Environmental Engineering and Management Journal November 2020, Vol.19, No. 11, 1975-1982
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

MODELING OF IN-SEASON WINTER WHEAT NITROGEN REQUIREMENTS USING PLANT REFLECTION INDICES

Uğur Yegül[1*], Maksut Barış Eminoğlu[1], Ufuk Türker[1], Ahmet Çolak[1], Cengiz Koparan[2]

[1]Department of Agricultural Machinery and Technologies Engineering, Faculty of Agriculture, Ankara University, Ankara, Turkey
[2]Clemson University, Department of Agricultural Sciences, Clemson, South Carolina, USA

Abstract

A significant reduction in nitrogen (N) losses from agricultural fields will make a positive impact on the environment. Managing nitrogen for the optimum application provides economic benefits as well as environmental protection. This study presents a model that was developed to determine the optimum ratio of N to yield based on N sensor indices in winter wheat. A quadratic polynomial model was used to characterize the relationship between N and yield for the optimum N rate. The N was applied to the Bezostaja and Ahmetaga wheat varieties at 0 $kg\,N\,ha^{-1}$, 80 $kg\,N\,ha^{-1}$, 120 $kg\,N\,ha^{-1}$, 160 $kg\,N\,ha^{-1}$ and 200 $kg\,N\,ha^{-1}$ ratios. The results showed that the most economical mean estimated N rate was 167.6 $kg\,N\,ha^{-1}$ for Bezostaja and 206 $kg\,N\,ha^{-1}$ for Ahmetaga.

Keywords: fertilizing, precision agriculture, vegetation index, wheat, yield

Received: August, 2019; Revised final: April, 2020; Accepted: May, 2020; Published in final edited form: November, 2020

1. Introduction

One of the most important issues in the world's wheat production is to increase the yield of wheat while ensuring the best fertilizer management strategy. It was determined that an optimal amount of N fertilizer should be applied to increase N utilization efficiency. N fertilizer optimization and application times are the most important factors for determining maximum wheat yield. N fertilizer applications will provide a significant contribution to the world economy, and it will be possible to reduce the environmental pollution caused by fertilization.

Wheat yield increase and the reduction of N fertilizer costs depend on effective N management practices. Correct prediction of the N status is very important for managing its application to increase yield.

This study aimed to establish a model using an optical sensor to determine the actual in-season N requirements based on the relationship between the normalized difference vegetation index (NDVI) and the N status for mid-season wheat yield. It is necessary to know the real N status level in the field to develop successful variable applications of it. Also, the negative environmental effect of using chemical inputs can be reduced.

Experiments that were conducted under a different NDVI growing RI suggests that correct prediction of the RI for the yield at Feekes growth stages 5, 9 and 10.5 can be made for 23 winter wheat species. This capability to determine the responsiveness of the crop to additional N at an early level of growth requires alteration of N management schemes and potentially elevates the yield and effectiveness of N use (Mullen et al., 2003).

Smil (1997) suggested that reducing N fertilizer usage may be possible by increasing efficiency with more suitable fertilization methods. Methods to reduce losses in N fertilizers include the

*Author to whom all correspondence should be addressed: e-mail: yegul@ankara.edu.tr; Phone: +90 5412581983; Fax: +90 3123183888

application of soil and plant analysis to determine fertilizer used according to plant needs, the adoption of a fertilization strategy that is suitable for the quantity of annual rainfall and distribution, the preference for split applications and the absence of a fertile surface (Mosier et al., 1996; Türker et al., 2012).

Studies show that leaf chlorophyll values indicate a close relationship between plant N content and yield (Peltonen et al., 1995; Tindall et al., 1995).

Cassman et al. (2002), Mullen et al. (2003), and Raun et al. (2002) suggested that the N contents of plants can be detected with optical sensors and that fertilizer applications can be made accordingly, as an alternative to leaf analysis. The spectral reflection values produced by plants have come to the fore with thoughtful precision agriculture approaches, which can be identified through proximal or remote sensing techniques. An example of precision agriculture studies on N is the attempt to improve spread fertilizer applications, where the readings are made through optical sensors to alter the usage parameters automatically. Solie et al. (1996) stated that the optimal area size of the data to obtain the most profitable N fertilization strategy, as well as the most efficient use of N (NUE) values, is one square meter.

It has been reported that the variation in these areas can only be determined by optical sensors and that automatic manure regulation can be made accordingly (Stone et al., 1996), which will increase the NUE value across the field. The implementation of automated manure regulating systems in the state of Oklahoma in the US was promoted, and it would be profitable due to the large size of its farms where 64.8% of the agricultural enterprises use small plots of 5 hectares. The application of these types of automated systems would not be profitable in Turkey because of its relatively small farm sizes – except large corporations that include the General Directorate of Agricultural Research and Policy of Turkey. Farmers in the US are generally applying N to wheat for a short period (Olson and Swallow, 1984), because it is cheaper to harvest in the autumn and less expensive to implement once it is known that the application of N in the US increases the NUE values (Raun and Johnson, 1999).

