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Second Cycle Degree (MSc)
in
Sustainable Agriculture

Variable rate nitrogen optimization based on ground survey and UAV technology: A case study of Borettana onion in open fields

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ABSTRACT

This study aims to investigate the effectiveness of precision agriculture techniques utilizing variable rate fertilization in enhancing nutrient management for onion cultivation in Isola della Scala, Italy. The primary objectives encompass determining the optimal nitrogen fertilizer rate, assessing crop vigor and soil conditions through drone and NDVI analyses, and evaluating the impact of site-specific fertilizer application on yield.

The experimental design employed a completely randomized block design, utilizing four treatment levels for nitrogen fertilizer application rates as comparison. Data collection involved soil sampling, aerial surveys utilizing a multispectral sensor mounted on a drone, as well as biometric measurements of aboveground and belowground plant biomass. Statistical analyses were conducted to compare treatment effects on above- and below-ground biomass, nitrogen content, bulb diameter, plant height, and nitrogen use efficiency.

The study's findings indicated that there were no noteworthy distinctions in onion bulb biomass among the various treatments during harvest. However, the N150 treatment demonstrated a noteworthy enhancement in apparent nitrogen use efficiency when contrasted with the N200 and N220 treatments. The correlation of NDVI mapping with subterranean and aerial onion biomass as well as nitrogen content suggests that close-range sensing has the ability to identify variations in onion growth. To affirm the credibility of the acquired outcomes, further monitoring studies are needed to validate the results obtained. Precision agriculture techniques, including real-time monitoring of crop growth and nutrient requirements, can be useful to enhance nutrient management in onion cultivation under open-field conditions. The utilization of drones and NDVI analysis enables accurate assessment of crop vigor and soil conditions, thereby facilitating more precise, real-time, fertilization practices. Additionally, the study identifies areas of nutrient deficiencies and surpluses, allowing for targeted interventions to optimize nutrient uptake.

These findings highlight the advantages of precision agriculture approaches in increasing agricultural output while reducing environmental impact, suggesting its effectiveness compared to conventional fertilizer application methods, by guaranteeing less environmental impacts and to be more cost-effective.

The implications of this research extend to sustainable agriculture and food security. Precision agriculture techniques contribute to resource efficiency, reduced environmental pollution, and increased crop yields. The study's findings can help agronomists, farmers, and policymakers establish efficient nutrient management methods and promote the use of precision agricultural practices.

More research is needed to determine the long-term impacts of precision agriculture technologies on soil health, crop resilience, and economic viability. Furthermore, investigations spanning multiple areas and crops might be done to confirm the efficacy and applicability of these technologies. We can meet the task of feeding a growing global population while reducing the environmental effect of agricultural operations by increasing precision agriculture.

Keywords: precision agriculture, nutrient management, drones, NDVI, targeted fertilization, crop vigor, onion cultivation, sustainable agriculture, food security.

1. INTRODUCTION

Historically, traditional fertilizer application techniques by farmers involved valuation of crop nutrients requirement and timing of application regardless the spatial variability of the field, i.e. applying the same amount of fertilizer to the entire field without regard to the individual nutrient needs of each area. However, this technique resulted in inefficient resource use, increased fertilizer costs, and maximization of environmental risks (Sishodia et al., 2020) such as excessive nutrients that leached out of the field to surface and groundwater, or enhanced GHG emissions due to low efficient use of mineral and organic N fertilizers.(Zaman, 2023) Earlier methods of fertilizer placement could lead to overuse, nutrient loss, and soil degradation(Miles, 2019). This has been mitigated by the advent of precision agriculture, a modern approach to farming and a data-driven approach that enables farmers to tailor their management practices to the specific needs of their crops, applying inputs such as fertilizers, plant production products or water only where and when they are needed, reducing costs, minimizing the risk of environmental damage, and maintaining crop development and yield(Masi et al., 2022; Monteiro et al., 2021a; Sishodia et al., 2020).

The use of precision agriculture has grown rapidly in recent years, driven by technological advances and an awareness of the need to produce food in a sustainable and efficient manner(Masi et al., 2022; Monteiro et al., 2021a; Sishodia et al., 2020). This approach has been shown to increase yields, reduce waste, and improve the profitability of farming operations(Masi et al., 2022; Sishodia et al., 2020).

Regarding precision agriculture to the application of fertilizers, strategies for precision fertilization have been developed based on the study of spatial tracking data that can be provide by soil (e.g., spatial, variability in texture, soil organic carbon, soil moisture, etc.) or vegetation) e.g., valuation of yield maps, plant vigor, etc.) (Figure 1), which can be acquired through technologies such as proximal or remote sensing combined with GPS (Global Positioning System) and GIS (Geographic Information System).

Figure 1: Example of aerial scene during a wet growing in Iowa during 2014. Dark green areas indicate maize that is sufficient in N nutrition, while yellow areas covering large parts of fields indicate N deficiency(Franzen et al., 2021).

These precision agriculture technologies can help farmers improve their productivity, profitability and sustainability. By using real-time data and advanced technologies to make informed decisions about crop management, farmers can achieve better results while minimizing their environmental impact(Miles, 2019). Farmers can use these technologies to determine if certain parts of their farms need more or less fertilizer. Precision agriculture is used in contemporary agriculture to make better use of resources while reducing environmental impact. Precision fertilization is a key component of precision agriculture. These solutions seek to deliver the right nutrients to crops at the right time.

The ability of precision agriculture to maximize crop yields is one of its primary advantages. Using real-time data on soil conditions, weather patterns, and crop growth, farmers can make informed judgments about planting, fertilization, irrigation, and pest control(Masi et al., 2022; Sishodia et al., 2020). This data can be gathered using numerous technologies, including GPS, sensors, drones, and GIS. By applying inputs only where and when they are required, farmers can maximize yields while minimizing input costs (Sishodia et al., 2020). This strategy can also aid in waste reduction and agricultural productivity enhancement. In addition to maximizing crop yields, precision agriculture can reduce the environmental impact of cultivation. Reducing the use of fertilizers, pesticides, and water is one of the most crucial means of achieving this objective(Gebbers & Adamchuk, 2010). Farmers can reduce the risk of nutrient and pesticide runoff, which can contribute to soil and water contamination, by only applying inputs where necessary(Gebbers & Adamchuk, 2010; D. Lobell & Gourdji, 2012). This strategy also contributes to the conservation of natural resources, such as water, which is becoming increasingly scarce in many regions of the globe. In addition to addressing the issue of food security, precision agriculture improves crop production efficiency (D. Lobell & Gourdji, 2012). Farmers can contribute to a sustainable food supply for the world's expanding population by producing more food with fewer resources. This is particularly crucial in developing nations where food supply is a significant concern (Gebbers & Adamchuk, 2010).

Another advantage of precision agriculture is its ability to increase agricultural production's profitability. By reducing input costs and increasing yields, farmers can enhance their bottom line and overall profitability(*Climate Change and Food Security: Risks and Responses*, n.d.). This is particularly vital for small-scale producers, who frequently operate with extremely slim profit margins. Precision agriculture is essential to modern cultivation. It allows producers to produce more food with fewer resources, thereby decreasing their environmental impact. This strategy is essential for addressing issues of food security, resource scarcity, and environmental sustainability (*Climate Change and Food Security: Risks and Responses*, n.d.; D. B. Lobell & Gourdji, 2012). Precision agriculture will become increasingly essential in the coming years in order to provide a sustainable and secure food supply for future generations as technology advances(*Climate Change and Food Security: Risks and Responses*, n.d.).

1.1 Why must we utilize precision agriculture?

Precision agriculture is a crucial instrument for addressing the issues of contemporary agriculture. Farmers must produce more food, feed and fibers with limited resources as the global population and food demand continue to rise. In addition, there is a growing awareness of the need to preserve the environment and reduce agriculture's impact on natural resources(Masi et al., 2022; Monteiro et al., 2021a; Sishodia et al., 2020). Precision agriculture provides a solution to these issues by allowing producers to produce more food with fewer inputs and a smaller environmental footprint.

Recognizing the inherent diversity of farmland is one of the primary reasons of precision agriculture adoption. Each farming parcel has a unique blend of soil type, terrain, microclimate, and plant features. Ignoring this heterogeneity and considering the entire farmland as a homogeneous unit might result in wasteful resource utilization, including fertilizer use. Conventional agricultural operations often apply fertilizer in a blanket application across the whole field, resulting in over-fertilization of certain regions and under-fertilization of others. This imbalance not only results in wasteful expenses, but also in contamination of the environment, as surplus nutrients can drain into bodies of water, producing eutrophication and other ecological harm.

Precision agriculture, on the planting side, provides tailored solutions to overcome regional heterogeneity in soil and vegetation. Detail data on field features may be acquired using modern technologies such as remote sensing, Geographic Information Systems (GIS), and Global Positioning Systems (GPS). This information, together with soil testing and historical yield data, forms the basis for comprehensive field maps that illustrate changes in soil nutrient content, moisture levels, and vegetation health(Tey & Brindal, 2012).

These field maps are useful for optimizing fertilizer application. Precision agriculture may administer the correct nutrient in the right spot, taking into consideration the individual demands of each region, rather than providing a standard quantity of fertilizer to a whole field. places with nutrient-rich soils, for example, may require less fertilizer inputs, whereas places with nutrient deficits may require more fertilizer. This method not only assures effective fertilizer usage, but it also reduces the possibility of nutrient loss to nearby ecosystems.

Furthermore, precision agriculture extends beyond simple nutrient control. It entails a thorough understanding of the entire agroecosystem, including elements such as water availability, insect pressure, and crop health. It is feasible to monitor crop development and respond to any departure from the expected trajectory by combining real-time data from sensors, drones, and satellite photography(Tey & Brindal, 2012). Precision agriculture, for example, may conduct focused interventions if a portion of an onion crop shows indications of stress or illness, reducing the need for broad-spectrum treatments and minimizing the usage of agrochemicals.

Precision agriculture has evolved into an essential instrument in the goal of sustainable agriculture. This approach's dynamic and adaptable character is congruent with the ideas of agroecology, which is the incorporation of natural processes into farming techniques. Precision agriculture is no longer a choice; it is a must in today's agriculture. Precision agriculture promises a shift in how we maximize resource usage, increase crop quality, and limit environmental effect for commodities such as onions, which play a critical part in world nutrition and commerce.

1.2 The precision agriculture technologies used in this study

1.2.1 GPS

The Global Positioning System (GPS) is a satellite-based navigation system that provides accurate location data to help farmers determine the location of crops and equipment in their fields(Erickson & Fausti, 2021; Gebbers & Adamchuk, 2010). It can also be used to develop extremely detailed field plans, which makes it easier for farmers to apply fertilizer and pesticides only where they are needed(Erickson & Fausti, 2021). It can also be used to monitor the movement of field equipment. Farmers can maximize planting and harvesting by using GPS tracking devices to determine the location of their vehicles and other equipment, which can reduce fuel costs and improve overall productivity(Erickson & Fausti, 2021; Gebbers & Adamchuk, 2010). Using GPS data and other mapping tools to illustrate differences in soil types, topography, and other factors, GPS also enables farmers to create detailed maps of their region. In the future years, precision farming is likely to become more efficient and effective as GPS technology continues to advance(Erickson & Fausti, 2021; Gebbers & Adamchuk, 2010).

1.2.2 GIS

Geographic Information Systems (GIS) is a strong precision agricultural technology that integrates and analyzes data from various sources, including GPS, sensors, and other mapping tools(Contributor, 2012). It works by layering various types of spatial data such as satellite images, aerial photography, drone photography, and ground sensors(*GIS-Based Precision Agriculture and Smart Farming*, n.d.; *Use of GIS in Agriculture - Cornell Small Farms*, 2017). These data layers can be used to generate comprehensive maps that display information such as soil type, topography, and agricultural production. Farmers can acquire insight into the features of their fields, detect areas of change, and adapt management strategies by aggregating and evaluating different layers of information(*GIS For Agriculture*, 2022; *GIS-Based Precision Agriculture and Smart Farming*, n.d.; *Use of GIS in Agriculture - Cornell Small Farms*, 2017). They can, for example, use soil maps to identify low fertility areas and change fertilizer application rates accordingly, thereby facilitating variable rate applications (VRAs) for inputs such as fertilizers and pesticides(Contributor, 2012).

