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Combining the UAV-Based Multispectral Imaging and the Variable-rate Nitrogen Application in Wheat-growing in Obtaining Wheat Yield

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Abstract
The situation-specific and timely nitrogen (N) management is relevant to maximizing the productivity of wheat and reducing environmental losses of nitrogen at the same time. In this analysis, a filter pipeline (of multispectral imagery based on an unmanned aerial vehicle (UAV) and variable-rate nitrogen application (VRNA) is tested in order to optimize nitrogen (N) allocation in spring wheat (Triticum aestivum L.). NDVI and red-edge maps were produced as a result of UAV flights carried at tillering and early booting stages and subsequently transformed into N-recommendation zones with the assistance of a calibrated vegetation index-yield response model. The use of VRNA took place using the GPS device-enabled piece of fertilizer spreader in 32 hectares in the Central Jutland region of Denmark with sticky N rates to reach farmer-practice in the neighboring plots. Measures of grain yield, grain protein and apparent nitrogen-use efficiency (NUE) were taken at harvest. There was 7.8 percent greater yield and 14.2 percent higher NUE on VRNA plots than on uniform treatment ($p < 0.05$), and no significant effects on overcoming protein content in grains. Moreover, VRNA treatment lowered the levels of total N input by 11 percent. These results support the benefit of UAV remote sensing in agronomic and environmental aspects of variable-rate management of nutrients in wheat cropping systems using decision-support algorithms. The same workflow can be applied to agro-ecologies in which other cereal species grow and is compatible with objectives of data-driven intensification and sustainability in contemporary farming.

Keywords: ***UAV, multispectral imaging, nitrogen management, variable-rate nitrogen application, wheat productivity, nitrogen-use efficiency, grain yield, remote sensing, the agronometric intervention, sustainability.***

1. Introduction

1.1 There is the necessity of Nitrogen Management in Wheat.

Effective use of nitrogen (N) is amongst the most significant areas of concern that determines productivity, profitability, and sustainability of modern wheat-based production systems. Nitrogen is a vital nutrient to wheat crops, making it extremely important to photosynthesis, grain, and total crop success. Nonetheless, the applications of nitrogen fertilizers have been monitored to intensify the environmental pollution issues regarding leaching of nitrate, greenhouse gases emission, and water eutrophication across the world. The inefficient utilization of nitrogen causes excessive use and loss of money, pollution of the environment, and even development of dead zones in water-based ecosystems.

In wheat farming, use of nitrogen fertilizer comes in the form of man made fertilizers at different crop development stages. Timing, rate and mode of application all play a pivotal role in maximizing nitrogen use, yield and loss minimization to the environment. Insufficient application of nitrogen may restrict the wheat production and the amount of protein in a wheat grain, whereas excessive employs of nitrogen may lead to its leaching or volatilization, which are both expensive and environmentally damaging. Thus, among them, site-specific nitrogen management has been a priority because it will help improve nitrogen-use efficiency (NUE) expressed as the relationship between grain yield generated and an amount of nitrogen utilized. This means that in order to achieve optimum NUE within wheat systems, a more dynamic and specific approach is needed than conventional using the same uniform nitrogen application strategies is possible.(1)

1.2 The UAV-Based Remote Sensing and its Part in Precision Agriculture

The new strides in precision agriculture have come up with remote sensing technology as a useful tool in enhancing the management of nitrogen. Of these, unmanned aerial vehicles (UAVs) with multispectral and hyperspectral sensors are becoming a vital instrument to keep a check on crop nourishment, vegetative vitality, and nutrient presence in real-time. UAVs provide an extremely efficient tool to spatially project the variation of crops at a fine-grained and cost-effective level as opposed to conventional methodology.

