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ENHANCING NITROGEN FERTILIZER USE EFFICIENCY FOR MAIZE GROWN IN AN ALLUVIAL SOIL IN EGYPT USING NORMALIZED DIFFERENCE VEGETATION INDEX

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Abstract

A need-based nitrogen (N) management strategy using normalized difference vegetation index (NDVI) measured by an active optical sensor was evaluated for maize grown in an alluvial soil in Egypt. During 2019-2020, field experiments were performed to establish and validate an algorithm for refining the application of N fertilizer using NDVI. In the first season, an increasing rate of N fertilizer was applied to establish plots with different yield potentials and NDVI measurements were collected at V9 growth stage of maize. The second season aimed at validating the developed algorithm from the first season data by applying a corrective dose at V9 growth stage of maize.The results indicated that application of a prescriptive dose of 71 kg Nha^{-1} with sowing and 71 kg N ha^{-1} at 30 days after sowing, followed by a corrective dose guided by the sensor resulted in higher yield than the general recommendation with lower total fertilizer application. This treatment used 244 kg N ha^{-1} compared with 285 kg N ha^{-1} in the general recommendation. Recovery efficiency of N due to using the sensor was improved by 12.8 % (71.4 % in the sensor-guided application, whereas in the general recommendation was 5.8.6 %).This study revealed that using sensor-guided management, N fertilizer in maize could be managed more efficiently than the current general recommendation.

Key words : maize, nitrogen management, NDVI, algorithm.

Introduction

Nitrogen (N) fertilizer in maize in Egypt is managed in large areas following a prescriptive general recommendation. Yet, in order to ensure high yields, farmers often apply N fertilizer in quantities greater than the general guideline. Temporal and spatial variability, however, results in the application of N fertilizer more or less than the actual crop requirement, thus reducing the efficiency of fertilizer usage. Based on worldwide assessment, the N fertilizer recovery efficiency has been found to be about 33% for maize (Krupink *et al.,* 2004). It means that significant amounts of N fertilizer are lost from the soil. In addition to environmental degradation, the low recovery efficiency of N fertilizer is responsible for high costs (Bijay-Singh and Yadvinder-Singh, 2003; Fageria and Baligar, 2005). Maize in Egypt consumes about 23.8% of N fertilizer, representing the nation's largest N-consuming crop (Heffer, 2013).

Because of the large number of pathways of transformation and loss, N is well known as the most difficult plant nutrient to handle. The soil loss pathways include dentrification, volatilization, surface runoff and leaching (Raun and Johnson, 1999). Therefore, one of the key causes of low N fertilizer use efficiency is poor synchronization between soil N supply and crop demand (Raun and Johnson 1999; Cassman *et al.,* 2002; Varinderpal-Singh *et al.,* 2011; Ali *et al.,* 2015a). The uniform application of N fertilizer to spatially variable areas is another major factor causing low N-use efficiency (Ferguson *et al.,* 2002; Mamo *et al.,* 2003; Hurly *et al.,* 2004; Scharf *et al.,* 2005; Lambert *et al.,* 2006). Due to the absence of synchrony between crop supply and demand, the existing practices of N fertilizer application use a suspected method and ignore the within field variability.

Historically, the normalized ratio between near infrared and red reflection, known as the Normalized Difference Vegetation Index (NDVI), is well known vegetation index (Rouse *et al.,* 1973). This index has been shown to be useful for acquiring information such as photosynthetic efficiency, potential for productivity and potential yield (Peñuelas *et al.,* 1994; Thenkabail *et al.,* 2000; Ma *et al.,* 2001; Raun *et al.,* 2001; Baez-Gonzalez *et al.,* 2002; Teal *et al.,* 2006; Ali*et al.,* 2014; Ali *et al.,* 2020; Bijay-Singh and Ali, 2020). Work done by Stone *et al.,* (1996) and Ali *et al.,* (2020) on wheat showed that N uptake highly correlated with NDVI. Moreover, in-season measurements of NDVI could satisfactorily predict total N uptake in rice at maturity (Ali *et al.,* 2015b) and wheat (Ali *et al.,* 2020). Several studies have shown that the N requirement for maize can be quantified accurately using optical sensors (Ma *et al.,* 2014; Ali *et al.,* 2018). GreenSeeker^{TM} optical sensor is emerging as a hand-held tool for measuring NDVI in the field. Raun *et al.,* (2002) could improve N-use efficiency in wheat by more than 15% when developed an algorithm using NDVI measurements by the sensor that can estimate in-season N requirement. Ali *et al.,* (2015b) proposed an algorithm based on in-season prediction on N uptake that could maintain high grain yield along with high N-use efficiency in rice. In another study, they used the same concept on maize in calcareous soils of Egypt that could achieve similar yield as the general recommendation, but with using a lower quantity of N fertilizer (Ali *et al.,* 2018).