1.2.3 Unmanned Aerial Vehicles (UAVs)

Drones, also known as unmanned aerial vehicles (UAVs). The use of UAVs in agriculture has gained popularity in recent years(Kerry & Escolà, 2021). The combination of UAV technology and precision farming operations has improved the efficiency of fertilizer application strategies. UAVs can be equipped with a variety of sensors, cameras and other data collection tools to provide farmers with high-resolution images and crop information(Meola, 2021). Drones equipped with sensors such as multispectral cameras, thermal imaging cameras and LiDAR can collect data on crop health, nutrient deficiencies and soil moisture(Meola, 2021). For example, multispectral cameras acquire images of various spectral regions to assess the spectral characteristics of crops. These spectral fingerprints reveal crop health, nutrient deficiencies, and stress levels. Conversely, thermal imaging cameras can detect temperature changes in the crop and predict water and fertilizer stress. Drones equipped with high-resolution cameras and multispectral sensors can provide accurate crop health data and pinpoint problem areas. In this study, drones equipped with NDVI (normalized vegetation index) sensors helped us assess crop health, and we used this data to determine if additional nitrogen fertilizer was needed and to estimate crop yields.

The use of unmanned aerial vehicles (UAVs) is promising, providing a nuanced approach to understanding and exploiting spatial variability in soil and vegetation. However, this approach has its own complexities and trade-offs, and the advantages and disadvantages compared to other sensing methods need to be thoroughly assessed, especially in the context of optimizing fertilizer application based on observed spatial variability(Barbedo, 2019).

The use of UAVs has several advantages that make it a pioneer in assessing spatial variability. One of the most important advantages is that drones provide high spatial resolution images(Delavarpour et al., 2021). These detailed images have the ability to pinpoint specific areas of interest and gather intricate details about soil composition, plant health, and stress indicators. With this fine-grained data, spatial patterns can be recognized, which in turn allows management strategies to be tailored to individual plots in the field. Real-time monitoring is another advantage of drones. Unlike ground-based sensors, which may provide intermittent readings, drones can provide instant data updates, quickly detecting changes in soil moisture, vegetation vigor and other parameters(Delavarpour et al., 2021). This is especially important for making timely adjustments to fertilizer applications to ensure that crops are getting nutrients when and where they need them most. Drones are also a versatile toolset for collecting all types of data. Multi-spectral and thermal sensors carried by drones can capture critical information about plant health and stress, such as chlorophyll content and water status. These insights are critical to designing precise fertilization strategies that meet the unique requirements of different areas of the field.

While UAVs offer numerous advantages, they also face a number of challenges. One obvious disadvantage is their vulnerability to weather conditions. Wind, rain, or inclement weather can disrupt flights, causing delays in data collection and potentially hindering decision-making. This reliance on favorable weather conditions can sometimes limit the feasibility of using drones, especially in areas susceptible to severe weather. Operational complexity is another concern. Piloting a UAV requires specialized skills, and obtaining the necessary flight permits can be time-consuming. In addition, maintenance of UAVs requires technical knowledge, which adds another layer of complexity for agronomists who may not have extensive experience with such technology. Battery life poses a limitation to UAVs, affecting their flight time and coverage. Large fields may require multiple flights to collect comprehensive data, potentially leading to gaps in monitoring and analysis. The high initial investment required to purchase a UAV and associated sensors is also a noteworthy financial consideration(Kerry & Escolà, 2021).

Comparing UAVs with other sensing technologies, such as satellite imagery, ground-based sensors, and satellite radar, provides a holistic view of the efficacy of UAVs in addressing spatial variability in fertilizer application optimization(Rodrigues et al., 2021). Satellite imagery, while having the advantage of covering large areas, often lacks the spatial resolution needed to pinpoint small-scale variability. Ground-based sensors can provide continuous monitoring but may miss the big picture. Satellite radar can overcome cloud cover, but its spatial resolution may not be comparable to that of drones.

The key to exploiting spatial variability is to optimize fertilization. Soil and vegetation variability is key to understanding differences in nutrient requirements between fields. Each region may have different nutrient deficiencies or surpluses, so fertilizer application strategies need to be tailored to achieve optimal crop yields and environmental sustainability. By combining drone data with precision agriculture practices, prescription maps are created to guide variable speed fertilizer application. These maps delineate areas with similar characteristics, enabling precise fertilizer application based on the requirements of each area. High-resolution images taken by the UAVs help to accurately identify areas and help to capture spatial trends in soil composition and plant health.

In addition, UAVs can help monitor the effectiveness of fertilizer application in real time. Fertilizer effectiveness can be measured by tracking changes in vegetation vigor and soil nutrient levels. This iterative approach ensures real-time adjustments are made to ensure optimal nutrient uptake and reduce the risk of over- or under-fertilizing.

Using drones to assess spatial variability in fertilizer optimization offers an exciting avenue. While drones offer significant advantages in terms of high-resolution imagery, real-time monitoring, and versatile data collection, they also present challenges related to weather dependence, operational complexity, and cost. By weighing the pros and cons and comparing drones to other sensing technologies, spatial variability can be effectively utilized to design precise fertilizer application strategies. The combination of drone technology and precision agriculture practices is expected to promote sustainable crop production, minimize resource waste, and optimize yields on a field-by-field basis(Monteiro et al., 2021b). The images and data collected by the drones can be processed with GIS to generate detailed maps of crop health and growth patterns, maximizing the efficiency of agricultural monitoring and saving people time and money.

1.2.4 Soil

Soil analysis is a research method to determine the soil properties such as nutrient content, pH, organic matter and other physical properties of soil. Typically, soil analysis involves collecting soil samples from different locations in a field for analysis, and several strategies can be applied, e.g. the random or stratified sampling methodologies, in order to evaluate the soil property variability with the field (*SL 190/SS402: UF/IFAS Nutrient Management Series: Soil Sampling Strategies for Precision Agriculture*, n.d.; *Soil Sampling for Precision Agriculture | CropWatch*, n.d.). Fertilizer application based on average or uniform application rates may lead to over- or under-fertilization of different areas of a field due to the fact that soil nutrient levels may vary widely across a field(*Soil Sampling for Precision Agriculture | CropWatch*, n.d.). The results of the analysis are used to generate detailed maps of soil nutrient levels and other soil properties that can be used to develop precise fertilization strategies. Soil samples can be collected at different times of the year, depending on the crops grown and the specific objectives of the analysis. In recent years, portable devices have become available that use techniques such as near-infrared spectroscopy (NIRS) to quickly and accurately measure soil properties in the field. They can be used to track changes in soil properties, enabling farmers to adjust management practices accordingly(*Soil Sampling for Precision Agriculture | CropWatch*, n.d.).

1.2.5 Variable Rate Application (VRA)

Depending on soil type, topography and other conditions, inputs such as fertilizers and pesticides are applied at different rates in the field, which is known as variable rate application (VRA)(Mary, 2022; *Variable Rate Application - an Overview | ScienceDirect Topics*, n.d.). However, this approach can lead to misuse of inputs in some areas, resulting in environmental damage and increased expenditures(Mary, 2022; *Variable Rate Application - an Overview | ScienceDirect Topics*, n.d.). Farmers can use VRA to get inputs exactly where they are needed, reducing waste and reducing the environmental impact of farming. For example, in a cornfield, soil characteristics vary from region to region. Some areas may have nutrient-rich soils, while others are nutrient-poor. With VRA, prescription maps can be created using data from soil sensors, historical yield maps, and other sources. These maps divide the site into areas with similar characteristics. Fertilizer application rates are then adjusted based on the prescription maps. In nutrient-rich areas, the amount of fertilizer applied can be reduced to avoid over-fertilizing, while in nutrient-deficient areas, the amount of fertilizer applied can be increased to meet the needs of the crop. This targeted approach ensures that each area receives the optimal amount of nutrients to improve crop health and yield.

The VRA technology is supported by a variety of technologies, including GPS, sensors and GIS software(*Variable Rate Application - an Overview | ScienceDirect Topics*, n.d.). Farmers can identify areas of variability in their fields by collecting data on soil types, topography and other features(“Variable Rate Application,” 2023). And this can be a challenge for small farmers, which require collecting and processing large amounts of data, who may not have access to the technology or expertise needed to apply VRA effectively. As the cost of precision agriculture equipment continues to decline, VRA may become an affordable technology for all farmers(“Variable Rate Application,” 2023). On the other hand, the VRA technique can be based on catching the spatial variability of the crop, e.g. by identifying using proximal or remote sensors the vegetation status at a certain scale. NDVI data can inform the creation of VRA prescription maps, optimizing the application of resources based on the actual health and vigor of the crop. Example: In a wheat field, drone imagery shows that certain areas are experiencing water shortages, resulting in lower NDVI values. A VRA system equipped with this NDVI data can adjust irrigation rates accordingly. Water can be directed to stressed areas, ensuring that plants receive the water they need to recover and grow. At the same time, in areas with healthy vegetation, irrigation rates can be moderated to prevent overwatering. This integration minimizes water waste, improves crop performance, and promotes efficient use of resources.

1.2.6 NDVI

The Normalized Vegetation Index (NDVI) is computed by measuring the reflectance of visible and near-infrared light from plants, and it indicates the chlorophyll content of plant tissue. Chlorophyll is the pigment responsible for photosynthesis, and thriving plants contain more chlorophyll, resulting in a greener appearance. NDVI is calculated as a ratio between the red (R) and near infrared (NIR) values in traditional fashion:

$$NDVI = \frac{NIR_{reflectance} - Red_{reflectance}}{NIR_{reflectance} - Red_{reflectance}}$$

Here, NIR represents the reflectance value in the near-infrared band, and Red represents the reflectance value in the red band. Healthy vegetation (chlorophyll) reflects more near-infrared (NIR) and green light than other wavelengths. But it absorbs more red and blue light (Figure3). Healthy vegetation contains a lot of chlorophyll and cellular structures that tend to absorb a lot of visible light while reflecting near-infrared light. On the other hand, unhealthy vegetation does the opposite. It reflects more visible light while absorbing near-infrared light. NDVI can utilize the unique reflective properties of healthy plants to distinguish vegetation from non-vegetation or unhealthy vegetation, making it possible to monitor the growth and health of vegetation and identify areas of stress or damage(*NDVI- Normalized Difference Vegetation Index*, 2021) (Figure 2). The NDVI values range from -1 to 1. It is computed using information derived from satellite images or sensors affixed on drones or other aerial platforms. The data is processed with GIS software to generate a map of NDVI values for the entire field. Areas with high NDVI values are regarded as healthful and productive, whereas those with low NDVI values may be experiencing stress or disease. Consequently, the NDVI index can be utilized throughout the growing season to monitor crop health. In addition to monitoring crop health, NDVI can be used to determine which areas of a field require various management techniques(*Vegetation Indices: A Key Tool in Precision Agriculture | Pix4D*, n.d.). For instance, an area of a field with consistently low NDVI values may indicate poor soil quality or drainage issues. Due to the close relationship between NDVI values and crop biomass, they can be used to predict crop yields prior to harvest. This indicates that NDVI indices can assist producers with crop marketing and planning for the next planting season(*NDVI- Normalized Difference Vegetation Index*, 2021; *Vegetation Indices: A Key Tool in Precision Agriculture | Pix4D*, n.d.).

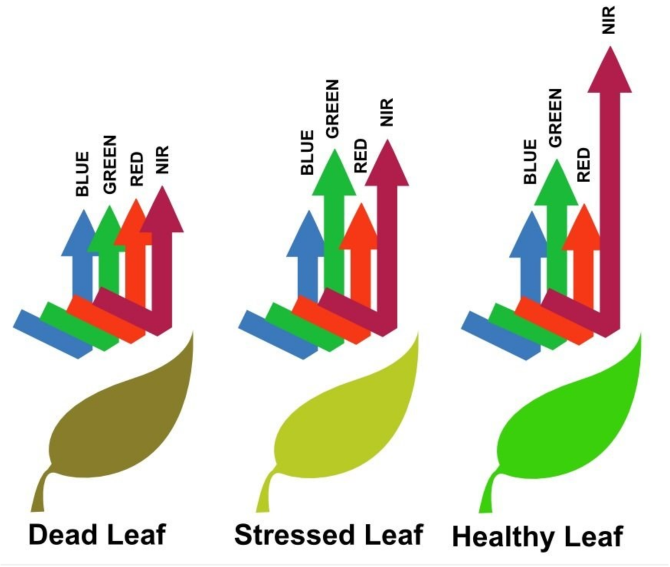


Figure 2: The healthy plant shown here has a high absorption of blue and red wavelengths. It reflects the green color and especially the infrared (near infrared) which is not visible to the naked eye.