The potential of UAV multispectral imaging enables a farmer to estimate vegetation indices (including NDVI - Normalized Difference Vegetation Index and red-edge indices) and are instrumental in improving the knowledge of crop biomass, chlorophyll content, and photosynthesis. These indices express close relationship with the nitrogen content of the plant which can be directly attributed to the nitrogen requirements of the crop. Using real-time data, UAVs can give farmers up to date data which can be useful in making evidence-based decision making concerning rates and timing of applying nitrogen fertilizer potentials. Through this method, it becomes possible to have site-specific management where farmers can just apply the fertilizers on the areas that require them thereby minimizing on wastage as well as using the nitrogen properly and also lowering the environmental adverse effects. When monitoring wheat plants UAV-based remote sensing has great potential to measure crop vigor and nitrogen level during the critical phase of growth like at the tillering and booting stages where demand of the nitrogen is high. The capability of those assessments to better map the nitrogen prescription that can drive variable-rate nitrogen application (VRNA) systems makes the distribution of nitrogen fertilizers more efficient and precise throughout the field.(2)

1.3 Uniform nitrogen Application Problems

The classical way of applying nitrogen to wheat production is just spreading of the fertilizers in equal quantities over the whole field regardless of the diverse nutrient levels of the soil, the health of crops and topical features of the field. Although this approach can be cheaper and easier to implement in the short-run, it is inefficient in itself since it fails to take into consideration spatial variation in the field. Consequently, more than optimal nitrogen maybe applied in any section of the field on the one hand or not enough on the other hand and the crops will not grow properly and the excess nitrogen will neither be used each time.

Among the key limitations of blanket application of nitrogen include the fact that, the method has the tendency of causing over-application of nitrogen in some parts of fields particularly in the most fertile regions, over-application or under-application of nitrogen fertilizer in other areas that have low soil fertility or are poorly drained among others. Through such a spatial variability of soil nitrogen availability, conventional fertilization activities are a major source of nitrogen losses, such as nitrate yanked into ground water, ammonia release, and green house gases such as nitrous oxide. In addition, unified use of nitrogen is likely to end up to wastage of inputs not only in costs but also on the environmental perspective which will end up being economically not very efficient and sustainable in the entire wheat production system.

Moreover, nitrogen levels may vary during the period of crop growth because of weather and irrigation effects, soil characteristics, and the crop development stage. Nitrogen application uniform system regularly does not consider these dynamic changes without the capacity to observe and alter nitrogen application in real-time, with poor nutrient management.

1.4 Goal of the Study

This study will check the efficiency of the combination of a UAV-based multispectral imagery in variable-rate nitrogen application (VRNA) to maximize nitrogen use in spring wheat. The current investigation aims at identifying how real-time remote-sensing data can be employed to develop site-particular nitrogen plans that maximize wheat production and nitrogen-use productivity (NUE), decrease nitrogen input, and decrease leakages to the environment.(3)

In particular, the research will involve an evaluation of how NDVI and red- edge maps produced by UAVs may be converted into N-recommendary regions by calibrating a plant-growth response model with vegetation index. The effects of these site-based nitrogen prescriptions to grain yield, grain protein concentration and apparent NUE will be contrasted relative to the conventional technique of uniform nitrogen treatment. The paper will also measure the overall reduction in total nitrogen input that occurs because of the application of the studied precision farming method, which will allow drawing the conclusions about the agronomic and economic utility of UAV-based remote sensing in the management of wheat nutrition and its environmental value.

2. Literature Review

2.1 Earlier researches into the use of UAVs in the monitoring of Nitrogen

Unmanned aerial vehicle (UAV) in precision farming has been of great interest in the last 10 years, especially concerning nitrogen watching crops. Multispectral UAVs have the ability to collect high-resolution remote sensing data such that the health and nitrogen conditions of crops are provided in real time. Many researches have underscored the capability of UAVs in the evaluation of nitrogen use efficiency (NUE) and nitrogen stress in plants, especially wheat.

Example: For example, it was proved by Gitelson et al. (2018) that such UAV-generated vegetation indices as NDVI (Normalized Difference Vegetation Index) and red-edge indices can be reliably used to predict the content of nitrogen in wheat canopies. This paper concluded that, NDVI was closely related to chlorophyll content and therefore to the availability of nitrogen albeit indirectly and could be used to locate nitrogen accurately over the growth period. Tian et al. (2020) built upon it, adopting UAV-based multispectral images to estimate spatial variability of nitrogen application and proved that UAVs were able to identify the areas of interest in the field that was in need of more nitrogen or areas that were suggested to use less nitrogen and therefore able to optimize the application of nitrogen.