The first major objective of this study was to develop an optical sensor algorithm that can be used to convert NDVI measurements into a suitable application in-season N to ensure high maize yields and efficiency of N fertilizer in an alluvial soil in Egypt. The second major objective was to identify the optimal prescriptive N applications prior to the corrective dose as guided by the sensor.

Materials and Methods

The experimental site

Field experiments were conducted during 2019-2020 summer seasons on an alluvial soil at the Experimental Farm of Faculty of Agriculture, Cairo University, Egypt. The summer in this area is fairly dry with average daily temperature around 34° C and average night temperature around 21° C. Almost there is no rainfall events in summer. As reported in table 1, initial soil samples collected from the experimental site were mixed, air-dried, ground, sieved and analyzed for physical and chemical characteristics. According to Page *et al.,* (1982), soil texture was calculated using the pipette method. Soil pH and electrical conductivity (EC) values were measured in saturated soil paste and extract, respectively. Using the technique of Walkely and Black, as outlined by Page *et al.,* (1982), soil organic matter was determined. According to Dahnke and Johnson (1990), available N was extracted by 2 M KCl solution and then determined according to Page *et al.,* (1982) by micro-Kjeldahl technique. Available P and K were extracted from 1 M NH_4HCO_3 at 0.005 M DTPA with a pH of 7.6 adjusted (Soltanpour, 1991). Phosphorus, as described by Page *et al.,* (1982), was colorimetrically estimated using ascorbic acid and ammonium molybdate using a spectrophotometer. Potassium was measured using flamphotometer.

The experimental design and treatments

For the purpose of this study, two categories of experiments were established. The experiment in 2019 year was undertaken to develop an algorithm to translate the sensor's readings to appropriate amounts of N fertilizer. The treatments in this experiment consisted of an increasing rate of N fertilizer from 0 to360 kg Nha^{-1} applied as ammonium nitrate in three equal split doses. This range of N fertilizer rates was intended to establish plots with different yield potentials to develop the algorithm. The objective of the experiment conducted in 2020 year was to validate the developed algorithm. A prescriptive dose of 95, 190 and 142 kg N ha^{-1} applied in one or two splits was combined with a corrective dose as guided by the algorithm (Table 2). The experiments in both years were carried out in a randomized complete block design replicated thrice. The N-rich strip was also maintained in the experiments by applying 350 kg N ha^{-1} to ensure that N was not limited for the purpose of calculating the sufficiency index (SI) of NDVI. Triple-cross hybrid 321 maize was the cultivar used for these experiments.

Soil and crop management

Prior to sowing, the soil was ploughed twice and divided into 15 m^2 plots. Maize was sown in a row spacing of 25 cm ×70 cm. A basal dose of 50 kg of P_2O_5 ha^{-1} was added as a single superphosphate before sowing. In both years, during the last week of May, maize was sown by hand. Weeds, pests and diseases were managed as and when appropriate.

Sensor measurement

Spectral reflectance expressed as NDVI has been measured using a handheld Gree nSeeker TM active sensor (Trimble, Sunnyvale, CA, USA). The sensor has red (656 nm) and near infrared (774 nm) wavelengths of self-contained illumination.

$$NDVI = \frac{F_{NIR} - F_{Red}}{F_{NIR} + F_{Red}}$$

where F_{NIR} and F_{Red} are the fraction of near infrared and red radiations reflected back from the crop canopy to the sensor, respectively. The measurements were obtained by keeping the sensor at a walking speed of ~0.5 m s^{-1} by~1 m above the canopy.

Plant sampling and analysis

At maturity, from a net area of 6 m^2 in the center of each plant, maize crops were harvested and grain and stover samples were separated. The samples were dried at 70°C and ground in a hot air oven. Grain yields for reporting were set to 14% humidity. In the H_2SO_4-H_2O_2 mixture, the samples were digested and total N was determined using the micro-Kjeldahl method (Karla, 1997).