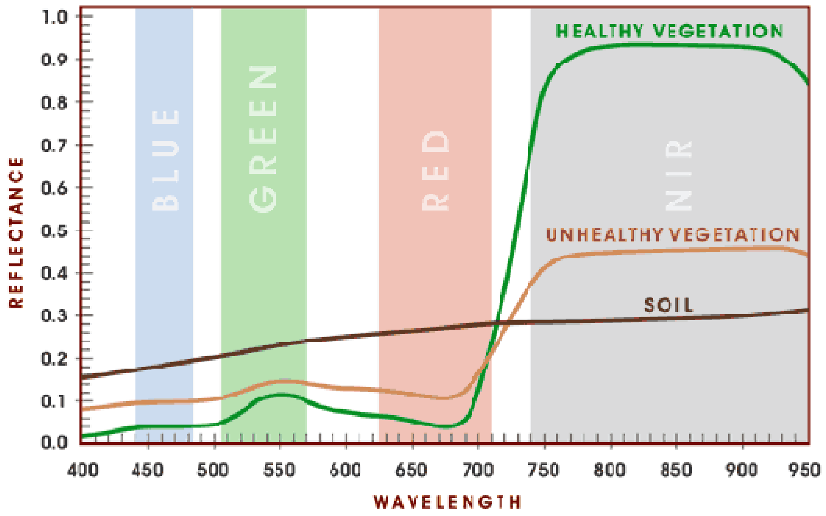


Figure 3: Reflectance spectra comparing reflectance profiles of healthy vegetation, unhealthy vegetation and soil.

1.3 Borettana Onions

Onions (Allium cepa L.) are annual or biennial herbs characterized by scaly leaves surrounded by a leaf sheath and a fleshy, semi-underground bulb. The plant's leaves are elongated and divided into two parts, the leaf sheath, which is tightly wrapped at the base of the stem, and the leaf blade, which protrudes from the center of the leaf sheath. The bulb of the plant is divided into inner and outer layers, the outer layer usually being thinner and the inner layer thicker. It is an important vegetable crop that is widely grown and consumed worldwide. Onions, an ancient crop, have a history of cultivation dating back to around 4000 BC. The earliest cultivation sites were probably located in the Asian region, and then gradually spread to other regions. In ancient Egypt, onions were not only an important ingredient, but were also used to perform mystical rituals and for medicinal purposes. By the time of Ancient Rome, onions were widely cultivated throughout Europe and were believed to have therapeutic properties(George E. et al., 2007).

Cultivation of onions requires a combination of factors, including soil conditions, climatic requirements, water management, fertilization techniques and pest control. At the same time, a focus on environmental sustainability is an important goal of global agricultural development, and proper fertilization and nutrient management can help reduce adverse environmental impacts. Effective use of fertilizers while maintaining crop yields is one of the most challenging issues. Many onion farms are still using traditional fertilizer application techniques, which may lead to fertilizer misuse and nutrient loss, such as water pollution and soil degradation.

According to the latest data of I.STAT 2023 onion (Allium cepa L.) is grown in Italy on more than 12,000 ha with a total annual production of about 400,000 tons, while in the Veneto region onion is grown on about 862 ha with a total annual production of about 30,000 tons, Italy is currently one of the most important European countries in the onion market, and Borettana onions are widely grown. The Borettana onion is a necessity for the farmers of the region due to its high quality and peculiar flavor. On the other hand, growing Borettana onions can be challenging as they require specific soil conditions and nutrient concentrations. Borettana onions are usually grown in granular, organic-rich soil with a pH between 6.0 and 7.5. Onions are more susceptible to nutrient deficiencies than most crops due to their shallow and unbranched root system (Gebretsadik & Dechassa, 2018)。As Lazzaro B., Dal Ferro N. et al. showed in 2018 in the results of crop yield simulations under the standard scenario DAYCENT, the highest yield values were obtained in the north-central plains of the Veneto region of Italy, where the interactions between the soil climate and the management conditions (e.g., high doses of nitrogen inputs) favored the optimal growth of the crop (Figure 4).

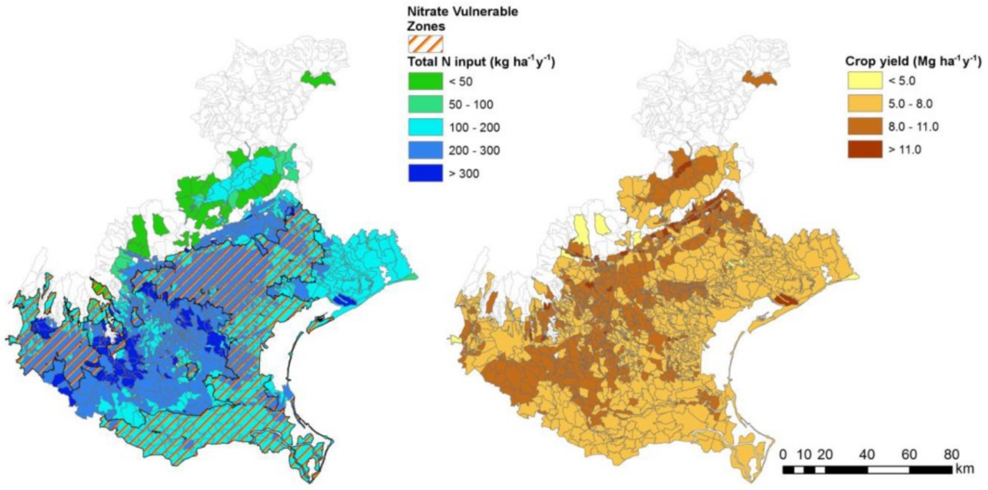


Figure 4: Total nitrogen loads (kg ha-1year-1) inside and outside of nitrate-prone areas using the DAYCENT model (left) and average crop yields (dry matter) across the Veneto region (right). (Lazzaro et al., 2018)

If too little nitrogen is available, onions may be severely stunted. However, onions fertilized with large amounts of nitrogen are not thought to store well. Finally, too much nitrogen late in the growing season is thought to delay ripening and cause double hearts. Ultimately apply nitrogen at least four times a few weeks before harvest. Nitrogen rates will vary depending on soil type, rainfall, irrigation, plant population, and method and timing of application.(George E. et al., 2007) In highly specialized areas, onions are usually grown on sandy soils characterized by low nutrient retention and high permeability, close to riverbanks or coastal areas, and are exposed to significant risks of degradation of groundwater quality and eutrophication of surface water, which can be a highly destructive process.(Messina et Al_2021_Monitoring Onion Crop “Cipolla Rossa Di Tropea Calabria IGP” Growth and Yield.Pdf, n.d.)In fact, excess nitrogen can determine accelerated growth, delay bulb maturity, increase susceptibility to pests and diseases, reduce dry matter content, limit shelf life, and lead to poor onion yield and quality(Gebretsadik & Dechassa, 2018) , large amounts of nitrogen oxides are emitted into the atmosphere. As a result of these emissions, and the fact that the world converts more atmospheric nitrogen into reactive forms through anthropogenic processes than all of the Earth's natural processes in terrestrial systems combined, the global nitrogen cycle has changed dramatically, even exceeding the global carbon cycle The global share of greenhouse gas emissions directly from cropland as a result of fertilizer application is about 23%(Casella et al., 2022). The negative impact of nitrogen on our food production is due to a general decline in nitrogen utilization efficiency (NUE) (Figure 5), which makes it particularly important to control the amount of nitrogen applied during crop cultivation.

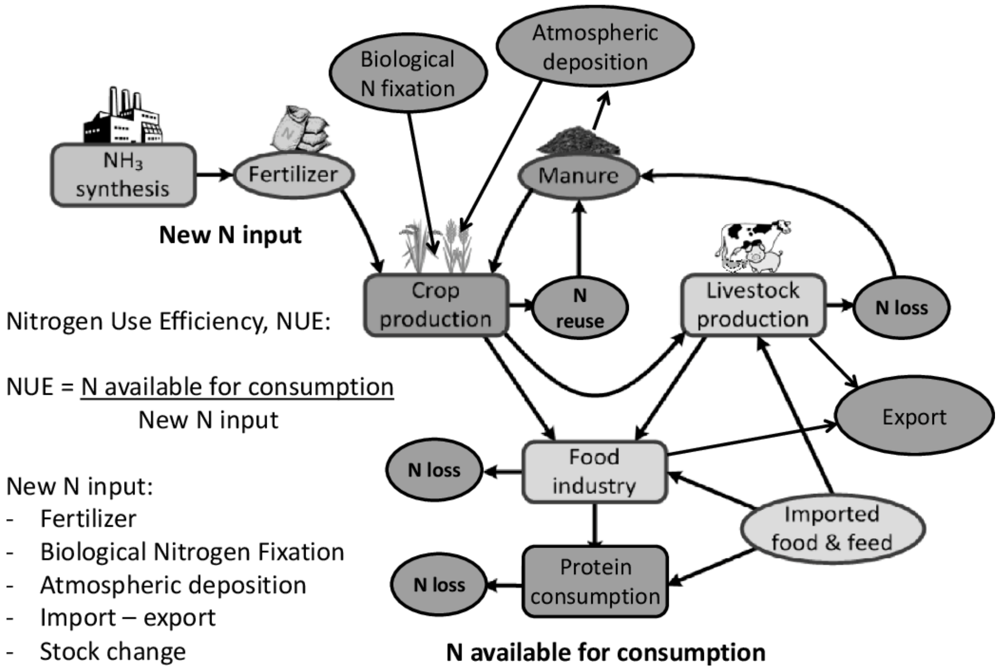


Figure 5:Full-chain nitrogen use efficiency (NUEFC) in the national food system. The figure also shows where nitrogen losses occur.(Erisman et al., 2018)

2. THESIS'S OBJECTIVE

This study seeks to develop and evaluate an accurate fertilization strategy for Borettana onion in open field cultivations based on soil and vegetation ground monitoring coupled with remote sensing UAV-drived imagery.The objective was to increase the efficient use of nitrogen by maintaining high standards of onion yield and quality, and provide information to develop precision variable rate fertilization strategies based on remote sensing surveys.

This thesis is part of a differential fertilization trial conducted by the Department of Agronomy, Animal, Food, Natural Resources, Animals and Environment of the University of Padova, Archetipo Srl, and Orti dei Berici Soc. Coop. over a three-year period from 2021 to 2023, with the goal of determining the optimal dose and distribution period of nitrogen fertilizer to increase the efficiency of nitrogen uptake using the precision agriculture techniques described above. The study's specific objectives include collecting soil samples from the field in order to calculate the N content and evaluate the chemical composition of the soil. Determine the relationship between proximity sensing and crop data utilizing values derived from NDVI maps and QGIS processing based on NDVI maps. Evaluation of the onion yield response to site-specific fertilizer application.

3. RESEARCH AREA

3.1 Location Selection

The experimental site for the cropping season 2022 was located at Isola della Scala, Italy, a municipality located in the province of Verona at 45.29 N, 11.07 E. The experimental field was a 25-hectare area cultivated with onion by Orti dei Berici Agricultural Cooperative Association, a leading company in this sector. The onion variety grown for this study is the Borettana onion, an Italian onion variety that plays an important role in the economic and pastoral development of the region.

The soils of the area from APRAV map (Figure 6: available at https://gaia.arpa.veneto.it/) classifies it as Arenosol (Figure 7), which was originated in ancient hypocaloric plains. It is composed of quartz or other gravels (usually between 0.063 mm and 2 mm in diameter) that can occupy 60% or more of the volume of the soil Arenosol soils are usually well drained, with low water retention and nutrients capacity due to the low organic matter and clay contents. In terms of land use, Arenosol soils are often used for irrigated agriculture and fruit tree cultivation due to their good drainage. However, due to the low organic matter and nutrients, they require additional soil amendments and fertilization to support plant growth. The soil consists of sand and decarbonized soil with fine sediments from the last glacial movement. These soil characteristics were considered by the farmer and conducting onion cultivation.

Figure 6: Soil map of the Veneto region (available at https://gaia.arpa.veneto.it/)

L2 - Sovraunità di Paesaggio - Carta dei Suoli del Veneto in scala 1:50.000

Latitude: 45.29
Longitude: 11.07

SOVRAUNITÀ DI PAESAGGIO: A8

Media pianura antica (risalente all'ultima glaciazione) costituita prevalentemente da sabbie, con suoli decarbonatati.

Figure 7: The soils classification

3.2 Experiment Field

This study covered an area of 7.1 ha and was part of a larger area in the study. Within the experimental site, a completely randomized block design was used to identify four different treatment in plots with an area of 48 x 72 m^2 each. The experiment was repeated five times with two sampling areas as sub-replications, for a total of 40 experimental units.