It was reported that N fertilization in the spring is not very important in terms of loss of evaporation in arid regions, but spring fertilization is advantageous in areas with relatively low precipitation (Christensen and Meints, 1982).

In addition to the autumn and spring comparisons, timing of spring fertilization has been studied by other researchers, and early use of fertilization in spring is required to reach the maximum biological yield (Feil, 1997).

Studies indicate that delaying spring fertilization will increase the content of NUE and grain protein (Banziger et al., 1994; Cassman et al., 2002; Feil, 1997).

It is important to reduce crop loss by determining the early fertilization times that would provide the best results in terms of both yield and protein (Palta et al., 2003).

2. Material and methods

2.1. Plant material, field trial, and sensor

Experiments were performed in randomized blocks with five repetitions at the Haymana Research Farm, Ankara, Turkey, over two consecutive years: 2016 and 2017. The specific coordinates of the experimental site within the farm were 39º37′00.05″ north and 32º41′39.09″ east. Field experiments were carried out with the two commercial varieties of bread wheat (T_1 = Bezostaja, T_2 = Ahmetaga) and N rates of 0 kg N ha^{-1}, 80 kg N ha^{-1}, 120 kg N ha^{-1}, 160 kg N ha^{-1} and 200 kg N ha^{-1} in the form of AN.

T1 and T2 represent the selected seed varieties. The Bezostaja was called T1, and the Ahmetaga was called T2. G1, G2, G3, G4, and G5 represented different fertilizing levels of AN. The fertilizing levels were 0 kg N ha^{-1} for G1, 80 kg N ha^{-1} for G2, 120 kg N ha^{-1} for G3, 160 kg N ha^{-1} for G4, and 200 kg N ha^{-1} for G5, respectively.

All other agricultural practices, including preplant fertilizing, were executed as recommended (before planting). Fertilization application was carried out on at 140th day after planting, NDVI values were collected in a different stage of plant growth including Z21 (225.9°C at 55th day after planting), Z30 (392.8°C at 86th day after planting), Z37 (568.8°C at 116th day after planting), Z50 (928.8°C at 136th day after planting), Z55 (1006.4°C at 146th day after planting), and Z60 (1122.7°C at 160th day after planting) using the Green Seeker handheld sensor (NTech, Ukiah, California).

The working principles of the GreensSeeker sensor (Trimble, California, U.S.A.) based on NDVI, which is a unit of measure that is designed to factor both near-infrared (NIR) and red light (R) reflectance. The NDVI was calculated from the NIR and R values using Eq. (1). Healthy vegetation reflects more red and blue light.

$$NDVI = (NIR-R)/(NIR+R) \quad (1)$$

where: *NDVI* – normalized difference vegetation index; *NIR* – near-infrared; *R* – redlight.

2.2. Data analysis

The data were analyzed using Tukey's multiple comparison method. Statistical Analysis System (SAS, SAS Institute, NC, US) software was used for analyses. The results of the analyses were assessed in relation to different N rates and seed varieties. The models acquired for estimating yield were used to calculate the optimum economic rate of N fertilizer. The mean values from two different trials were used to determine the optimum fertilizer rate.

The concept of response index (RI) was explored to determine the most suitable fertilization time. This index was computed for the NDVI and yield independently. The *RI* for yield is accepted to be $RI_{harvest}$ and indicates the crop response to applied N (Johnson and Raun, 2003), and in-season sensor measurements of the *NDVI* indicate N uptake between trial sites that received the N. Trial sites that did not receive N were used for computing the *NDVI* response index (Mullen et al., 2003) by using the following equations (Eqs. 2-3). The $NDVI_{max}$ represents the NDVI measurements of the plots that provided the maximum values. The $NDVI_{control}$ represented the *NDVI* measurements of control plots that were managed by farmers on the experimental site. The $Yield_{max}$ represented the maximum yield that was obtained from the plots. $Yield_{control}$ represented the maximum yield that was obtained from the control plots that were managed by farmers.

$$RI_{NDVI} = [NDVI_{(max)} / NDVI_{(control)}] \quad (2)$$

$$RI_{harvest} = [Yield_{(max)} / Yield_{(control)}] \quad (3)$$

where: RI_{NDVI} – the ratio of the *NDVI* measurement of the plot that provided the maximum value, and the *NDVI* measurement of the control plots; $NDVI_{(max)}$ – is the *NDVI* measurement of the plot that provided the maximum value; $NDVI_{(control)}$ – is the NDVI measurement of control plots; $RI_{harvest}$ – is the ratio of the maximum yield obtained from a plot and the yield obtained from the control plots; $Yield_{(max)}$ – is the maximum yield obtained from a plot; $Yield_{(control)}$ – is the yield value obtained from the control plot.