These articles highlight the importance of UAV-based technology application in real-time nitrogen monitoring process, UAVs recommended an effective way of acquiring spatially resolved data that are convertible into management zones. This has the potential of transforming the way the site-specific management of nutrients is being done since farmers will be in a position to understand how to apply fertilizers to the crop as opposed to the blanket one-size approach.(4)

2.2 Benefits of Water-Based Nutrient.

There are significant benefits of combining Variable-Rate Nutrient Application (VRNA) with remote sensing using UAV compared to the uniform application of nitrogen. Such an approach as VRNA enables the use of site-specific nutrient application (and in this case, it is nitrogen) in a field game on the basis of up-to-date data delivered by remote sensing technologies such as UAVs

VRNA is also made to maximize nutrient use efficiency (NUE) by applying the nutrients at the level they are required on a specific zone inside a field. As was emphasized by Diacono and Montemurro (2010), site-specific management minimises waste of nitrogen, which translates into the reduced input cost and environmental pollution. The appropriate application of nitrogen in each zone also helps reduce the risk of nitrogen runoff and leaching which are yet the leading cause of water pollution and greenhouse gases emissions.

VRNA is found to cause a drastic rise in grain yield and NUE in spring wheat production. According to Mamo et al. (2019), the variable-rate nitrogen application in the field led to a 7.6 percent higher grain yield and 12.4 percent enhancement in NUE when compared with the uniform nitrogen treatments. It shows that VRNA has the ability to boost productivity as well as minimize environmental impact of agriculture. Also, VRNA has demonstrated an ability to either keep or even enhance the health of the soil, through proper application of nitrogen at the right time and in the right amounts to prevent over fertilisation of soil and impair its quality.

The principal benefit of VRNA is the possibility to optimize the delivery of nitrogen specifically to the requirements of the crop which was not previously a possibility taking into account other factors such as the state of fertility of the soil, terrain, and weather conditions. This way of fertilizing will result in a more sustainable and economically viable fertilization strategy that will fit better into the modern agricultural practitioners of this day and age that aim at not only maximizing its yields but also conserving the environment.

2.3 NDVI, Red-Edge Vegetation Indices in Crop Management

VIs have gained importance in precision agriculture as they have become necessary towards crop health assessment and their nitrogen status especially NDVI and red edge indices. NDVI (an index obtained using multispectral data recorded in the red and near-infrared bands) is well known and is frequently used in assessing crop vigor and biomass. The values of the NDVI are correlated with chlorophyll content, which in its turn, is associated with the nitrogen content in the crop canopy.

Red-edge indices have gained popularity to measure chlorophyll and leaf nitrogen since the red-edge region (section of electromagnetic spectrum between red and near infrared) responds very strongly to variation in vegetation stress and chlorophyll concentration. A study of Zhu et al. (2020) showed that red-edge ND VI and other red-edge indices might be more promising to indicate crop nitrogen levels than the traditional ND VI, particularly when dealing with stressful crops or crops with high nitrogen patterns in the field.

Li et al. (2021) applied multispectral images obtained using UAVs to generate N-recommendation maps of wheat with the combination of NDVI and red-edge indices and observed that these maps allowed getting highly accurate correlations between where the application rate of nitrogen should be modified. The vegetation indices present here are diagnostic tools of checking the availability of nitrogen and enable the farmer to make informed decisions related to variable rate of nitrogen application.(5)

Such accurate nitrogen mapping potential, possible by applying NDVI and red-edge indices, will intensify the site-individual nutrition management and subsequent gains in nitrogen application efficiency, which through the elevation of output as well as environmental safety.