The map below depicts a view of the field:

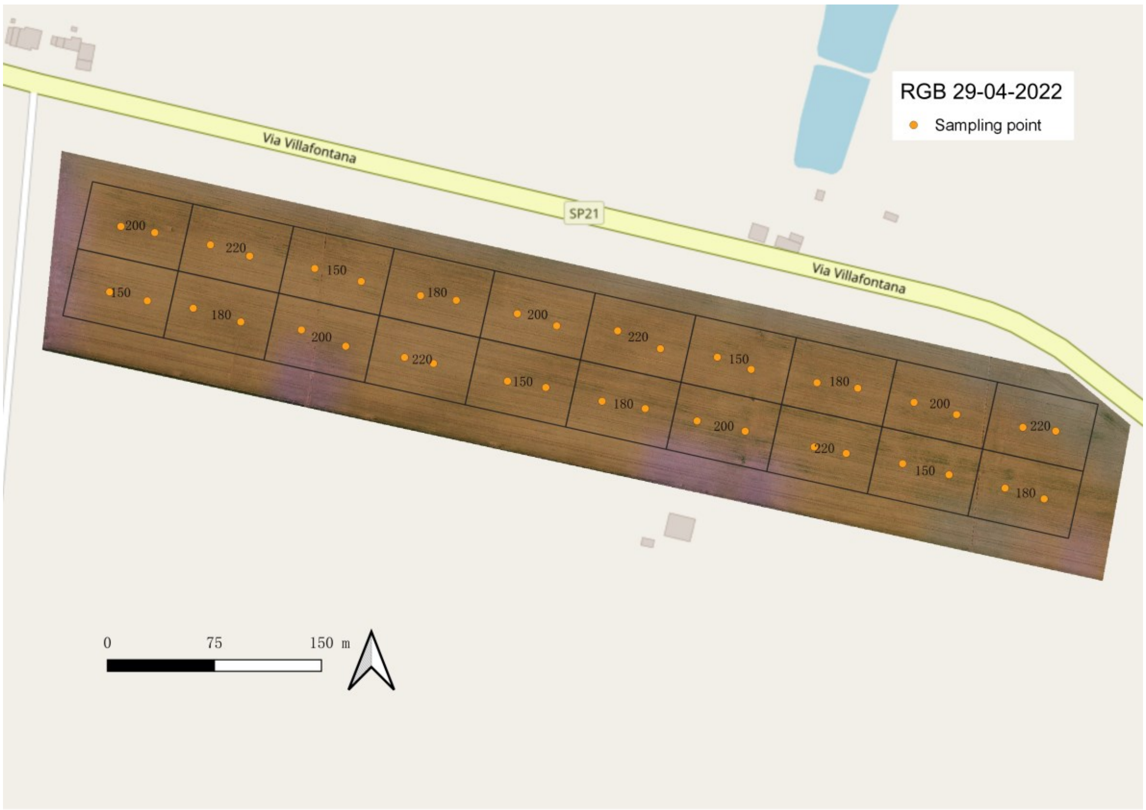


Figure 8: The site of the experiment. The sample places are marked, which means that there are two subreplicates for each plot that was treated. The numbers show which treatments are being compared for each spot, and as the numbers go up, so does the amount of fertilizer used.

The four different treatments were thought to study the effect of different levels of total nitrogen applied in the form of ammonium sulfate ($(NH_4)_2SO_4$), which was applied as top-dressing by splitting it over the cropping season in 6 times. The plots' fertilization levels ranged from 700 to 1050 kg/ha in total.

Table 1: Ammonium sulfate dose distribution based on comparitive treatments

Treatments	Fractional dose of ammonium sulfate (kg/ha)	Total distributed (kg/ha)
N150	90 + 90 + 140 + 140 + 140 +100	700
N180	120 + 120 + 170 + 170 + 170+100	850
N200	140 + 140 + 190 + 190 + 190+100	950
N220	160 + 160 + 210 + 210 + 210+100	1050

Throughout the experiment, a series of data was collected and analyzed to better understand the effects of the different treatment levels on the onion growth, total biomass and yields.

4. RESEARCH METHOD

4.1 UAV Data Collection and Analysis

During the cropping season, especially after the first fertilization event, five aerial imagery collection surveys were conducted using UAVs (Unmanned Aerial Vehicles) and the multispectral bands of IR and NIR were used to calculate NDVI (Normalized Difference Vegetation Index).

UAV development: for precise flight stability, the UAV was equipped with a Global Positioning System (GPS) receiver and an Inertial Measurement Unit (IMU) positioning system, as well as a specially configured "DJI Matrice 600 Pro" UAV, a large, versatile six-rotor aircraft. The helicopter is an L-class (light) unmanned aerial vehicle with a maximum launch weight of 12 kilograms. Due to the optimized motor balance and propeller efficacy, it is stable in winds exceeding 15 km/h.

Figure 9: The DJI Matrice 600 drone is utilized for aerial monitoring.(image on the left), Instrument Topcon Hiper pro 2 GPS/GNSS receiver for ground topographic surveys(image on the right)

Data acquisition and processing: aerial images were acquired in the field using UAV equipped with RGB and multispectral sensors. Specifically, multispectral aerial images were captured with the RedEdge MX MicaSense sensor, which is capable of simultaneously capturing blue, green, red, near-infrared, and infrared spectral bands(Radoglou-Grammatikis et al., 2020). Connected to this during image acquisition is the Downlight Sensor (DLS2), which measures ambient light conditions during flight to acquire more precise data under variable light conditions(Radoglou-Grammatikis et al., 2020).

Data imageries were then processed with the QGIS software platform. First, a polygon file was generated to the projected coordinate system WGS84 / UTM 33N. In this step, NDVI raster maps were superimposed onto a shapefile representing a 2x2m area surrounding the sampling points. Subsequently, a rescaling was performed of the NDVI raster maps using QGIS software in order to reduce noise and include a representative area (region of interest) of the entire plot which cloud be associated with soil and vegetation ground survey in the same areas. From NDVI raster images statistical metrics, including the mean, median, maximum, and minimum values were then extracted. Then, we identify the georeferenced sampling points in each plot and generate attribute tables, such as ID, fertilizer application rate, etc. Finally, data obtained from field surveys and UAV imagery were added to attribute tables for statistical analysis to determine if there were significant differences between treatments (fertilizer application) in above- and below-ground biomass, N content of above- and below-ground biomass, bulb diameter, plant height, N uptake, and N use efficiency.

4.2 Monitoring of Soil and Vegetation Growth

A number of field visits and surveys for data collection were carried out to estimate the crop growing dynamics and eventually harvest of the onions. These included regular vegetation observations, soil monitoring and aerial surveys using drones.

Table 2 provides a summary with sample dates and identifiers (survey IDs). These identifiers will be used in subsequent charts to facilitate differentiation and understanding.

Therefore, a high priority was given to collecting and recording the sample throughout the study to ensure the reliability and consistency of the data. Combining these sample data with other datasets and observations can form a more comprehensive picture to support the evaluation and optimization of onion growing and management strategies. Such consistency and accuracy are critical for decision-making in agricultural practices, helping us to make more informed decisions and achieve better-growing results.

Table 2: Dates of the surveys carried out in the year 2022.

Data	Survey ID	Fertilization	Monitoring
2022/3/31		x	
2022/4/4	T0		Soil
2022/4/20		x	
2022/4/29	T1		Vegetation/ NDVI (UAV)
2022/5/10		x	
2022/5/16	T2		Vegetation/ Soil/ NDVI (UAV)
2022/5/24-26		x	
2022/5/31	T3		Vegetation/ Soil
2022/6/1			NDVI (UAV)
2022/6/11-13		x	
2022/6/20	T4		Vegetation/ NDVI (UAV)
2022/6/27	T5		Vegetation
2022/6/30			NDVI (UAV)
2022/7/5	T6		Vegetation/ Soil

During the first field trip, which took place on 4 April 2022, the study focused on the collection of soil samples. The analysis of these samples helped to understand the texture, nutrient content and moisture status of the soil, providing an important basis for subsequent planting and management work.

As can be seen from the graphs, temperature changes during the growing season play an important role in the growth of onions, and in 2022 the Italian temperatures were uncharacteristically high, with a sharp drop in precipitation that was compensated by frequent irrigations as can be seen from the figure below.

During the same period, by monitoring the soil moisture in the experimental area. The results showed that soil moisture was maintained between 10%-15%, with an average of about 10%. By comparing the data from previous years, it was realized that the average rate of change in soil moisture was about 5%.

Through hese field trips and data collection efforts have resulted in a more comprehensive understanding of the environment in which Borettana onions are grown. This information is important for developing optimal planting and management strategies.

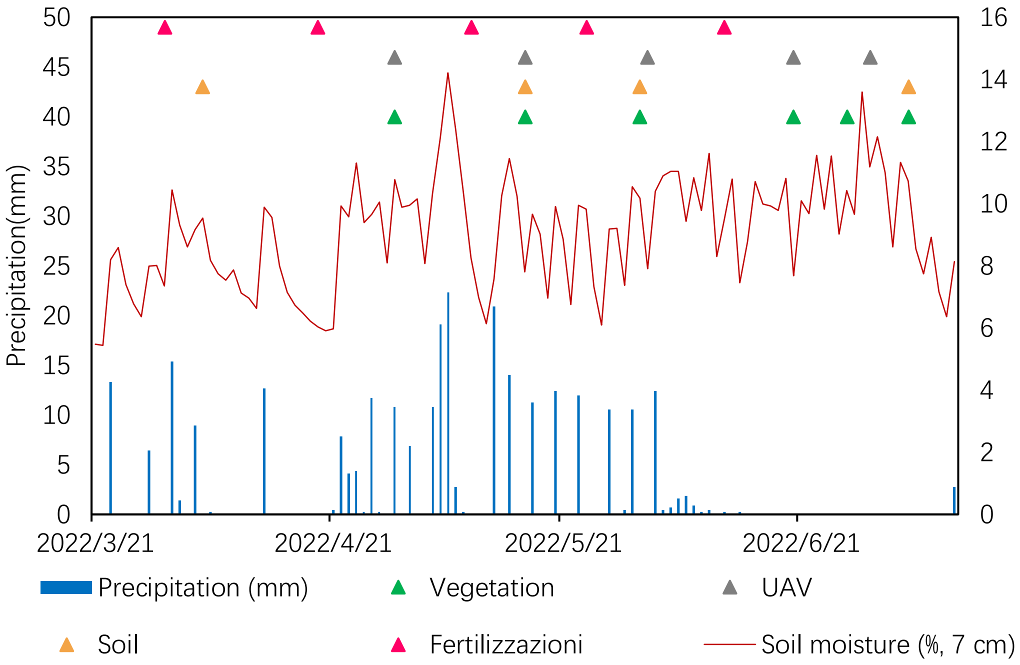


Figure 10: Precipitation and soil moisture for the period 15 March to 15 July 2022. Coloured triangles indicate the period of fertilizer application (pink) and the period of field surveys of soil (orange), vegetation (green) and drones (grey).

4.2.1 Soil Sampling and Measurements

Soil chemical-physical analyses were conducted at each identified sampling site, and analyses were completed on various dates. We collected surface-disturbed soil samples using a hand auger at depths of 0-20cm.On 4 April 2022, prior to the first fertilizer application, soil samples were collected at the DAFNAE Department's laboratory and the following analytical steps were performed. Soil samples were collected three times during the crop growing season at the same depth in the same location (Figure 11). The samples were brought back to the laboratory and placed in aluminum foil containers at room temperature to dry for SOC and texture analysis. The dried soil samples were sieved 2 mm for texture analysis and 0.5 mm for SOC analysis. Soil samples for ammonium nitrogen and nitrate nitrogen analyses were stored frozen prior to analysis to avoid degradation and transformation of nitrogen.

Figure 11: Images of the identification of sampling points, the collection of soil samples, and their preparation for subsequent analysis.

Then, the samples were analyzed as follows:

a) Organic matter content: expressed as soil organic carbon (SOC, %) using a Skalar Primacs elemental carbon analyzer.
b) Total N content: determined using the Kjeldhal method and expressed as a percentage (%).
c) Texture: The texture characteristics of the soil were determined by using a laser diffractometer (Malvern Mastersizer 2000).

Figure 12: Soil samples were collected for analytical processing, sedimentation, shaking, mixing and using Skalar Primacs Elemental Carbon Analyser.

4.2.2 Plant Sampling and Measurements

At each of the identified sampling plots, we conducted biometrics (plant height, leaf length, bulb diameter, bulb number) and chemical analyses (total nitrogen) above and below the crop on six different dates. We sampled 0.25 x 0.25 m^2 of plant biomass from all identified sampling plots, corresponding roughly to 35-to-40 single onion plants. Fresh biomass was collected and stored in a portable cooler to prevent moisture loss until fresh biomass analysis was performed. Prior to biomass analysis, onion samples were washed to remove soil particles and residues, and the number of plants ($1/m^2$) in each sample was counted. The size of the diameters of onion bulb samples from the remaining growth periods was measured using a circular ruler, except for onion bulbs at the T1 stage, where the diameter was directly observable to be less than 5 mm in diameter above- and below-ground plants were separated separately with scissors and their fresh biomass was calculated. Each fresh sample was weighed (g/m^2) and labeled with an ID.