The computed values associated with RI in accordance with yield and *NDVI* were compared with each other. The highest correlation attained by comparing the two different sets of data indicated the most suitable period to apply fertilizer. The relationship between identical *NDVI* values and N rates was completed using linear regression methods to estimate the N requirements of the wheat.

The in-season yield estimation *(INSEY)* was used to evaluate the potential yield using GreenSeeker readings (Franzen et al., 2013). *INSEY* values were computed using *NDVI* readings in any period of growth divided by the cumulative growing degree day *(CGDD)* over the same period from planting to sensing (Lukina et al., 2001; Teal et al., 2006). Calculations for *INSEY* and *CGDD* are defined in Eqs. (4-5), respectively. Regarding the result of the correlation analysis between two extracted indexes for different periods of *NDVI* measurements, the period with the highest correlation indicated the most appropriate time for fertilizing. Then, the relationship between corresponding *NDVI* values and nitrogen rates at this period was used to estimate the nitrogen requirement by using a linear regression method.

$$CGDD = (T_{max} + T_{min}) / 2 - T_{base} \quad (4)$$

$$INSEY = NDVI / CGDD \quad (5)$$

where: *CGDD* – is the cumulative growing degree day; T_{max} – is the daily maximum air temperature; T_{min} – is the daily minimum air temperature; T_{base} – is the basic temperature at which product development begins; *INSEY* – is the in-season yield estimation; *NDVI* – is the normalized difference vegetation index.

Determining the optimum amount of N in the N fertilizer used is crucial, and the optimum economic amount of N depends upon the highest possible wheat yield. The average yield values were used to estimate the response functions to N to determine the optimum N rate. Meaningful data from the Haymana research farm trials were used to calculate the N rate from the *NDVI*-based calibration equation. The use of the equation obtained maximizes the economic return and avoids unnecessary consumption of N. The effect of the two seed varieties on the *NDVI* values were statistically significant ($p < 0.05$), and the relationship between *NDVI* and additional N rates were determined for both seed varieties.

3. Results and discussion

The relationship between the yield values and the N fertilizer rate was statistically significant, which is shown in Table 1. As the most applicable statistical model, quadratic polynomial curves were used for estimating yield values. It is critical to understand when the N is applied and when the N uptake by plants occurs. Different opinions have been put forward in the literature reports on this subject. Out of the entire development period, at least 80% of the N uptake occurs during the vegetative growth stage (Austin et al., 1977; Heitholt et al., 1990; Oscarson et al., 1995; Palta et al., 1994; Van Sanford and MacKown, 1987). Báez-González et al. (2002); Teal et al. (2006); and Ali et al. (2014, 2015) stated that *NDVI*, as measured by GreenSeeker sensor, is useful in acquiring information such as potential yield, and N status studied the relationship between *NDVI* measurements with GreenSeeker and grain yield of and found that R^2 values ranged from 0.49 to 0.63. Feng and Yang (2011), indicated that correlated *NDVI* measured at jointing to filling stages with grain yield of wheat and found the values ranged from 0.31 to 0.82. Ali et al. (2018) studied on rice, and maize proposed that fertilizer N application should be based on the relationship between in-season GreenSeeker measurements and total N uptake at maturity.

N fertilizer is a crucial factor in wheat production; it results in a significant increase in grain yield compared to no-N treatment (Ercoli et al., 2013), and yield is increased to a comparable extent by N application (Zhang et al., 2016). Sapkota et al. (2020) determined yield and N_2O fluxes under two tillage systems and five N for both rice and wheat. Their finding proposed that N rates between 120–200 kg N ha^{-1} in rice and 50–185 kg ha^{-1} in wheat This survey contribute the 'optimum' range for fertilizer N rate for rice and wheat to maximize crop yield and economic profit and to minimize. Ma et al. (2019) were accomplished to investigate the effects of N regime on wheat yield, photosynthesis, and N balance at different locate, field experiments including five N levels, from 0 to 300 kg ha^{-1}.