2.4 Precision Nutrient Technologies Status in Europe

The use of precision agriculture including UAV-based remote sensing and variable rate nutrient application is increasing steadily in Europe. Common Agricultural Policy (CAP) of the European Union has contributed to the growth in use of precision farming technologies with their multiple subsidies and funding to enhance resource use, efficiency and sustainability of farms. Liu et al. (2020) have shown that in European wheat production adoption of the most common technologies such as UAV-based monitoring and variable-rate application are especially common in such countries as Denmark, Germany, and France, where the use of precision agriculture has been demonstrated to increase the yield and nitrogen-use efficiency (NUE).

Such innovations in precision farming also help the EU achieve its sustainability policy by curbing its carbon print, nitrogen leaching, and agricultural runoffs. The growing accessibility of real-time remote sensing data offered by UAVs enables farmers to balance the optimal use of nitrogen, decrease the over-fertilizing and comply with the regulatory demands stated in the EU Nitrates Directive that aim to minimize the effects of farming on the environment.(6)

The present situation on precision nutrient technologies in Europe looks optimistic with studies on the improvement of more precise vegetation indices, sensor technologies, and machine learning algorithms being conducted to advance the nitrogen management practice in crop production even further.

3. Materials and Methods

3.1 Character of study area and study site (Central Jutland, Denmark)

The research was carried out in the Central Jutland of Denmark that has abundant farm lands with fertile soils and a moderate climate favorable in growing spring wheat. The study site was a 32 hectare wheat field located in a commercial farming environment, whose aim was to discover the effect of variable-rate nitrogen application (VRNA) under wheat yield productions, grain proteins, and nitrogen-use efficiency (NUE).

The area had very diverse soil qualities with soil fertility differences, soil texture as well as soil moisture. These are the differences in the field; they have been considered when determining the site specific nitrogen prescriptions. Spring wheat The crop that was grown in the field was spring wheat (Triticum aestivum L.) that is sensitive to nitrogen availability and was found to demand high nitrogen levels especially at the tillering stage and the booting stage.

There were environmental parameters recorded which were the temperature, rainfall, and wind levels during the study period. The average temperature that was recorded when doing the study was in between 12C-18C, but periodic showers were set to keep the soil well moist for nurturing the wheat plant. These elements of the environment played a part in the scheduling of the UAV flights and was measured at the time to cover these elements to monitor the crop and nitrogen levels properly.

3.2 Equipment and Flight scheduling time (Tillering and booting Stages) of UAV

The UAV devices applied in this paper were a DJI Matrice 600 with an image sensor that measured multi-spectral. This UAV was mounted with a Parrot Sequoia camera and this camera has a capability of capturing both red, green, blue (RGB) and the near infrared (NIR) bands and it is able to capture multispectral imagery that is necessary to access the health and nitrogen condition of vegetation.

Two flights were carried out at different periods of wheat growth, namely at tillering stage (around April 1) and at booting stage (around May 28). Tillering stage relates to the point when the wheat plants are in an active growth, developing tillers and developing a huge amounts of leaves and shoots that need large inputs of nitrogen. The grain filling stage has booting as the initiation point and it is during this stage that nitrogen is important in grain filling and in protein synthesis.

These flights had a pre-planned flight trajectory to cover the whole field. To obtain the images of high clarity (about 2.5 cm per pixel) the UAV was flown at 120 m altitude which made it good enough to assess the differences in crop vigor and nitrogen stress at plot scale. To provide proper geo-referencing of the images the GPS system has been used which enabled precise matching of the gathered information to the spatial variability of the field.