The plant samples were then dried at 65°C until constant weight and their dry biomass (g/m^2) was measured. The dried samples were weighed and then grinded into powder using a mortar, pestle, and/or hybrid grinder. These powdered samples were sent to the laboratory for total nitrogen and residual humidity analysis. Photographic documentation of the vegetation under different treatment conditions was also collected (see Appendix for details). Figure 13 shows some moments of the field and laboratory activities.

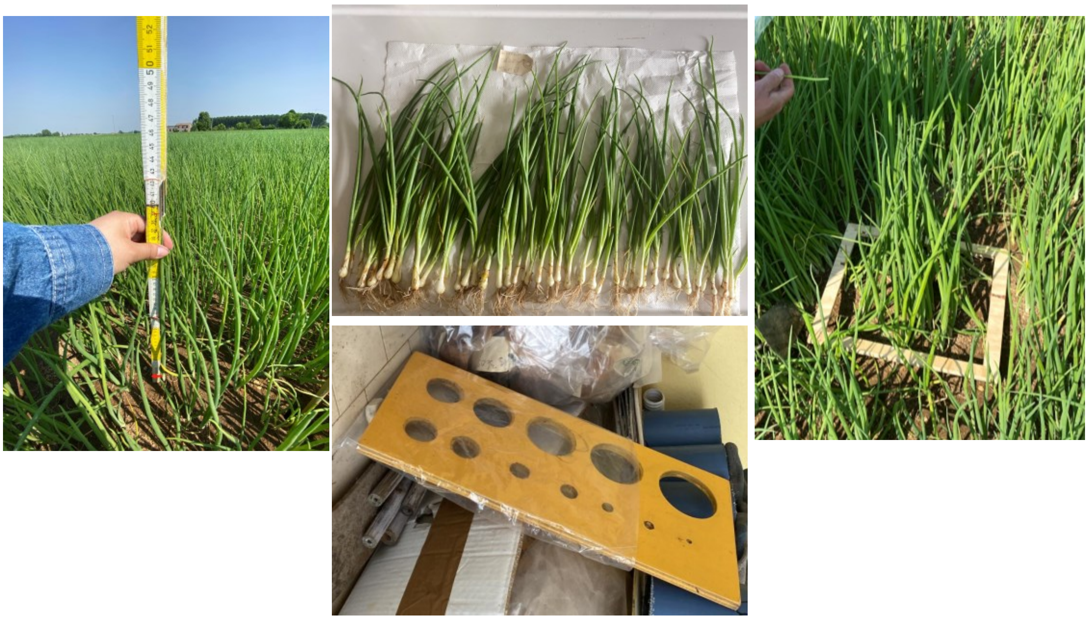


Figure 13: Diagram of experimental preparation of plants

4.3 Statistical analysis

Statistical analyses have been performed to identify whether significant differences occurred between treatments (fertilizations) in terms of aboveground and belowground biomass, N% in above and below ground biomass, bulb diameter, plant height, N uptake and NUE. A randomized block design script in R was used. Statistical differences were identified by using a multiple comparison Tukey HSD test. Only histograms reporting different letters within each sampling date were significant at $p < 0.05$.

5. RESEARCH RESULTS AND DISCUSSION

5.1 Soil Sampling Results

The average content of sand (>50 μm), silt (2-50 μm) and clay (2 μm) in the test soils was on average 71.43%, 14.17% and 14.4% respectively. Soil organic carbon (SOC) content was consistently below 0.6% and nitrogen content below 0.06%. This also resulted in a tendency for a C/N ratio around 10, indicating substantial equilibrium between N losses and C accumulation (Table 3). It is worth noting that lower C/N ratios may have an impact on onion growth and soil fertility, as nitrogen plays a key role in protein synthesis in plants, while carbon is is involved in the construction of organic matter and energy storage processes.

Table 3: Mean characteristics and variability (± standard error) of the soils in the monitoring plots.

	Sand (%)		Silt (%)		Clay (%)		SOC (%)		N-tot (%)		C/N	
N150	71	±0.6	14	±0.4	15	±0.2	0.57	±0.02	0.06	±0.00	10.15	±0.22
N180	70	±1.9	15	±1.0	15	±0.9	0.58	±0.02	0.05	±0.00	10.53	±0.12
N200	72	±1.2	14	±0.7	14	±0.5	0.59	±0.04	0.06	±0.00	9.81	±0.55
N220	73	±0.9	13	±0.6	14	±0.4	0.58	±0.04	0.05	±0.00	11.01	±0.64

The soil characteristics are more evident in the folded and spatial distribution maps below, with coarser soils and high sand content. A more pronounced difference can be seen in the spatial maps, with coarser dark reddish soils in the central plots (northwest), but lower levels of chalks and clays being palepink (Figures 15-17). Thus, especially in the northeast and southwest sampling sites, the texture, while still sandy loam, is approaching sandy clay loam.

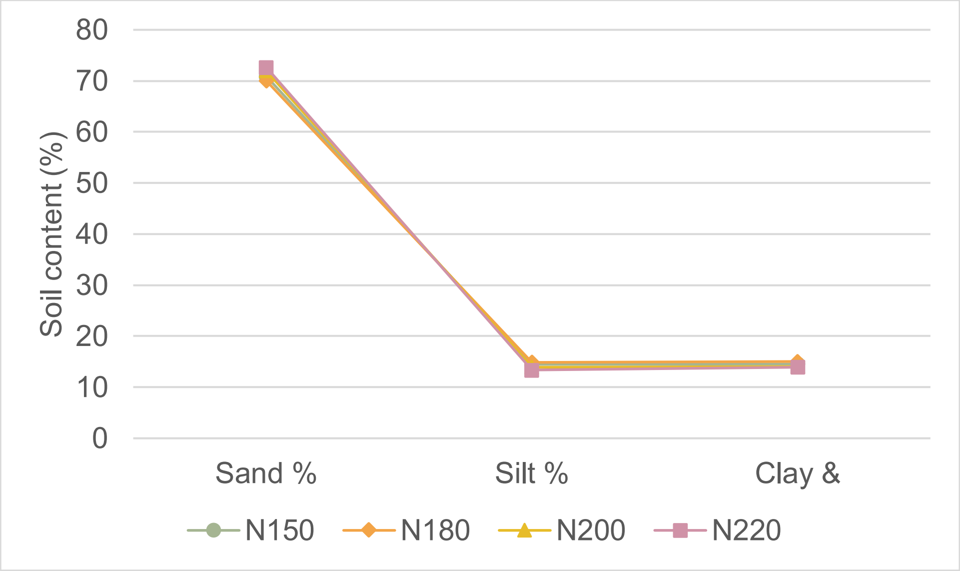


Figure 14: Line graph of sand, silt and clay content in the soil of the experimental plots

Figure 15: Mean characteristics and variability (± standard error) of the soils in the monitoring plots.

Figure 16: Slit content of the sampling area.

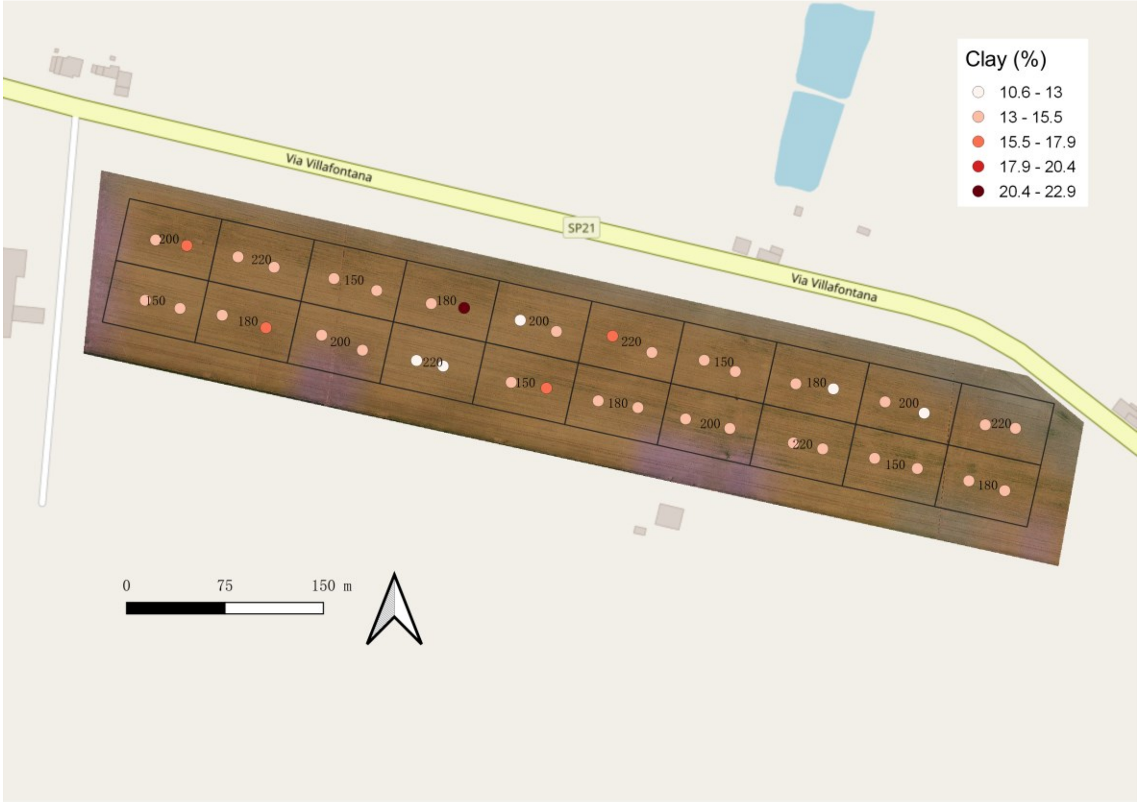


Figure 17: Clay content of the sampling area.

5.2 Vegetation sampling results

5.2.1 Height

The plant's height can be observed in the field throughout its complete growth cycle, but before harvest when the leaves are completely dried. Indeed onion is a 2-year cycle plant, and at harvest the vegetation has completed the first year of growing being it sown according to its management. The following graph (figure 18) depicts the height of the plant in centimetres. The plant heights of N150 and N220 were comparable at the initial time point (T1), ranging between 14.8 and 16.8 cm, respectively. The vegetation grew rapidly until it reached 53 centimetres in T4 and reached stability in T5. At the end of the cycle, all leaves were desiccated and partially decomposed, making precise measurements impossible. From the beginning of T1 (April 29, 2022) and throughout the planting season, there were no statistically significant differences in plant heights, with a maximal difference of 3 cm between the mean heights of N150 and N220.Concerning the heights of the plants in T2, the mean value recorded at the lowest nitrogen dose application (N150) was 31.1 cm, while the mean value recorded at the highest nitrogen dose application (N180) was 33.1 cm. The larger nitrogen concentrations (N200 and N220) did not substantially differ from the two preceding groups, with respective values of 33.4 and 32.84 cm. The period corresponding to the May 31, 2022 (T3) field survey revealed that the N150 plant was 43.21 cm taller than the N220 plant, which received a higher nitrogen dosage. The final field survey measurement (T5, 27 June 2021) revealed that plant heights for the N150 and N220 regimens converged to 53.38 and 53.13 inches, respectively.

Comparing the data of 2021 and 2022 the following differences can be observed, probably due to the nutrient status of the soil, the nitrogen uptake capacity of the plant and other environmental factors, there were more significant differences in plant height between different nitrogen fertilizer treatments in the data of 2021, whereas in the data of 2022, the differences in plant height between the treatment of the highest fertilizer application (N220) and the treatment of the medium fertilizer application (N150) were not significantly different from each other.

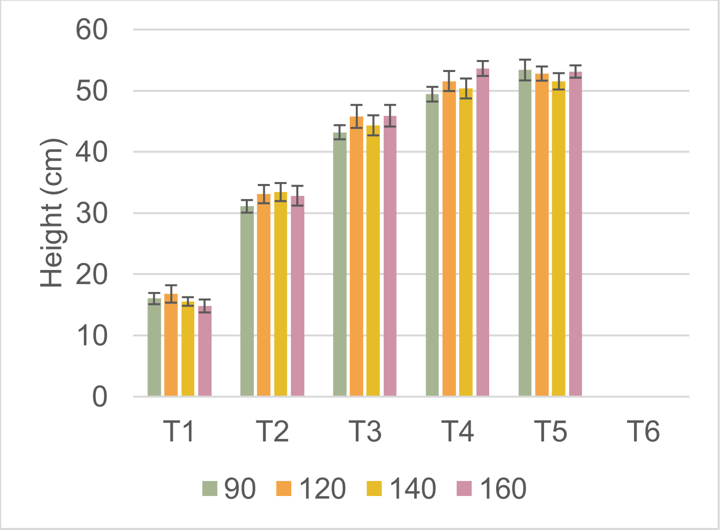


Figure 18: Height of the plants.