Data analysis

The analysis of variance (ANOVA) was performed, as defined by Gomez and Gomez (1984), to evaluate the effects of N treatments on the data obtained. The Least Significant Test (LSD) was used to test the mean differences at $P < 0.05$. As defined by Cassman *et al.* (1998), the recovery efficiency of N (RE_N) has been calculated as:

$$RE_N(\%) = \frac{\text{Total Nup take in fertilized plot - Total Nup take in control plot}}{\text{Quantity of applied N fertilizer}}$$

Results and Discussion

Grain yield of Maize and N uptake relationship

The multi-rate N fertilizer treatments produced a high degree of grain yield and N uptake variability in the first season experiment. Average maize grain yield reacted to N uptake by a quadratic function (Fig. 1). The maximum N uptake for maximum yield was determined by setting the first quadratic equation derivative to zero to 348 kg N ha^{-1} at around 8406 kg ha^{-1} grain yield. It is estimated that grain yield of 7986 kg ha^{-1} can be achieved with a N uptake of 260 kg ha^{-1} by setting the optimum yield at 95% of the maximum yield. Therefore, 260 kg N ha^{-1} is the goal uptake for which the N fertilizer application level can be calculated using the algorithm being created in this study.

Relationship between total N uptake and the sensor

Previous studies by Ali *et al.,* (2015& 2018) on rice and maize proposed that N application should be based on relationship between in-season NDVI measurements and total N uptake at maturity. The concept SI can account for the spatial and temporal variability. The in-season response index based on NDVI measurements from a N-rich reference strip showed a viable method in managing N fertilizer for crops (Mullen *et al.,* 2003; Ali *et al.,*2018). In the present study, N fertilizer was applied to a strip at a rate of 350 kg N ha^{-1} to ensure that N was not limited. The SI was then calculated as:

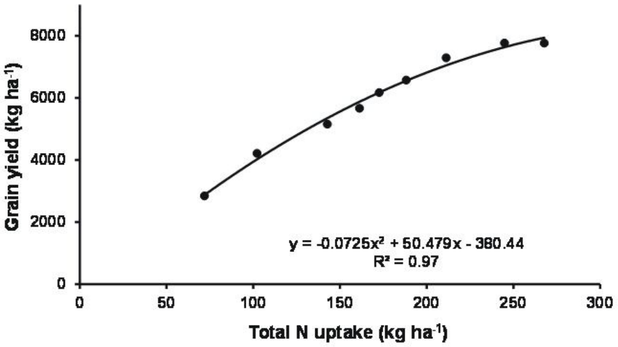

Fig. 1: The relationship between total N uptake and maize grain yields.

$$SI = \frac{\text{NDVI of the measured treatment}}{\text{NDVI of the reference treatment}}$$

Total N uptake was regressed against SI of NDVI at V9 growth stage and a strong power function was obtained (Fig. 2). The empirical model that can be used to predict total N uptake was found to be:

$$\text{Nup take}(\text{kg ha}^{-1}) = 369.08 \times SI^{7.4045}$$

Creation of the N fertilizer optimization algorithm

The plannedtotal N uptake (taken as 260 kg N ha^{-1}) and the estimated from the sensor can provide an estimate of the required fertilizer to correct the uptake. The difference must, however, be divided by an efficiency factor as some of the added fertilizer will be lost. As reported by Ali *et al.,* (2018), the efficiency factor to be used for development of an algorithm for maize is 0.6.

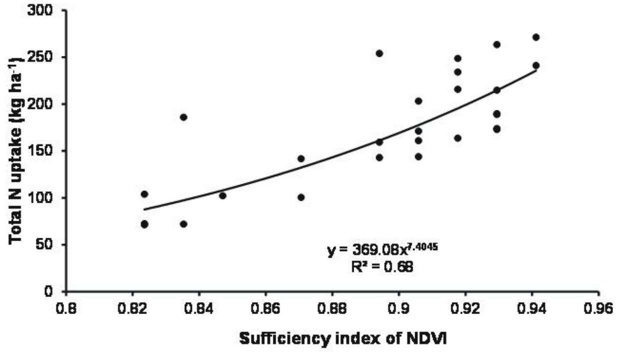

Fig. 2: Relationship between total N uptake and NDVI measurements at V9 growth stage of maize fitted to power function.

Table 1: Some physical and chemical properties of the topsoil (0-30 cm) of the experimental site.

Texture	pH[a]	EC[b]dS/m	Organic matter, %	Available N, mg kg^{-1}	Available P, mg kg^{-1}	Available K, mg kg^{-1}
Clay loam	7.93	2.01	1.97	102.9	17.2	322.3

[a]Saturated soil paste.

[b] Soil paste extract.

Table 2: Maize grain yields, total N uptake, and N recovery efficiency as influenced by different N fertilizer treatments.