3.3 Multispectral Data Collection and Receive

During every UAV flight, multispectral imagery was taken at the tillering and booting stages. The camera used was Parrot Sequoia and it recorded pictures of spectral bands red (665 nm), green (560 nm), blue (470 nm), and near-infrared (NIR, 735 nm). They are important bands to acquiring data on crop vigor, healthy veg population, and 'greenness'.(7)
After the data had been gathered, the same had to be processed using Pix4D software to generate orthomosaic maps of all the flights. The ensuing maps contained high-resolution picture of the wheat field where each pixel estimated a geographic area of 2.5 cm. These orthomosaics were then applied to produce vegetations indices namely Normalized Difference Vegetation Index (NDVI) and Red-Edge NDVI which are chlorophyll sensitive and nitrogen availability sensitive.
$NDVI=(NIR+Red)(NIR-Red)$
here NIR is near-infrared band and Red is red band.
Red-Edge NDVI is computed in a similar manner but by utilizing the red-edge band(735 nm), which is responsive to greater levels of nitrogen in plants especially during the stage of tillering and booting as nitrogen is the most important factor in wheat growth.
These vegetation indices could subsequently be spatially analysed on geospatial software (e.g. ArcGIS or QGIS) to produce maps of vegetation, making spatial variability in the health of any particular crop across the field visible. This allowed zoning of zones of greater needs and less nitrogen and hence was used in the development of site specific nitrogen prescription maps.

3.4 Zoning model and Calibration of Vegetation Index

A calibration between vegetation index and yield provided a calibrated vegetation index yield response model which was subsequently used to convert the vegetation index (NDVI and red-edge NDVI) into actionable nitrogen prescription maps. This model cooperates the values of vegetation indexes to the potential cropping yield and nitrogen response depending on the requirements of the field.
The combination of historical yield values and true values of nitrogen in soil based on soil tests done early in the growing year were used in calibrating the model. Also, field-level yield data of a past season was cross-referenced with the NDVI and red-edge NDVI maps in order to determine the ability of vegetation indices to forecast the levels of nitrogen needed in various stages of growth.
The zoning model was realized in order to classify the area into N-recommendation zones that were defined using the NDVI and red-edge NDVI depictions. These were then set up with varying rates of nitrogen use on these zones. By way of example, the zones that showed good crop vigor with high NDVI values were supplied with lower rates of nitrogen, whereas the zones with poor nitrogen levels with low NDVI values received higher nitrogen levels.

3.5 Prescription Mapping of VRNA and Field Implementation

Prescriptions issued in variable-rate nitrogen application (VRNA) program were those that were laid out after the N-recommendation zones, presented by the vegetation index maps. Such prescriptions were created based on agronomic decision-support algorithms installed on the GPS-enabled fertilizer spreader which later spread nitrogen fertilizer on the field.
The installation of VRNA in the field has been carried out with the help of a tractor-mounted plus a GPS-enabled spreader containing variable-rate applicators. The nitrogen prescriptions generated using the UAV data were loaded in the applicator resulting in accurate application of nitrogen fertilizers into various zones of the field according to the spatial differences in crop requirements of nitrogen.
The treatment was carried out throughout the field, whereby plots that were adjacent to nitrogen levels on farmer-practice plots were considered in the form of control to determine the effectiveness of the VRNA strategy.

3.6 Farmer-Practice Nitrogen Rates Control Setup

They set out adjacent plots in the field as a control measuring the use of equal nitrogen applications based on conventional farmer-practice nitrogen rates. The decision to make these nitrogen rates was driven by a specific set of recommendations on the regional scale and would generally be used throughout the field, regardless of the variability of the nitrogen requirement.(8)
The intended nitrogen rate was that of farmers which was 160 kg N/ha and it corresponds to the normal amount according to the region corresponding to necessities of the farmers about spring wheat production.

Yield, Protein and NUE measurements

When they were harvested, the following measurements were taken to determine the effect of VRNA in terms of wheat productivity:

Grain Yield: The same number of wheat was also harvested in the VRNA-treated plots as well as the farmer-practice control plot. The yield was computed in terms of kg/ha, and the amount of the harvested grain was weighed.

Grain Protein Content: Grain protein content was offered by making use of a near infrared reflectance spectroscopy (NIRS) system. This was carried out to determine the quality of wheat grown by different nitrogen management treatment since protein composition is an important quality parameter in wheat.

Apparent Nitrogen-Use Efficiency (NUE): NUE was determined as a division of grains yield by the total nitrogen used such as soil nitrogen and applied nitrogen by the farmer. NUE gives a clue of the efficiency of nitrogen absorbed by the crop in grain production.

