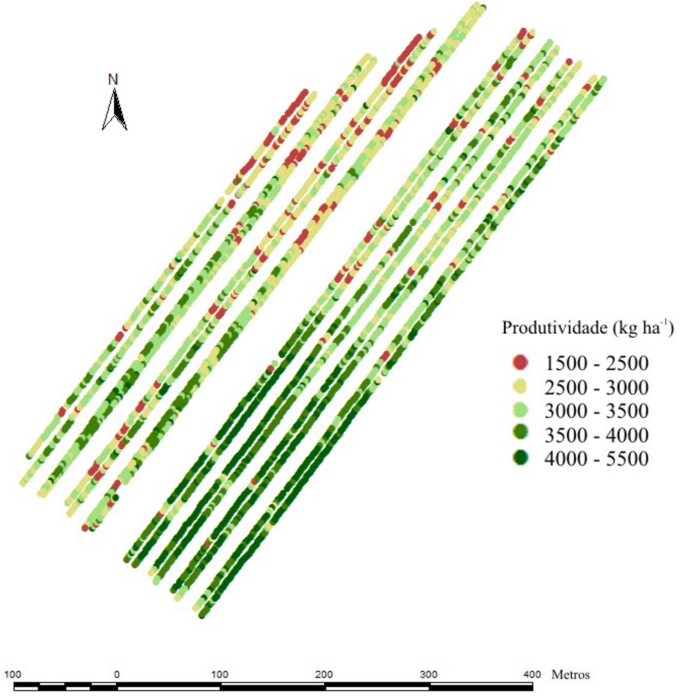

Figure 16. Yield map collected by the John Deere combine.

Ps: In each pair of strips, the left one is the 120 kg/ha of N and the right one is the variable rate application.

There is NDVI spatial variability even in the regions where fixed rates of nitrogen were applied, showing that crops respond in different ways inside the same field. The methodology used to apply nitrogen in variable rate, using the crop as an indicator and optical sensors to measure is really promising, being able to save nitrogen in places where there is less use by the plants.

However, optical sensors do not consider yield potential. Reflected light by the crop in a high yield zone can show an appropriate content of N at the moment of measurement, but N can still be deficient before maturation. In a low yielding zone, reflected light may suggest a higher need for N, inducing an excess rate application for plants that are limited by other factors [38].

Large differences were found between two corn fields, one with yields <12,000 kg/ha and the other with yields >17,000 kg/ha [39]. These authors suggested that considering climate conditions between planting date and the measurements could lead to a better relationship between yield estimation and actual yield because climate varies among areas and among years. Even when data from different areas and years are combined, the resulting model may not be reliable due spatial and temporal differences. These differences are some of the primary problems in developing a model that can be used widely to estimate yield by optical sensors. They also highlight that there is much room for improvement.

Variables that affect N availability were included, such as organic matter and soil exchange capacity, and variables that are related to N demand by the crop, such as solar radiation [40].

Additionally, the variability of rain distribution and water stored in soil at the time of planting can affect yield and management decisions [41].

Based on the observations of long-term experiments, it was found that the treatments with higher yield did not always correspond to higher N application rates. In some years, maximum yields were observed with low N application rates. In 3 long-terms experiment, there was no relationship between RI and yield. These results indicated that RI and yield are independent, and so they need to be estimated separately. Any practice that does not consider the independence of RI and yield can lead to misinformed recommendations. If yield potential varies among years along with N demand, the obvious solution to the increased efficiency of N recommendations is to be able to estimate crop response to N and yield potential [42].

8. Conclusions

The NDVI obtained from optical sensors are data that look very promising to map and analyze spatial variability of crop's development and for nitrogen management. It is possible to find significant regressions between NDVI and many crops' parameters. The technology of using optical sensors to recommend nitrogen showed high savings of the nutrient, making agriculture more profitable and with lower risk of water contamination by nitrate. Research with the application of optical sensors in agriculture is still scarce and need to expand to a wide range of conditions, for many other crops and applications.

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