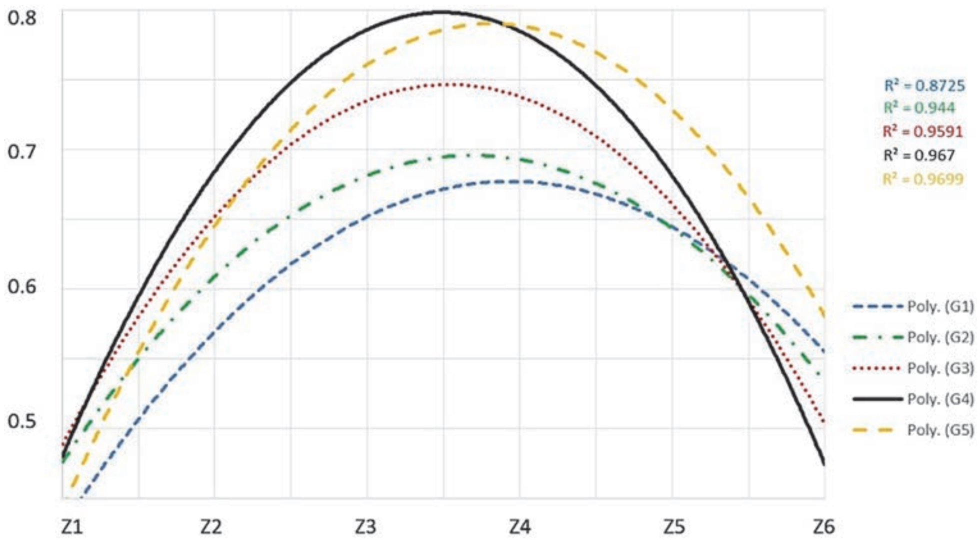

Fig. 1. NDVI changes in different measurement periods according to the Zadoks growth scale

They obtained the grain yield increased with N rate, and the maximum values were application rates of 250 and 337 kg N ha^{-1}, respectively. Aizpurua et al. (2010) were found the optimum amount of N fertilizer required to maximize income of soft red winter wheat in Alava(Spain. Economically optimum rates of N application (Nyield) varied from 142 to 174 kg N ha^{-1} depending on the price of both N fertilizer and wheat. Campillo et al. (2010) carried out a research in southern Chile, and they found that optimal economic N rate ranged from 248 to 274 kg ha^{-1}; also, they found the increase of applied N continuously decreased nitrogen efficiencies use in both productive cycles. Eitel et al. (2008) stated that spectral indices are useful for estimating crop yield potential and basing in-season N fertilizer applications, and *NDVI* is positively related to crop N status. They found that the *NDVI* and other simple indices were highly correlated with LAI ($r^2 \leq 0.84$) and chlorophyll ($r^2 = 0.70$). Li et al. (2012) carried out a research in southeast Germany and the North China Plain from 2007 to 2010. They conducted experiments with different N rates for five German cultivars and four Chinese cultivars of winter wheat, and they found that biomass strongly affected the relationships between vegetation indices and N concentration before the heading stage. They also stated that N fertilizer use efficiency and to reduce the pollution potential by monitoring N concentrations after the heading stage.

3.1. Evaluation of statistical analyses

Wheat price and net return values derived from the net return equation used values of 167.6 kg N ha^{-1} for Bezostaja and 206 kg N ha^{-1} for Ahmetaga to find the most economic optimum N rate corresponding to yield. The wheat yield values were obtained when 160 kg N ha^{-1} (for Bezostaja) and 200 kg N ha^{-1} (for Ahmetaga) of N was applied in accordance with the statistical analysis. To create this equation, *INSEY* was computed from four *NDVI* readings after the fertilizer was used. *NDVI* for different measurement periods, according to the Zadoks growth scale, is shown in Fig. 1. The potential yield was estimated at the experimental site using (Eq. 6). The estimated potential yield at the experimental site where the response of the *NDVI* values to N fertilizer is important (with no additional N fertilizer) was as follows:

$$Potential\ Yield = 6952\ INSEY – 2.302\ (R^2=0.7674) \quad (6)$$

Given that *CGDD* were 928.8°C – with reference to *INSEY=NDVI/CGDD*.

The influence of different N rates on yield is shown in Fig. 2. The result of variance analysis showed that all quantities and quality parameters were significantly affected by N rates. The *INSEY* can be used to calculate potential yield without additional N fertilizer. GreenSeeker sensor readings were used to determine the optimal timing for using N fertilizer. To achieve this purpose, RI was calculated from different *NDVI* measurements and yield over different measurement periods.