5.2.2 Diameter

The graph below represents the bulb diameter in millimeters (Figure 19). As can be seen from the figure, bulb diameter gradually increased with time. Except for the T1 field survey (date of sampling April 29, 2022) because the bulbs were smaller than 5 mm. On the T2 sampling date we observed that bulb diameter averaged 7.83 mm at the lowest N fertilizer dose applied (N150), 7.91 mm at the N fertilizer dose applied (N180), and 17.51 mm and 7.43 mm at the larger N fertilizer doses applied (N200 and N220), respectively. At harvest, mean bulb diameter was 34.61 mm for N150, 34.04 mm for N180, 36.61 mm for N200, and 34.88 mm for N220, and no significant differences were observed. Since bulb quality is a significant factor determining the quality of the final product and therefore its price, these results suggest that nitrogen fertilization rates have a negligible effect on the bulb size, whose most valuable should have a size between 3 and 5 cm.

Compared to the same experiment in 2021, there was a gradual increase in bulb diameter in all cases, but the rate of increase and trend may have been slightly different. there was no significant variability in the comparison of data from 2021 and 2022, and the values of bulb diameter under the different nitrogen fertilizer treatments varied slightly at different points in time, but these differences were relatively small. Similarly, differences in bulb diameter under different nitrogen fertilizer treatments were not significant and no significant differences were observed at harvest.

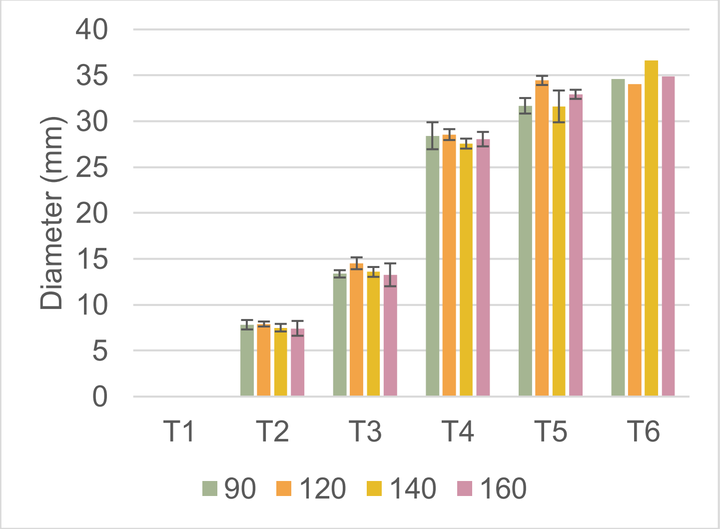


Figure 19: Diameter of the plants.

5.2.3 Biomass

The graph below represents aboveground fresh biomass (g/plant). Fresh leaf biomass varied with crop growth period, and according to nitrogen applicati only at T5 period, while it did not affect the aboveground biomass during the early stages, from T1 to T4 (April 29, 2022 and June 20, 2022). Regardless the lack of N significance, is some cases also the trend in aboveground biomass did not respond to N fertilization, such as in T3 when the lowest N doses (N150 and N180), has some slight increase in biomass with respect to N200, with recorded values that averaged 8.18 g/plant. At the same sampling date T3, at higher N doses (N200 and N220), average values were observed, which were 6.9 g/plant and 8.43 g/plant, respectively. As shown in the figure, after T4, the aboveground fresh biomass decreased, bulbs began to develop, and the tops of the green leaves began to turn yellow and dry (T5), eventually collapsing a little above the tops of the bulbs (T6). This will be clearer by looking at the NDVI index later in the paragraph 5.2. Instead, during the T1 sampling period, the plants were at the seedling stage, so there was not a significant amount of fresh biomass in the field, being always <1g/plant.

Comparison of dry biomass with fresh biomass yielded almost identical differences between the means, but in this case no significant difference was ever found between N fertilization, suggesting that N fertilization in T5 may determine some of the vigor of the aboveground vegetation that has been found by increasing the water content in the leaves.

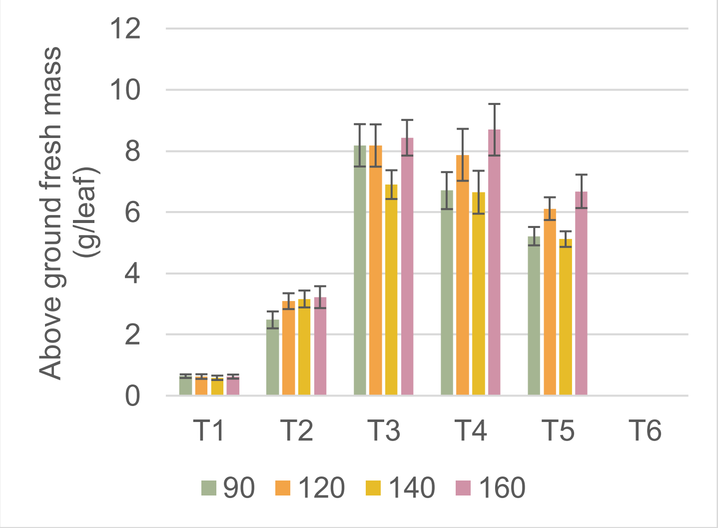


Figure 20: Above ground fresh biomass (g/plant).

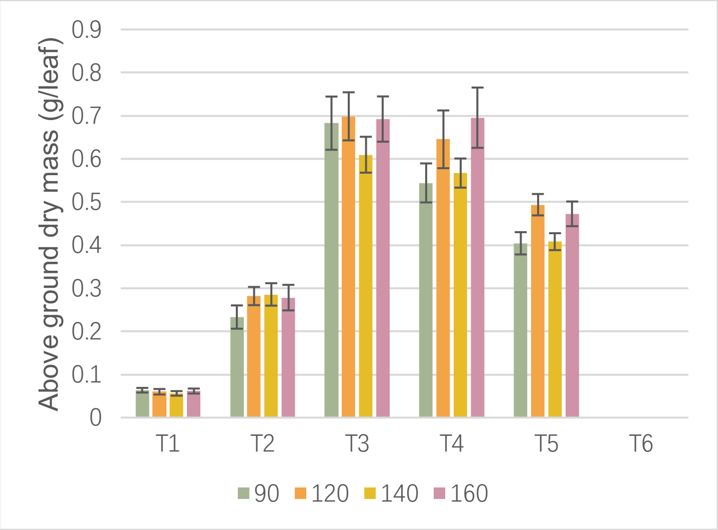


Figure 21: Above ground dry biomass (g/plant).

The graph below (Figure 22) shows the belowground fresh biomass in grams per plant. Fresh bulb biomass varied depending on the period of the growing season, and different doses of nitrogen fertilizer application did not prove to make a difference. However, at time period 6 (T5) on June 27, 2022, the N application rate of N200 showed a large variation compared to N180, despite significant differences were not observed. In terms of fresh biomass of sub-surface crop, the lowest N fertilizer application (N150) recorded 14.9 g/plant, while the N fertilizer application (N180) recorded 17.4 g/plant, whereas the larger N fertilizer application (N200 and N220) recorded only 14.5 g/plant and 16.1 g/plant, respectively. However, the biomass of fresh bulbs in the final pre-harvest period (T6) tended to vary consistently from 16.2 g/plant for N150 to 17.5 g/plant for N220, which was not significant at the macro level.

The same contrast between fresh bulb biomass and dried bulb biomass was not significant (Figure 23).

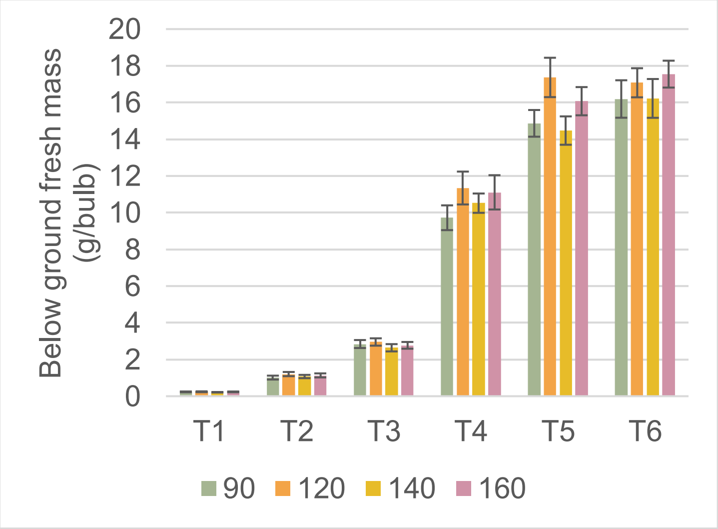


Figure 22: Below ground fresh biomass (g/bulb).

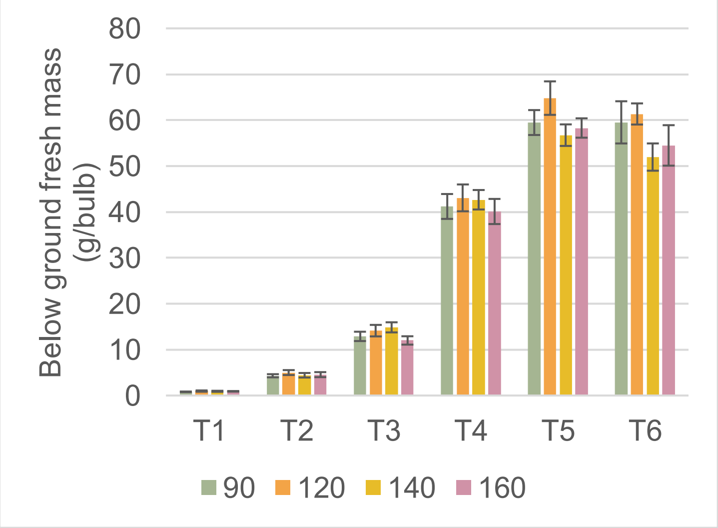


Figure 23: Below ground dry biomass (g/bulb).

5.3 Nitrogen

5.3.1 N content

The percentage of nitrogen content in the leaves is shown in the accompanying graph, which compares the effects of various fertilization treatments (Figure 24). There was observed to be no statistically significant difference between the T1 and T6 treatments, however some slight N% increase was observed at increasing N dosages in all growing periods that have been sampled. In a manner comparable to bulbs, the initial nitrogen concentration of T1 was greater, coming in at around 3.6%, but it dropped to approximately 1.8% in T5. In contrast to bulbs, the amount of nitrogen remained virtually unchanged from T2 to T5.

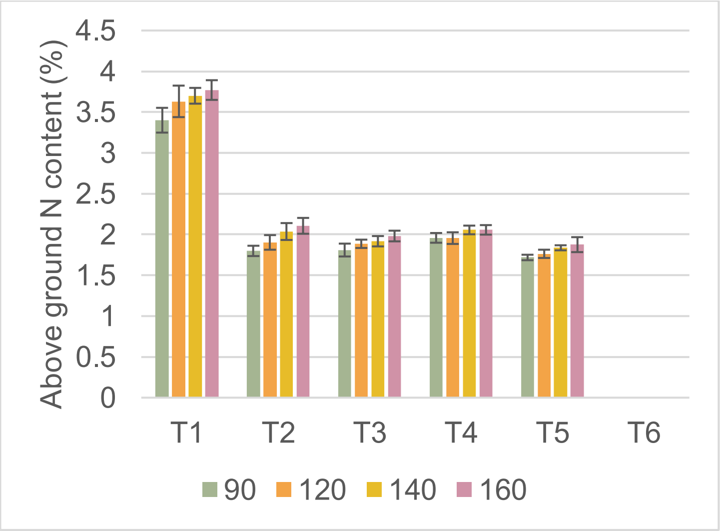


Figure 24: Nitrogen percentage in leaves.

The following graph shows the percentage of nitrogen content in bulbs (Figure 25). According to the statistically analyzed graphs, some changes were observed in the period of T6, T5 and also T4, while no differences in nitrogen content were found in early sampling stages. The dynamics of nitrogen content in bulbs showed a decrease from about 2.74% in T1 to about 1% in T3 and finally a slight increase until about 1.65% in T6, which suggests that the final accumulation of nutrients may be related to the transfer of leaves at the end of the growth cycle when they dry.

Compared to the data from the same experiment in 2021, the main observation was that the difference between the highest fertilization treatments, N220 and N150, was not significant. For example, at T5, bulbs from the N220 treatment had a N content of 1.46 while bulbs from the N150 treatment had a N content of 1.36, whereas the results obtained from the same experiment in the previous year (2021) showed a significant difference between the highest fertilizer treatment and the lowest fertilizer treatment. Despite the fact that the two experiments were in close but not identical locations, the observation that there was a non-significant difference between the highest fertilizer application rate treatment and the lower fertilizer application rate treatment in the 2022 experiment, while there was a significant difference in the 2021 experiment may suggest that factors such as stabilization of fertilizer effects, soil differences, or the plant growth cycle have an impact on the results of the experiments. Further research is needed to delve into the causes and effects of these variations.

