DEVELOPMENT AND VALIDATION OF AN ALGORITHM FOR OPTICAL SENSOR-BASED NITROGEN FERTILIZATION OF DURUM WHEAT IN CENTRAL ETHIOPIA

I. ALGORITHM DEVELOPMENT

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ABSTRACT

Despite Ethiopia's vast agricultural potential, durum wheat productivity remains low due to widespread nitrogen (N) deficiency and reliance on blanket N fertilizer recommendations. This study aimed to develop and validate a sensor-based algorithm for N fertilization of durum wheat in central Ethiopia. Field trials demonstrated that total N uptake at maturity could be predicted from NDVI readings at the Feekes 6 stage, with a power function explaining 65% of the variation. The developed algorithm is based on the prediction of total N uptake from normalized difference vegetation index (NDVI) measured by *GreenSeeker* canopy sensor. The algorithm translates NDVI readings into optimized N application rates, offering a cost-effective tool to enhance productivity and nitrogen use efficiency. Future field experiments will validate the algorithm under diverse conditions.

INTRODUCTION

Ethiopia possesses vast agricultural potential, with abundant water resources, and diverse agro-ecologies that are conducive to the cultivation of various crops, including durum wheat. Despite these advantages, the productivity of cereal crops, including durum wheat, remains substantially lower than global averages. This productivity gap is exacerbated by smallholder-dominated production systems that often rely on rainfed agriculture with limited access to modern inputs.

Among the constraints to crop productivity in Ethiopia, nitrogen (N) deficiency in soils is particularly pronounced. While nitrogen fertilizers are critical to addressing these deficiencies, the country has long relied on blanket N recommendations that do not account for the heterogeneity of its agro-ecological zones. Such generalized approaches often lead to suboptimal nitrogen use efficiency (NUE), with significant environmental and economic consequences.

Precision nutrient management tools, particularly proximal optical sensors like the GreenSeeker canopy sensor, offer a promising pathway for addressing these challenges. Optical sensors provide real-time, non-destructive measurements of crop canopy vigor through indices like the normalized difference vegetation index (NDVI), which correlates strongly with crop nitrogen status. This technology has been successfully employed in other cropping systems to optimize in-season N applications, enhancing NUE and crop yields (Raun et al., 2002; Ali et al., 2018). Ali et al. (2015) showed that N uptake of rice at maturity can be predicted using in-season NDVI measurements. Other studies have also indicated that N requirement can be adequately quantified using optical sensors (Barker and Sawyer 2010; Ma et al. 2014). Raun et al. (2002) developed an algorithm using NDVI measurements that improved N-use efficiency in wheat by more than 15%.

The in-season nitrogen (N) fertilizer corrective dose, as guided by an optical sensor, should ideally be applied only once, serving as the final application. Hence, the use of an optical sensor necessitates the application of optimal prescriptive N fertilizer rates prior to the sensor-guided dose. Therefore, the main objective of this study was to develop an optical sensor algorithm capable of translating NDVI measurements into appropriate N application rate to achieve high yields and improved N fertilizer use efficiency. A second objective was to determine optimal prescriptive N rate that is applied before the sensor-guided corrective dose.

Materials and methods

Field experiments were conducted for two years at Debre-Zeit Agricultural Research Centre (DZARC) to develop an algorithm for need based N management of wheat using GreenSeeker canopy reflectance sensor. Data on the relation between grain yield of wheat, total N uptake and NDVI measurements were used to develop the algorithm. The relationships between total N uptake and grain yield, and total N uptake and NDVI readings were the basis for the developed algorithm. The nitrogen treatments (rates) (0, 46, 92, 138, 184, 230, 278 and 322 kg ha^{-1} N) were tested in randomized complete block design (RCBD) with three replications. NDVI readings were taken using the GreenSeeker handheld optical sensor, and NDVI readings at Feekes stage 6 were used to work out the relationship between NDVI and total nitrogen uptake at maturity. Plant samples were collected at maturity to determine total nitrogen uptake.

Laboratory analysis of plant tissue samples was done using the Kjeldahl method to quantify N content, which was then multiplied by biomass weight to calculate total N uptake. Microsoft Excel was used for calculations and fitting curves. Analysis of variance (ANOVA) was also conducted to determine N treatment effects on several agronomic parameters such as yield and yield component. Fisher's LSD method was used to test differences between means at $P < 0.05$.

RESULTS AND DISCUSSION

Relationship between total N uptake and grain yield

Because the algorithm being developed depends on predicted N uptake, it is crucial that a reasonable uptake limit be established to reflect the optimum grain yield. Grain yield of wheat was found to be dependent on total N uptake following a second-degree function (Figure 1). Derivation analysis of the function revealed that the maximum grain yield is 5074.06 kg ha^{-1} which can be achieved by a total N uptake of 232.8 kg N ha^{-1}. By setting the optimum grain yield at 95% of the maximum yield, it is projected that grain yield of 4820.4 kg ha^{-1} can be achieved at a total N uptake of around 185.8 kg N ha^{-1}.