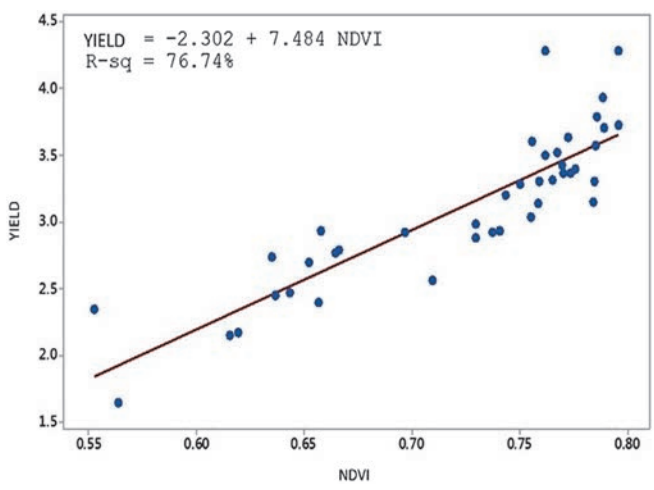

Fig. 2. Relationship between yield and *NDVI* values

The conclusion of the regression analysis to determine the relationship between RI_{NDVI} and the corresponding $RI_{harvest}$ is shown in Table 1. The degree of N fertilizer used is calculated from the above equation (Eq. 7). As a result, the computed *NDVI* values using GreenSeeker can be used to estimate the N status.

$$NDVI = 0.0341 \text{ Fertilizer Rate} + 0.6073 \quad (R^2=0.92) \quad (7)$$

3.2. Estimation of the optimal N rate

The experimental results showed that the potential winter wheat yield could be found from the ratio of *NDVI* measurements after fertilization and *CGDD*. The application of N fertilizer at 928.8°C *CGDD* was recommended, as this gave the highest correlation between *NDVI* indices with respect to the *RI* of *NDVI* and yield at harvest.

The necessity for fertilizer can be computed using the response function of *NDVI* to different fertilizer degrees. The effects of different N fertilizer rates (kg N ha^{-1}) on *NDVI* values and estimated regression parameters and R^2 values for the averaged winter wheat yield response functions to N, and the estimated regression parameters and R^2 values, are shown in Table 2 and Table 3, respectively. Also, the relationship between RI_{NDVI} and $RI_{harverst}$, and the relationship between yield and *INSEY* values, are shown in Fig. 3 and Fig. 4.

3.3. Simple cost analysis

Control plot is considered a farmer practice and is the amount of fertilizer applied by the farmer. Five nitrogen treatments were selected based on farmer practice on the experimental region. Thus, considering the amount of 160 as the conventional N rate, other experimental rates were selected as higher and lower rates than farmer practice in order to show what the optimal nitrogen rate exactly is. The values obtained as a result of the research were 167.6 kg N ha^{-1} for Bezostaja and 206 kg N^{-1} ha for Ahmetaga. The economic analysis was carried out with the current price of ammonium nitrate (AN) fertilizer at 143 \$ ton^{-1}.

The Haymana, Research and Application Farm, grows crops on 57 hectares of wheatland, and they apply 200 kg ha^{-1} of pure N. However, we find the optimum amount of N (167.6 kg ha^{-1} of pure N) which was applied in this study. The difference was 32.4 kg ha^{-1} of pure N; thus, 97.2 kg of AN fertilizer more than necessary was applied to 1 hectare because AN manure composition has 33% pure N. For 57 hectares, approximately 5540.4 kg of manure and at least 792 \$ was lost each year. As a result of this study, this loss was prevented. Since it is the preferred wheat variety by the farmer, simple cost analysis has been made for the variety of Bezostaja.

Table 1. Relationship between RI_{NDVI} and corresponding $RI_{harvest}$

RI_{NDVI}	$RI_{harvest}$
RI_{NDVI} - first reading	8.81
RI_{NDVI} - second reading	11.21
RI_{NDVI} - third reading	69.37
RI_{NDVI} - fourth reading	77.51
RI_{NDVI} - fifth reading	76.57
RI_{NDVI} - sixth reading	65.30

Table 2. The effects of different N fertilizer rates (kg N ha^{-1}) on *NDVI* values

N rate	*NDVI-1*	*NDVI-2*	*NDVI-3*	*NDVI-4*	*NDVI-5*	*NDVI-6*
0	0.404±0.075 A	0.608±0.090 A	0.679±0.066 B	0.622±0.039 B	0.646±0.102 AB	0.567±0.106 A
80	0.460±0.149 A	0.637±0.093 A	0.679±0.035 B	0.696±0.066 AB	0.614±0.043 B	0.549±0.089 A
120	0.495±0.102 A	0.646±0.059 A	0.734±0.067 AB	0.716±0.067 A	0.701±0.063 AB	0.485±0.109 A
160	0.467±0.117 A	0.714±0.060 A	0.784±0.032 A	0.747±0.019 A	0.709±0.093 AB	0.468±0.063 A
200	0.425±0.118 A	0.685±0.044 A	0.747±0.053 AB	0.767±0.022 A	0.740±0.045 A	0.581±0.102 A