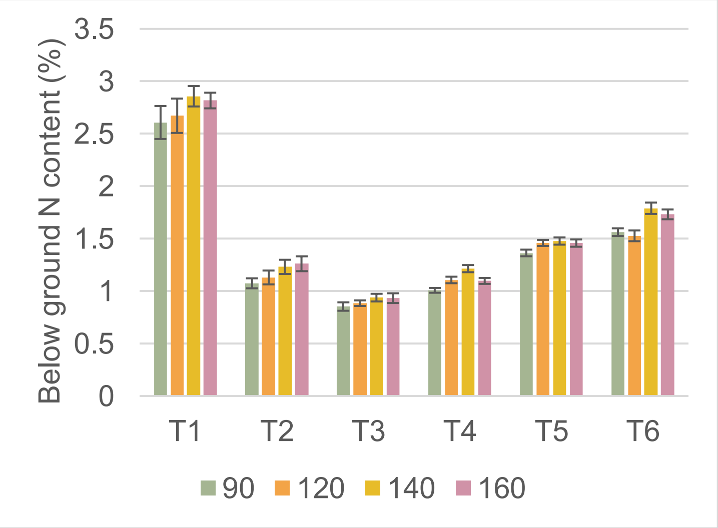


Figure 25: Nitrogen percentage in bulbs.

The following graph shows the average bulb yield (tons/ha) expressed as fresh biomass at harvest. Notably, no significant differences were observed between the different fertilization treatments, due to the large differences between the replicates, suggesting the importance of including spatial variability when fertilizations are to be applied. Surprisingly the average bulb yield at final harvest was higher in the least N dose application group N150 than in the maximum N dose application group N220(as noted above, no statistical differences were opbserved). e.g. the maximum yield was 105.38 t/ha in N180, followed by 102.24 t/ha in N150, 95.14 t/ha in N220, and finally 89.5 t/ha in N200. From this we can see that variable rate fertilization precision agriculture technology can effectively apply the least amount of nitrogen to produce the most amount of product is feasible.

Yield data per unit area are presented below, and as can be seen in the figure below, there is some spatial variation in biomass yields (Figure 26), which does not appear to be related to fertilizer application. In particular, the highest yields were recorded in the central part of the plot, the western zone, where yields exceeded 82 t/ha, both in the plots with high fertilizer application and in the plots with low fertilizer application. In contrast, the northeastern plots seem to have lower yields, whether the plots were fertilized with 220, 180 or 150 doses.

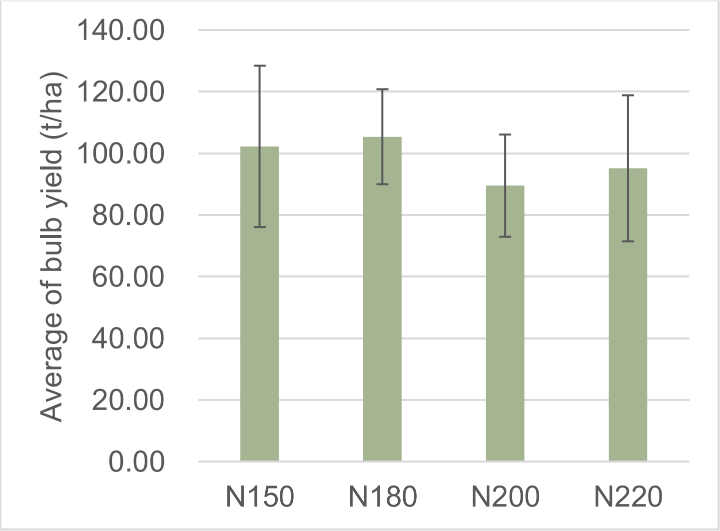


Figure 26: Average of production yield (t/ha).

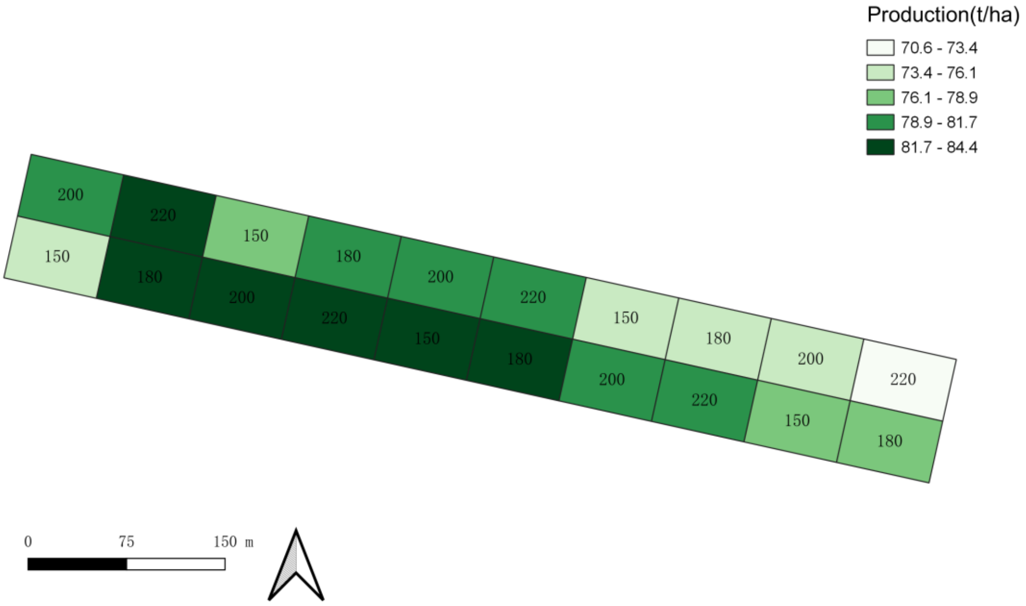


Figure 27: Map of bulb yield (t/ha) in the different tested plots.

5.3.2 N uptake

Figure 28 depicts the nitrogen uptake in kilograms per hectare. Nitrogen absorption values for onions in each plot were computed using nitrogen fertilizer application rates of N150, N180, N200, and N220. The graph's upper and lower bounds represent the maximum and minimum fertilizer application values, respectively. The total nitrogen intake of bulbs was determined to be 148.3 kg/ha for the minimal fertilizer application (N150), which rose to 149.96, 148.88, and 149.1 kg/ha for N200, N180, and N220, respectively. The effect of varied fertilizer application strategies on the ultimate N absorption of bulbs was statistically insignificant.

Some statistical differences in thew bulb N uptake were found, with the highest uptake that was found in N200 and N220, followed by lower values in N150 ans N180 trhat had similar results. Some spatial variability was found as can be seen from the map. For instance, the N uptake differed largely amongst plots that received the same fertilizer treatment. For example, with the N220 treatment, N intake was lowest (125 kg/ha) and maximum (> 165 kg/ha) (Fig. 19). Onions growing in the northeastern section of the experimental field had the lowest N absorption, independent of fertilization method.

The spatial variation in total N removal (Figure 29) is worth considering, with plots of the same treatment showing different levels of N removal. For example, plots 220 and 200 had the highest N removal (>1120 kg N/ha/yr).

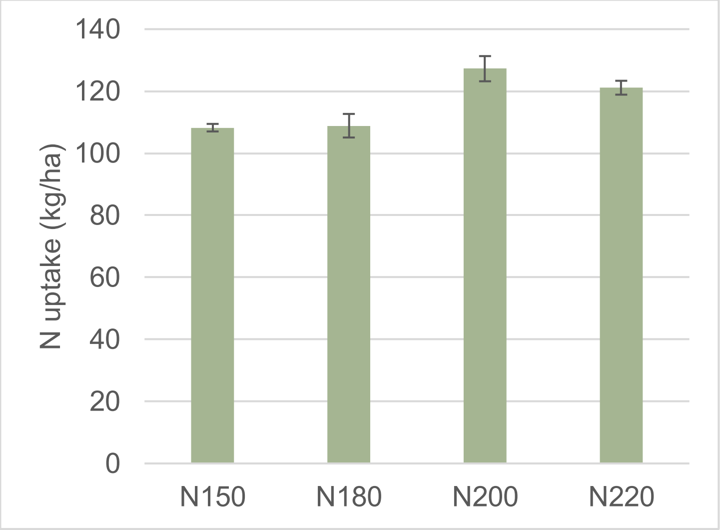


Figure 28: Nitrogen uptake (kg/ha).

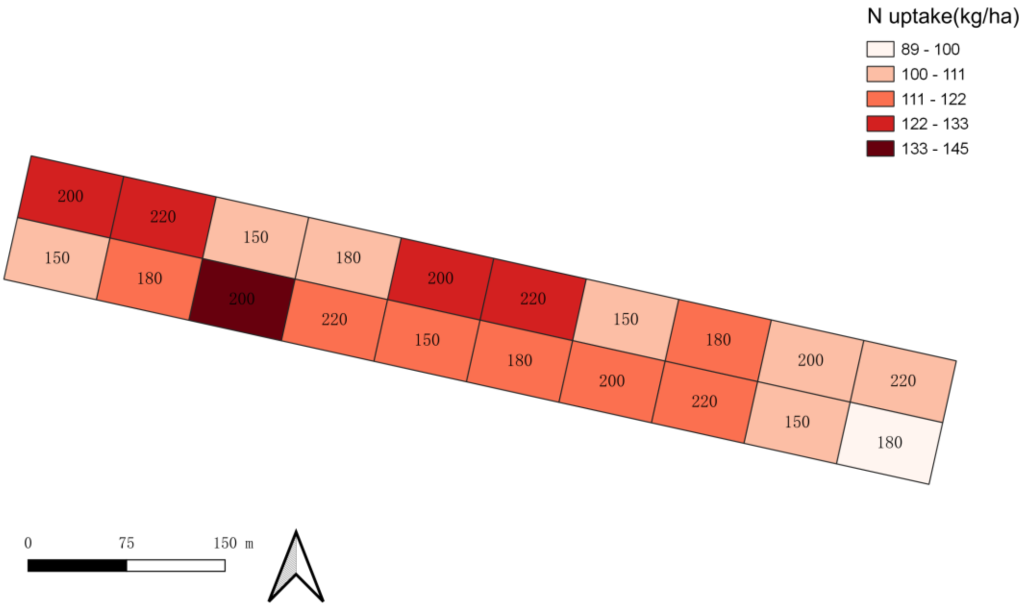


Figure 29: Map of N uptake (kg/ha) in the different tested plots.

5.3.3 Nitrogen Use Efficiency

The graph below depicts nitrogen utilization efficiency (NUE), which is computed as the ratio of nitrogen bulb absorption to total fertilizer N input. There were statistically significant differences between treatments in crop production and N uptake. The N150 treatment had the highest NUE value of 0.72, which was substantially higher than all other treatment, which had NUE values of 0.60, 0.63 and 0.55 in N180, N200, and N220, respectively. The results showed that the lowest N fertilizer rates of 150 kg/ha and 200 kg/ha were the most effective throughout the growing season. The following map (Figure 31) below depicts the differences across plots according to the spatial variability of the experimental field. For example, most plots in the N150 treatment had the highest N fertilizer uptake (0.7-0.75), while plots in the N220 treatment had the lowest N fertilizer uptake (0.5-0.54).

From a spatial perspective, plots with lower nitrogen fertilizer inputs are more efficient, especially the four N150 and one N200 plots, random plot variation in the experimental plots appeared to be independent of fertilizer treatment.

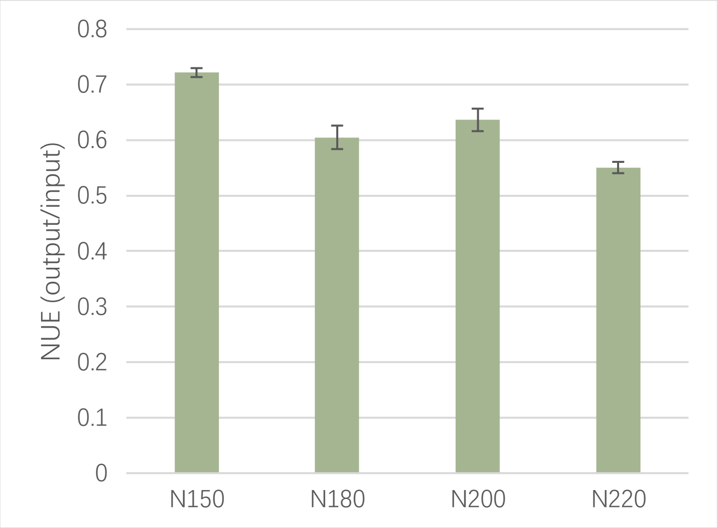


Figure 30: Nitrogen Use Efficiency.