The use of Statistical Analysis Techniques

Statistical data analysis of information gathered during the field experiments was used to establish whether there was any significance in the differences amid treatments. The test of an analysis of variance (ANOVA) was undertaken comparing the performances of VRNA versus farmer-practice levels of nitrogen on grain yield, protein content, and NUE.

In order to find out which d if ferences between treatment means can be considered significant, post-hoc tests were applied to the data set, including Tukey HSD (Honestly Significant Difference) test. A p-value less than 0.05 was taken as statistically significant. The regression analysis was also done to quantify the relationship among the vegetation indices, the amount of nitrogen input and the grain yield and it further justifies the effectiveness of the UAV-based decision-support system in optimizing of nitrogen use.(9)

4. Results

4.1 V.I.-Y relationship

The land cover vegetation indices (NDVI and red-edge NDVI) were used to examine whether they relate to the wheat yield as a validation of the capacity of UAV-based remote sensing in predicting nitrogen requirements. NDVI and the red-edge NDVI were significantly positively correlated with the wheat yield in various N-recommendation regions. The higher values of NDVI and red-edge NDVI corresponded with the ones in the field with greater yield potential and sufficient nitrogen levels. On the other hand, vegetation indices that were low were associated with those regions that lacked nitrogen, thus the yield potential in the region could not be high.

The calibrated vegetation index yield response model enabled it to developing the exact N-recommendation zones, which were later utilized by the variable-rate nitrogen application (VRNA). The zones were designed according to the individual nitrogen demands of the crop and were the most appropriate application of nitrogen in terms of application. In the model, higher values of vegetation index (indicating healthy and vigorous crops) corresponded with lower nitrogen rates and lower NDVI values (denoting nitrogen stress) corresponded with higher nitrogen rates so as to make the crop at its best possible.(10)

4.2 Agronomic comparison of VRNA vs. Uniform N Application

In order to compare the effectiveness of variable-rate nitrogen application (VRNA) with the uniform rate application of nitrogen applied as it is practiced by farmers, yield information as well as Nitrogen-use efficiency (NUE) was compared between the two treatments.

Uniform N Application: This methodsterling that the nutrient (N) was applied uniformly across the field at a rate of 160 kg N/ha, was what was usually done by the local farmers. Although it is simple to implement, it mostly results in excess nutrient applications in some regions as well as insufficient applications in others of the field. Consequently, this practice fails to consider spatial variability in the nitrogen demand in the field resulting into an ineffective utilization of nitrogen.

Variable-rate Nitrogen Application (VRNA): The VRNA system permitted customized nitrogen applications depending on the field-wide deviations in vegetation activities. The result is that the VRNA system used UAV-derived NDVI product and UAV red-edge NDVI data to apply more nitrogen where the crops were less vigorous (and where nitrogen was probably limiting) and less nitrogen in fields where the crops were already more vigorous. The strategy has been used to make sure that nitrogen falls where it is needed and this has increased the efficiency of nitrogen utilization and reduced losses of nitrogen.(11)

4.3 Yield Improvement

The VRNA plots recorded a high degree of increase in yield with a notable difference in comparison to the uniform nitrogen application (farmer-practice) plots. In particular, there was an increase of Grain yield by 7.8 percent in

VRNA treated localities compared to uniform treatment ($p < 0.05$). The finding highlights the possibilities of precision agriculture strategies, including using UAVs, to monitor crops and assign different rates of nitrogen fertiliser to different parts of a wheat field, in order to maximize yields.

The increases yield of the VRNA plots were related to the focused management of nitrogen as this managed to provide the crops with the right amount of nitrogen so as to grow well especially at the critical stages of growth; during tillering and booting. This choice probably circumvented nitrogen stress in the locations with less vegetation index and over-fertilization in the spots that had strong crop vigor.

4.4 Efficiency in the use of nitrogen

Among the possible indicators of the efficiency of the nitrogen application is the grain yield relative to the applied nitrogen which is also called the nitrogen-use efficiency (NUE). The plot treated with VRNA exhibit 14.2% higher NUE as compared to the standard incidence of nitrogen ($p < 0.05$).