Table 3. The effect of N fertilizer rates on yield at the Haymana experimental site

N Rate kg N ha^{-1}	*Yield*
0	2.153±0.380 B
80	2.623±0.485 AB
120	3.082±0.383 A
160	3.285±0.559 A
200	3.225±0.528 A

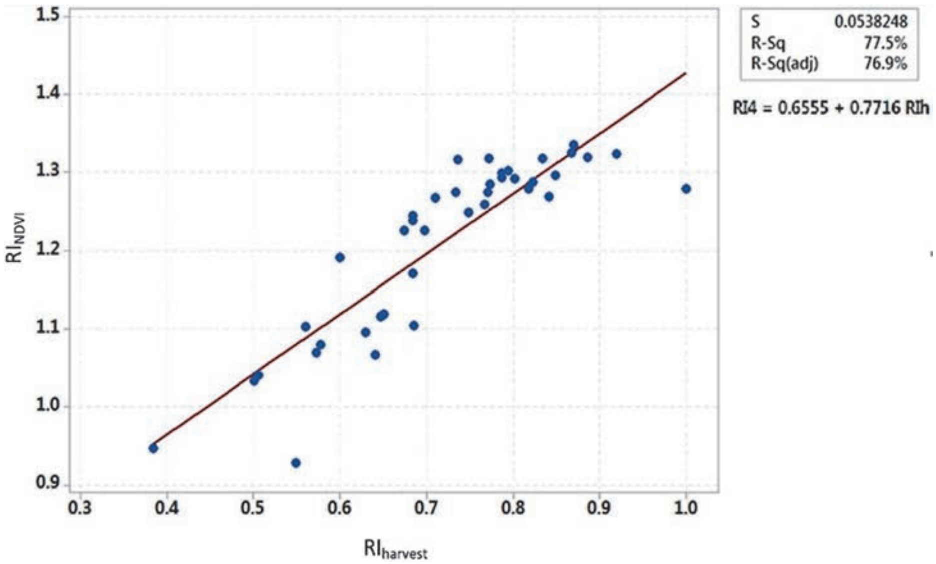

Fig. 3. Relationship between RI_{NDVI} and $RI_{harvest}$ obtained from the 4th reading after fertilization

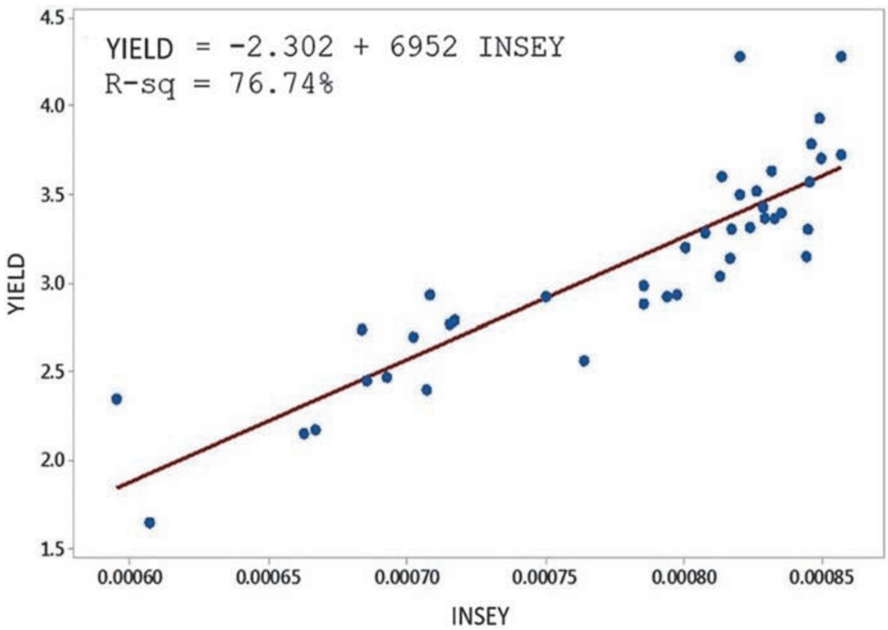

Fig. 4. Relationship between yield and *INSEY* values

4. Conclusions

Winter wheat growing efficiency is related to yield that is affected by nitrogen fertilizer. This study showed that the GreenSeeker sensor has the potential to evaluate in season grain yield-related to nitrogen level in winter wheat.

We observed an association between yield and *INSEY*. Determining the economically optimal nitrogen fertilizer rate in terms of wheat price and nitrogen fertilizer price based on yield applied nitrogen is was one of the crucial steps to assess the nitrogen requirement.Accordingly, the quadratic model was used to determine the relationship between the applied nitrogen rate and yield. In this study, applying different Nitrogen fertilizer rates had a significant effect on the yield parameters.