Treatment	Prescriptive doses of N (kgha^{-1})		NDVI [b] at 50 DAS	Corrective dose [c](kgha^{-1})	Total rate of N fertilizer(kgha^{-1})	Grain yield (kgha^{-1})	Total N uptake(kgha^{-1})	RE_N(%)
	0 DAS[a]	30 DAS						
1 (control)	0	0	0.61	0	0	3360 g	98 f	-
2 (general recommendation)	95	95	0.69	95 (fixed)	285	9414 a	265 a	58.6 b
3	95	0	0.65	220.1	315.1	7410 e	185 d	27.6 c
4	0	95	0.64	243.3	338.3	7952 d	198 d	29.6 c
5	47	47	0.67	166.5	260.5	8533 c	233 c	51.8 b
6	142	0	0.67	166.5	277.6	8804 bc	240 bc	51.2 b
7	0	142	0.68	135.6	277.6	9014 b	255 ab	56.6 b
8	71	71	0.69	101.6	243.6	9695 a	272 a	71.4 a
9	0	0	0.61	300.1	300.1	6333 f	168 e	23.3 c
LSD ($P<0.05$)	-	-	-	-	-	320	16.2	7.8

Means followed by different letters in the same column differ at $P < 0.05$ using leas significant differences test (LSD).

[a] DAS, days after sowing.

[b] NDVI in N-rich strip was 0.75.

[c] Corrective dose as guided by the developed algorithm.

Summing up these findings, the functional algorithm that can be used to define N fertilizer rate using NDVI measurements collected at V9 growth stage of maize can be written as:

$$\text{N fertilizer (kg ha}^{-1}) = \frac{260-(369.08\times \text{SI}^{7.4045})}{0.6}$$

Field validation of the established algorithms

Different N fertilizer management scenarios were evaluated using the developed algorithm. Prescriptive N management is shown in table 2 by applying various doses of N fertilizer at different times. As developed in this research, the sensor-based N fertilizer management was practiced at 50 DAS. Prescriptive N management, consisting of the application of 95, 190 or 142 kg N ha^{-1} at different times, combined with corrective N management driven by the developed algorithm. The variations in plant biomass caused by the various prescriptive N management scenarios should be resolved by the corrective dose. Amounts of total N fertilizer applied in Treatments 3 to 9 were markedly different due to different NDVI values at V9 growth stage. These varying levels have shown that the developed algorithms are highly capable of modifying recommendations for N.

The data referred to in table 2 indicate that there is a statistically different grain yields were obtained for different N treatments. In the N treatments, the mean grain yield varied between 6333 and 9695 kg ha^{-1}. The N management based on the sensor overcame the heterogeneity caused by different prescriptive N management in maize growth. The grain yield data showed that when applied at the V9 growth stage, maize has a remarkable ability to react to N fertilizer. This may be due to the high rate of uptake of N at this stage. The present result seems to be confirmed by Cox *et al.,* (1993), who noted that linear responses to growing N rates are shown by N maize concentrations between the growth stages of V8 and V16. In addition, Ali *et al.,* (2018) concluded that maize has a remarkable ability to response to N fertilizer when applied at V9 growth stage. The amount of N fertilizer driven by the sensor at the V9 growth stage was higher when the total prescription dose of N was applied in a single dose than when those applied in two doses. This is due to N being subjected to losses through different mechanisms with the passage of time after the prescriptive doses of N are applied. Therefore, application of N fertilizer in one prescriptive dose did not work well due to overestimation of the corrective dose. Treatment no. 8 consisting of applying 71 and 71 kg N ha^{-1} with sowing and at 30 DAS following by a corrective dose at V9 growth stage appear to be the most effective treatment.

Data pertaining to N use efficiency indicate that sensor-guided N treatments have resulted in higher use efficiency compared to the general recommendation (Table 2). When appropriate prescriptive N fertilizer was applied in two splits (71+71 kg N ha^{-1} with sowing and at 30 DAS) followed by corrective dose as guided by the sensor, an average increase of 12.8 % vis-à-vis general recommendation. This improvement in N-use efficiency was due to producing similar or higher grain yield, but with applying less N fertilizer. As a result, the use of sensor-guided N-management could effectively prevent yield losses with using lower total rate of fertilizer.

Conclusions

An active optical sensor can be reliably used for maize grown in alluvial soils in Egypt to enhance the efficiency of N use. An algorithm for the application of corrective doses was developed that could maintain high grain yield, but with higher N use efficiency compared with the general recommendation. Prescriptive N fertilizer consisting of applying 71+71 kg N ha^{-1} with sowing and at 30 DAS followed by a corrective dose as guided by the optical sensor at V9 stage can lead to saving in total N application. The performance of the developed algorithm needs to be tested and refined in diverse environmental conditions.

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