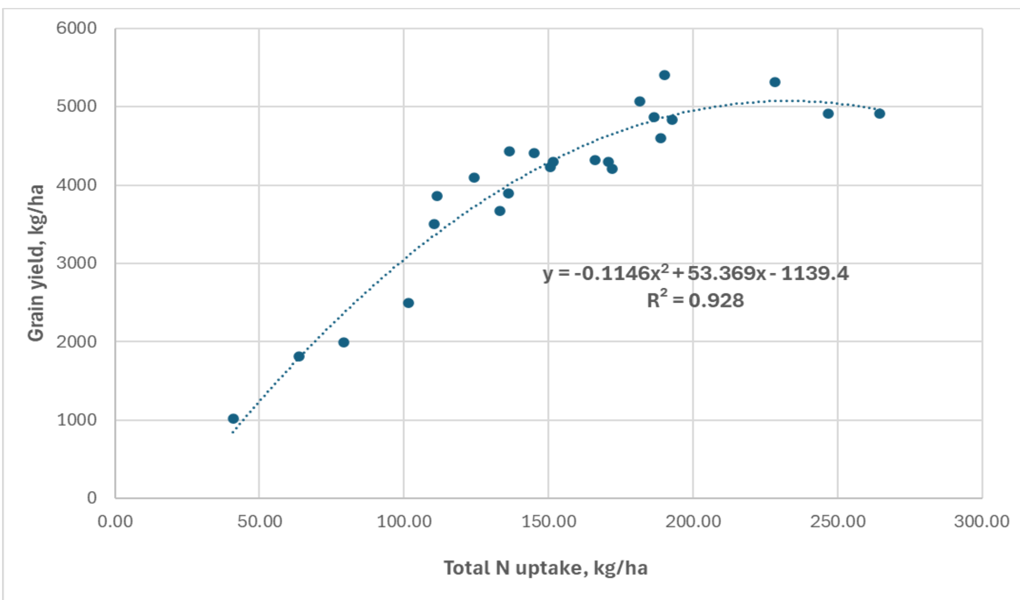

Figure 1. Relationship between Total N uptake and Grain Yield (kg/ha)

Relationship between NDVI and Total N uptake

Total N uptake at maturity was regressed against NDVI measurements collected at Feekes 6 growth stage of wheat and a strong power function was generated (Figure 2). The empirical model that can be used to predict total N uptake was found to be:

$$\boldsymbol{N\ uptake\ (kg/ha)\ = 229.74\ NDVI^{2.368}}$$

Where NDVI is the normalized difference vegetation index collected by the sensor.

The results indicated a robust correlation between NDVI readings measured at the Feekes 6 growth stage and total nitrogen (N) uptake at maturity. The regression analysis revealed a power function that provided the best fit, explaining 65% of the variation in N uptake (R^2=0.65) (Figure 2). This non-linear relationship is consistent with findings in other studies, where NDVI values at critical growth stages have been used to accurately estimate nitrogen status and uptake in wheat and other cereals (Raun et al., 2002; Teal et al., 2006; Ali et al., 2018).

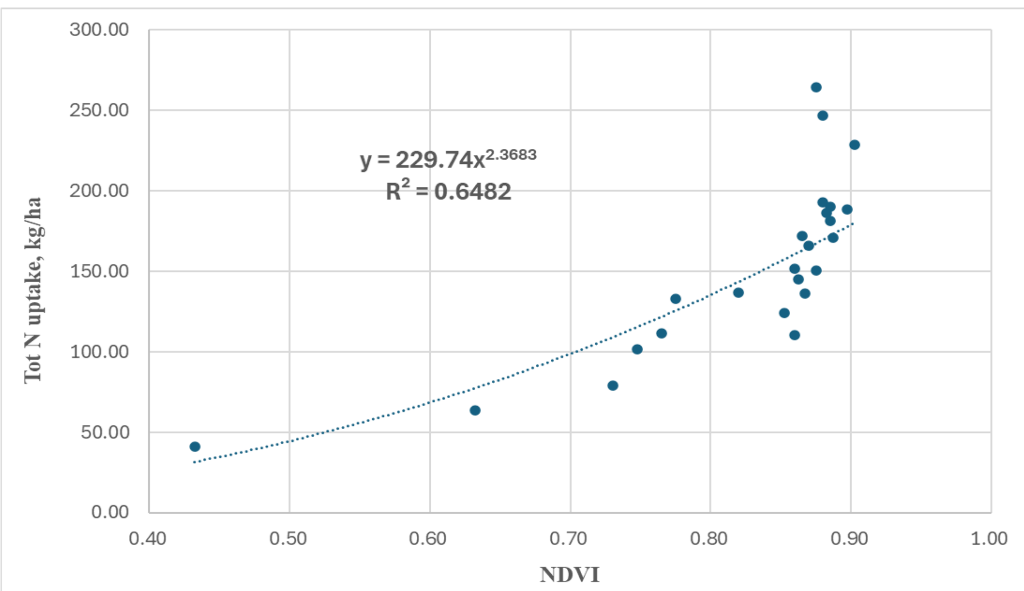

Figure 2. Relationship between total N uptake and NDVI measurements at Feekes 6 growth stage of wheat fitted to power function

The projected and estimated total nitrogen (N) uptake can serve as a basis for determining the required fertilizer application, but the difference must be divided by an efficiency factor as some of the applied fertilizer will inevitably be lost. On average, the recovery efficiency of N fertilizer applied at the Feekes 6 growth stage was around 60%, hence the value of 0.6 taken as an efficiency factor for the dose of N fertilizer as guided by the sensor. Based on these findings, the functional algorithm that can be used to define N fertilizer rate using NDVI measurements collected at Feekes 6 growth stage of wheat can be written as:

$$\boldsymbol{N\ fertilizer}\left(\frac{kg}{ha}\right) = \frac{\mathbf{185.8 - 229.74}\ \boldsymbol{NDVI}^{\mathbf{2.368}}}{\mathbf{0.6}}$$

Where NDVI is the normalized difference vegetation index collected by the sensor

CONCLUSION

The development of a sensor-based algorithm represents a significant progress in precision nutrient management for durum wheat in Ethiopia. The established relationship between NDVI and N uptake provides a scientific basis for optimizing in-season N applications, offering a practical tool to enhance productivity and resource use efficiency. Further validation of the algorithm will ensure its accuracy and practicality, contributing to improved durum wheat yield and N use efficiency.

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