According to the results, maximum yield was achieved when 167.6 kg N ha^{-1} for Bezostaja and 206 kg N^{-1} ha for Ahmetaga were applied, respectively. This study showed that crop reflectance values using optical sensors could be used to achieve efficient and lucrative fertilization levels.

References

Aizpurua A., Estavillo J.M., Castellón A., Alonso A., Besga G., Ortuzar - Iragorri M.A., (2010), Estimation of optimum nitrogen fertilizer rates in winter wheat in humid mediterranean conditions, II: Economically optimal dose of nitrogen, *Communications in Soil Science and Plant Analysis*, **41**, 301-307.

Ali A.M., Abou-Amer I.A., Ibrahim S.M., (2018), Using GreenSeeker active optical sensor for optimizing maize nitrogen fertilization in calcareous soils of Egypt, *Archives of Agronomy and Soil Science*, **64**, 1083-1093.

Ali A.M., Thind H.S., Sharma S., Varinderpal-Singh, (2014), Prediction of dry direct-seeded rice yields using chlorophyll meter, leaf color chart and GreenSeeker optical sensor in northwestern, *India Field Crops Research*, **161**, 11-15.

Ali A.M., Thind H.S., Varinderpal-Singh, Bijay-Singh, (2015), A framework for refining nitrogen management in dry direct-seeded rice using GreenSeeker optical sensor, *Computers and Electronics in Agriculture*, **110**, 114-120.

Austin R.B., Ford M.A., Edrich J.A., Blackwell R.D., (1977), The nitrogen economy of winter wheat, *Journal of Agricultural Science, Cambridge*, **88**, 159-167.

Báez-González A.D., Chen P.Y., Tiscareño-López M., Srinivasan R., (2002), Using satellite and field data with crop growth modeling to monitor and estimate corn yield in Mexico, *Crop Science*, **42**, 1943-1949.

Banziger M., Feil B., Schmid J.E., Stamp P., (1994), Utilization of late-applied nitrogen by spring wheat genotypes, *European Journal of Agronomy*, **3**, 63-69.

Campillo R., Fornazzari C.J., Claudio, Undurraga P., (2010), Effects of nitrogen on productivity, grain quality, and optimal nitrogen rates in winter wheat cv. Kumpa-INIA in Andisols of Southern Chile, *Chilean Journal of Agricultural Research*, **70**, 122-131.

Cassman K.G., Doberman A., Walters D.T., (2002), Agroecosystems, nitrogen-use efficiency, and nitrogen management, *Ambio*, **31**, 132-140.

Christensen N.W., Meints V.W., (1982), Evaluating N fertilizer sources and timing for winter wheat, *Agronomy Journal*, **74**, 840-844.

Eitel J., Long D., Gessler P., Hunt E.R., (2008), Combined spectral index to improve ground-based estimates of nitrogen status in dryland wheat, *Agronomy Journal*, **100**, 1694-1702.

Ercoli L., Masoni A., Pampana S., Mariotti M., Arduini I., (2013), As durum wheat productivity is affected by nitrogen fertilisation management in Central Italy, *European Journal of Agronomy*, **44**, 3845.

Feil B., (1997), The inverse yield-protein relationship in cereals: possibilities and limitations for genetically improving the grain protein yield, *Trends in Agronomy*, **1**, 103-119.

Feng M.C., Yang W.D., (2011), Changes in NDVI and yield of winter wheat cultivars with different plant types, *Chinese Journal of Eco-Agriculture*, **19**, 87-92.

Franzen D., Honggang B., Sharma L., (2013), *Relationship of Active-Optical Sensor Readings with Sugarbeet Yield and Quality, Sunflower Yield and Spring Wheat Grain Protein*, ASA-CSSA-SSSA, Tampa, FL, USA.

Heitholt J.J., Croy L.I., Maness N.O., Ngyuen H.T., (1990), Nitrogen partitioning in genotypes of winter wheat differing in grain N concentration, *Field Crops Research*, **23**, 133-144.

Johnson G.V., Raun W.R., (2003), Nitrogen Response Index as a guide to fertilizer management, *Journal of Plant Nutrition*, **26**, 249-262.

Li F., Mistele B., Hu Y., Yue X., Yue S., Miao Y., Chen X., Cui Z., Meng Q., Schmidhalter U., (2012), Remotely estimating aerial N status of phenologically differing winter wheat cultivars grown in contrasting climatic and geographic zones in China and Germany, *Field Crops Research*, **138**, 21-32.