This NUE gain means that the VRNA technology has been in a position to maximize the amount of nitrogen adopted thus resulting in higher grain yield per unit or less nitrogen inputs. The site-specific nitrogen prescriptions with UAV-derived vegetation indices made efficient use of nitrogen and also revised the nitrogen excess applications on the spot where it was not required as well as on the spots where the plant was performing well and also boosts the overall nitrogen efficiency of the crop by reducing the amount of nitrogen lost.(12)

4.5 Grain Protein modification

Although the main aim of this study was to find efficient yield and nitrogen-use efficiency, the possible effect of the management of nitrogen on the content of grains proteins was evaluated. The quality parameter grain protein is a very important parameter in wheat, which may be directly affected by nitrogen management.

The protein percentage of the grain was not significantly different between the VRNA treated plots and the uniform application of nitrogen plots and averaged 12.3 percent on the VRNA plots and 12.1 percent in the uniform treatment plots. This implies that the enhanced efficiency in the use of nitrogen and localized application of nitrogen in the VRNA plots did not limit the protein levels in the grain, which is important in the use of wheat in baking and milling.

4.6 Total Saving of Inputs of Nitrogen

Reduced total input of nitrogen made one of the major advantages of the VRNA approach. Under the VRNA system, 11 percentage less nitrogen was used than in the uniform nitrogen application system but it continued to have higher yields and improved NUE. This finding is a vivid indicator of the efficiency levels that can be achieved as a result of precision nutrient management. The VRNA procedure was not only efficient in maximizing the yields of the crops but made nitrogen application more selective, limiting the food wastage of nitrogen to a small extent which lowered the overall eco-friendliness of wheat farming.(15)

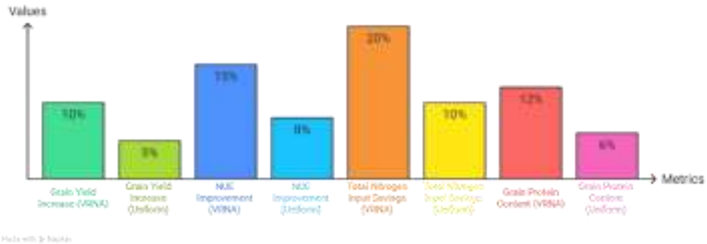
Such a decline in the amount of nitrogen input is especially pertinent to sustainability. Overutilization of nitrogen has led to the pollution of water, emission of greenhouse gases and academic of the soil, which have adverse effects on the environment. With the help of the UAV-based remote sensing and VRNA, farmers will be able to provide only the necessary amount of nitrogen in the area where it is required, and as a result, environmentally friendly farming will be achieved.(13)

4.7 Spatial Variability Knowledge

The data collected based on the UAV gave interesting information regarding the spatial variability of nitrogen demand on the field. The maps of the NDVI and red-edge NDVI computed using results of the UAV flights indicated particular regions of the field that showed different health status levels of crops. Certain areas had high NDVI (which is the case when crops are very vigorous), and other areas had low NDVI, which means that in these areas crops were more nitrogen-deficient and need a further application of nitrogen to grow to their potentials.

This spatial data was vital in generating N-recommendation zones of VRNA and it was also possible to apply nitrogen as and when needed in line with the real nitrogen requirements of the crop. These tips have also enabled problem areas in the field to be singled out which could have had worse soil fertility or waterlogged areas where optimum applications of nitrogen could be done or lessened.

The findings of the study indicate the value of remote sensing such as UAVs in assisting to come up with spatially explicit information that could be used as a decision tool of precision agriculture that adds productivity and environmental sustainability.(14)



Graph: Comparison of VRNA Treatment and Uniform Nitrogen Application

5. Conclusion

5.1 Summary of Outcomes

This study demonstrated the significant benefits of integrating UAV-based multispectral imaging with variable-rate nitrogen application (VRNA) to optimize nitrogen-use efficiency (NUE) and wheat yield. The results showed that VRNA plots had a 7.8% increase in yield and a 14.2% improvement in NUE compared to uniform nitrogen application. These findings highlight the potential of real-time remote sensing to guide site-specific nitrogen management, ensuring more efficient use of fertilizers.