Lukina E.V., Freeman K.W., Wynn K.J., Thomason W.E., Mullen R.W., Stone M.L., Raun W.R., (2001), Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake, *Journal of Plant Nutrition*, **24**, 885-898.

Ma G., Liu W., Li S., Zhang P., Wang C., Lu H., Wang L., Xie Y., Ma D., Kang G., (2019), Determining the optimal n ınput to ımprove grain yield and quality in winter wheat with reduced apparent N loss in the North China Plain, *Frontiers in Plant Science*, **10**, 181, https://doi.org/10.3389/fpls.2019.00181.

Mosier A.R., Duxbury J.M., Freeny J.R., Heinemeyer O., Minami K., (1996), Nitrous oxide emissions from agricultural fields: Assessment, measurement, and mitigation, *Journal of Plant and Soil Science*, **181**, 95-108.

Mullen R.W., Freeman K.W., Raun W.R., Johnson G.V., Stone M.L., Solie J.B., (2003), Identifying an in-season response index and the potential to increase wheat yield with nitrogen, *Agronomy Journal*, **95**, 347-351.

Olson R.V., Swallow C.W., (1984), Fate of labeled nitrogen fertilizer applied to winter wheat for five years, *Soil Science Society of America Journal*, **48**, 583-586.

Oscarson P., Lundborg T., Larsson M., Larsson C.M., (1995), Genotypic differences in nitrate uptake and nitrogen utilization for spring wheat grown hydroponically, *Crop Science*, **35**, 1056-1062.

Palta J.A., Bowden W., Asseng S., (2003), *Timing of Late Applications of N Fertiliser and Season on Grain Yield and Protein in Wheat*, Proc. of the 11th Australian Agronomy Conf., Geelong, vol. Crop Agronomy.

Palta J.A., Kobata T., Turner N.C., Fillery I.R., (1994), Remobilization of carbon and nitrogen in wheat as influenced by postanthesis water deficits, *Crop Science,* **34**, 118-124.

Peltonen J., Virtanen A., Haggren E., (1995), Using a chlorophyll meter to optimize nitrogen fertilizer application for intensively-managed small-grain cereals, *Journal of Agronomy and Crop Science*, **174**, 309-318.

Raun W.R., Johnson G.V., (1999), Improving nitrogen use efficiency for cereal production, *Agronomy Journal*, **91**, 357-363.

Raun W.R., Solie J.B., Johnson G.V., Stone M. L., Mullen R.W., Freeman K.W., Thomasson W.E., Lukina E.V., (2002), Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application, *Agronomy Journal*, **94**, 815-820.

Sapkota T.B., Singh L.K., Yadav A.K., Khatri-Chhetri A., Jat H.S., Sharma P.C., Jat M.L., Stirling C.M., (2020), Identifying optimum rates of fertilizer nitrogen application to maximize economic return and minimize nitrous oxide emission from rice–wheat systems in the Indo-Gangetic Plains of India, *Archives of Agronomy and Soil Science*, doi: 10.1080/03650340.2019.1708332.

Smil V., (1997), Global population and nitrogen cycle, *Scientific American*, **277**, 76-81.

Solie J.B., Raun W.R., Whitney R.W., Stone M.L., Ringer J.D., (1996), Optical sensor-based field element size and sensing strategy for nitrogen application, *Transactions of the ASAE*, **39**, 1983-1992.

Stone M.L., Solie J.B., Raun W.R., Whitney R.W., Taylor S.L., Ringer J.D., (1996), Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat, *Transactions of the ASAE*, **39**, 1623-1631.

Teal R.K., Tubana B., Girma K., Freeman K.W., Arnall D.B., Walsh O., Raun W.R., (2006), In-season prediction of corn grain yield potential using normalized difference vegetation index, *Agronomy Journal*, **98**, 1488-1494.

Tindall T.A., Stark J.C., Brooks R.H., (1995), Irrigated spring wheat response to top-dressed nitrogen as predicted by flag leaf nitrogen concentration, *Journal of Production Agriculture*, **8**, 46-52.

Türker U., Dayioglu M., Eroglu M., (2012), A research on site specific irrigation in irrigated maize in Cukurova region for energy and water saving, *Energy Education Science and Technology Part A: Energy Science and Research*, **28**, 821-826.

Van Sanford D.A., MacKown C.T., (1987), Cultivar differences in nitrogen remobilization during grain fill in soft red winter wheat, *Crop Science*, **27**, 295-300.

Zhang Y., Dai X., Jia D., Li H., Wang Y., Li C., Xu H., He M., (2016), Effects of plant density on grain yield, protein size distribution, and breadmaking quality of winter wheat grown under two nitrogen fertilisation rates, *European Journal of Agronomy*, **73**, 1-10.