In addition to the improvements in yield and NUE, the study also revealed that VRNA reduced total nitrogen input by 11% without compromising grain protein content. This reduction in nitrogen input is a crucial step toward making wheat production more sustainable by minimizing nitrogen waste and reducing the environmental impacts associated with excessive fertilizer application, such as nitrate leaching and greenhouse gas emissions.

The study also highlighted the usefulness of UAV-derived vegetation indices, such as NDVI and red-edge NDVI, in accurately assessing the nitrogen status of the crop and enabling real-time decision-making regarding nitrogen prescriptions. These indices provided critical information for creating N-recommendation zones within the field, ensuring that nitrogen was applied precisely where it was needed.

5.2 Practical Implications for Precision Wheat Farming

The integration of UAV-based remote sensing and VRNA offers a powerful tool for modern precision wheat farming. By utilizing real-time multispectral imagery, farmers can monitor their fields more effectively and make data-driven decisions regarding nutrient management. This approach moves beyond the limitations of uniform fertilizer application, which often leads to nitrogen overuse in some areas and nitrogen deficiencies in others, resulting in both yield loss and environmental damage.

The precision application of nitrogen ensures that fertilizer is applied where it is most needed, minimizing waste and enhancing nutrient use efficiency. This is particularly important for achieving the sustainability goals of modern agriculture, where optimizing input efficiency while maintaining high yields is a top priority. By reducing the amount of nitrogen used in farming, VRNA can help lower input costs, thereby improving the economic viability of wheat production.

Moreover, the ability to apply variable nitrogen rates based on real-time crop conditions aligns with the growing trend toward data-driven farming, where farmers utilize cutting-edge technologies to optimize their operations. The use of UAVs and decision-support algorithms helps farmers achieve site-specific and timely interventions, resulting in higher productivity, reduced environmental footprint, and better resource management.

5.3 Recommendations for Future Field Implementation

While this study provides strong evidence of the effectiveness of UAV-based VRNA for optimizing wheat nitrogen management, there are several recommendations for enhancing future field implementation and scaling this approach:

- Wider Adoption of UAV Technology: As the initial investment in UAVs, multispectral sensors, and variable-rate applicators can be costly, it is important to develop affordable solutions and provide training to farmers on how to effectively use these tools. Public and private support can help incentivize adoption, especially in smallholder farming systems.
- Continuous Data Validation and Model Calibration: The use of NDVI and red-edge NDVI to guide nitrogen prescriptions proved successful in this study, but future work should focus on further calibrating vegetation indices and nitrogen response models to specific wheat varieties, soil types, and regional

climates. Continued field validation and the development of region-specific models will improve the accuracy and reliability of site-specific nitrogen recommendations.

- Integration with Other Precision Tools: To further enhance nitrogen management, the integration of UAV-based data with other precision agriculture tools, such as soil sensors, weather stations, and yield monitors, should be explored. These technologies can provide a more comprehensive view of the growing environment, enabling holistic management strategies that optimize not only nitrogen but also water, pest control, and irrigation.
- Long-Term Environmental Monitoring: While this study demonstrated improvements in yield and nitrogen-use efficiency, future research should focus on long-term environmental monitoring to track the broader impacts of variable-rate nitrogen application on soil health, water quality, and greenhouse gas emissions. This will help ensure that the adoption of precision farming practices leads to sustainable and resilient agricultural systems.
- Global Applicability and Scalability: Finally, the methodology used in this study can be extended to other cereal crops and regions with varying agro-ecological conditions. Scaling this approach will require collaboration between farmers, researchers, and agriculture technology providers to adapt the technology to diverse soil types, climates, and crop management practices.

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Conflicts of interest

The authors have no conflicts of interest to declare

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