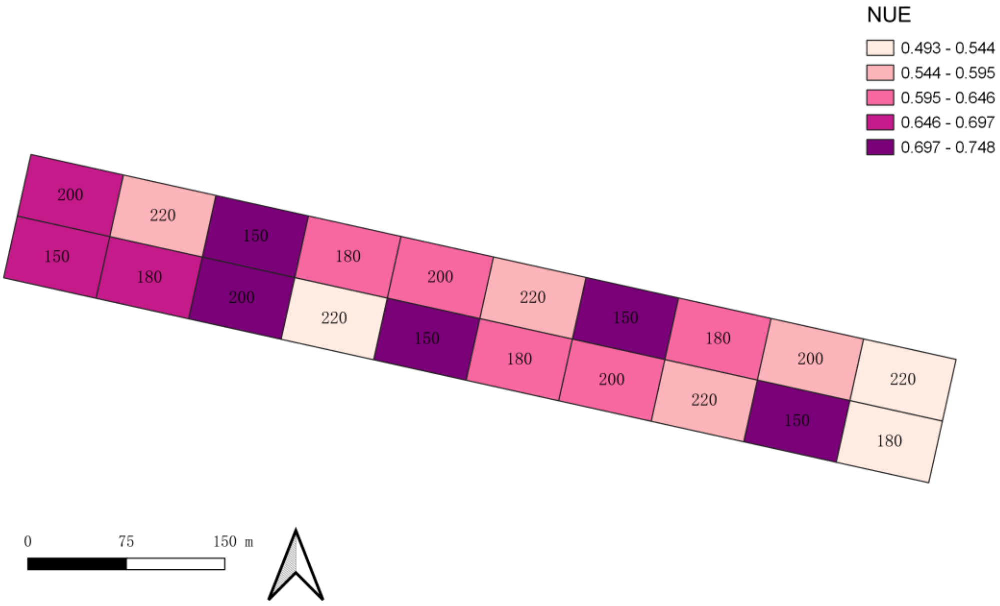


Figure 31: Map of Nitrogen use efficiency (output/input) in the different tested plots.

5.4 NDVI values from remote sensing

The NDVI imageries and values were obtained from UAV flights simultaneously with field surveys to associate ground-truth measurements with remote sensing NDVI estimates. The NDVI reveals a significant divergence during the cropping season, particularly with the sharp decrease from T3 to T4, which might be caused by the severe drought and high temperatures in 2022 that anticipated leaves desiccation. Some slight increase in NDVI is found from N150 to the highest fertilization doses (N200 and N220), however no statistical differences were found between treatments, as can be observed by the graph below and underlines also by the NDVI maps in Figure 32. The biomass map (Figure 33) derived from UAV data reveals the field variability of difference in vegetation vigor in the field, regardless of the fertilization level, suggesting that the level of fertilizer application was not the only factor affecting the crop growth. A higher NDVI index indicates that the plant has more green leaves and a higher leaf area index (Furlanetto et al., 2023). It might be due to variables like good plant growth, better vegetation density, and enough soil moisture.

Comparing Figures 9 to 11, it can be seen that the NDVI value of the plots with high sand content in some parts of the southwest is significantly lower, but it did not affect the final yield.

To note, also, that after the sharp drop from T3 to T4, some increase in NDVI was found until T5, which might be due to some emission of new green leaves as well as some leaves wetting in T4 that reduced the NDVI.

Compared to previous years' data, NDVI values in the 2021 data increased gradually over time, with a slight decrease during the harvest period. There was significant heterogeneity between plots under the same fertilization treatment, such as the difference in N uptake between the N180 and N160 treatments. In contrast, in the data of this experiment, the NDVI values decreased sharply from T3 to T4, and there were differences in the vigor of the vegetation in the field regardless of the fertilization level. This may have been influenced by drought and high temperatures.

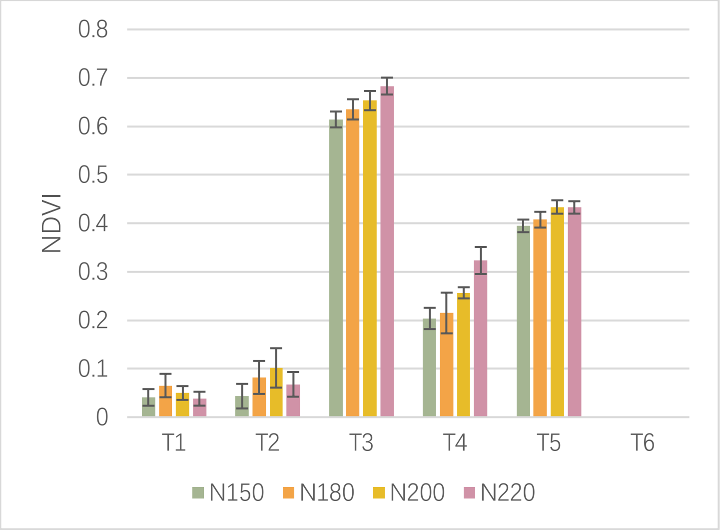


Figure 32: NDVI values during the cropping season.

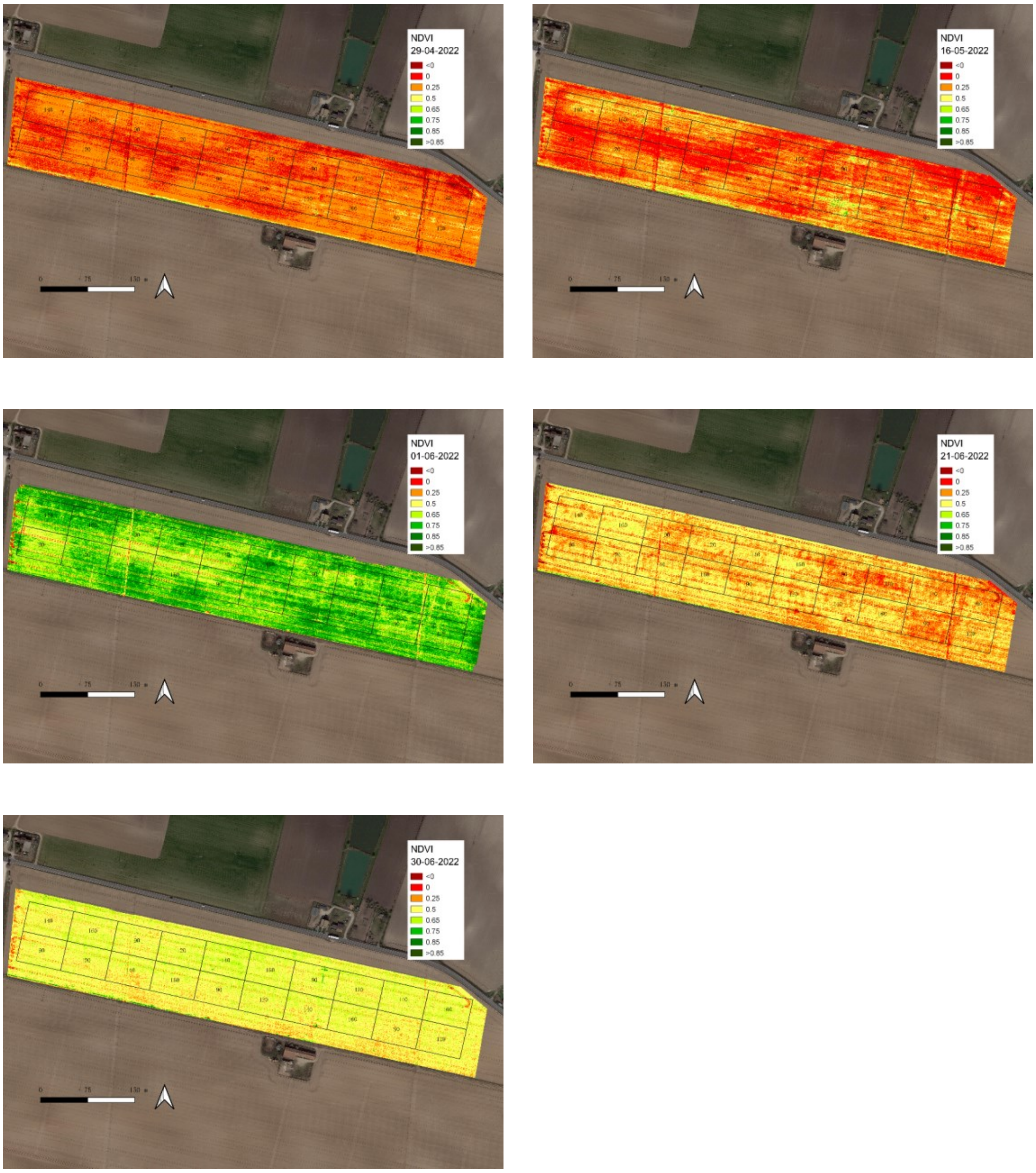
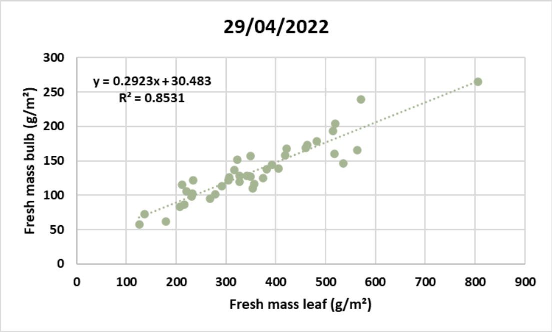
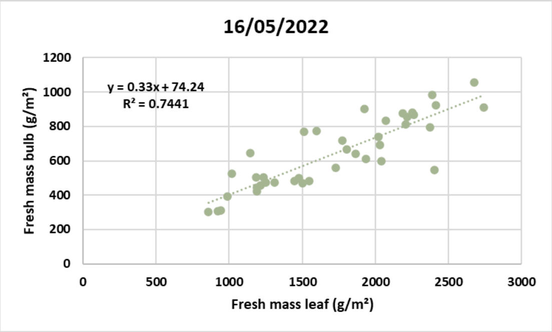


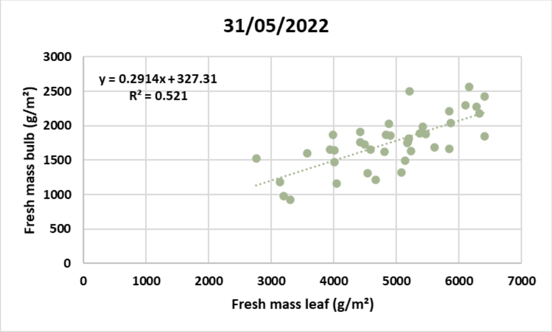
Figure 33: Maps of NDVI values during the cropping season: 29/04/2022, 16/05/2022, 01/06/2022, 21/06/2022, 30/06/2022.

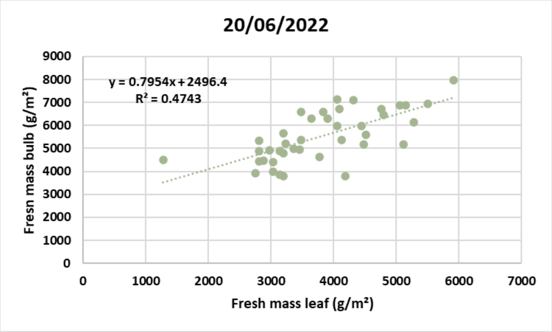
5.5 Relationship between NDVI and Crop Parameters

We examined the relationship between NDVI data and ground-truth crop parameters such as crop fresh biomass (from leaves and bulbs) to better understand whether a relationship between vegetation parameters exists, as well as whether the remote sensing values can be useful to predict crop growth and provide estimations of variable rate fertilizers application based on vegetation status following site-specific data. Figure 34 depicts the relationship between crop fresh biomass in onion leaves and bulbs, suggesting that above-ground biomass can serve as a proxy for below-ground biomass. In fact, the fertilization can be applied based on NDVI values that reveal the leaves status, but finally the crop production is referred to belo-ground bulbs. A significant linear relationship is found, suggesting that the higher ist he leaves biomass, the higher will be also the bulb biomass. This relationship was found for several sampling dates, suggesting a linear increase in bulb biomass all along the cropping season that was associated with the biomass increase in leaves.









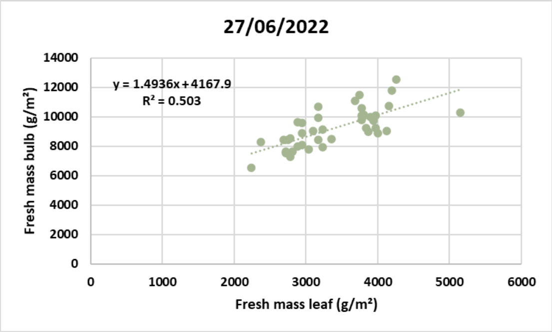
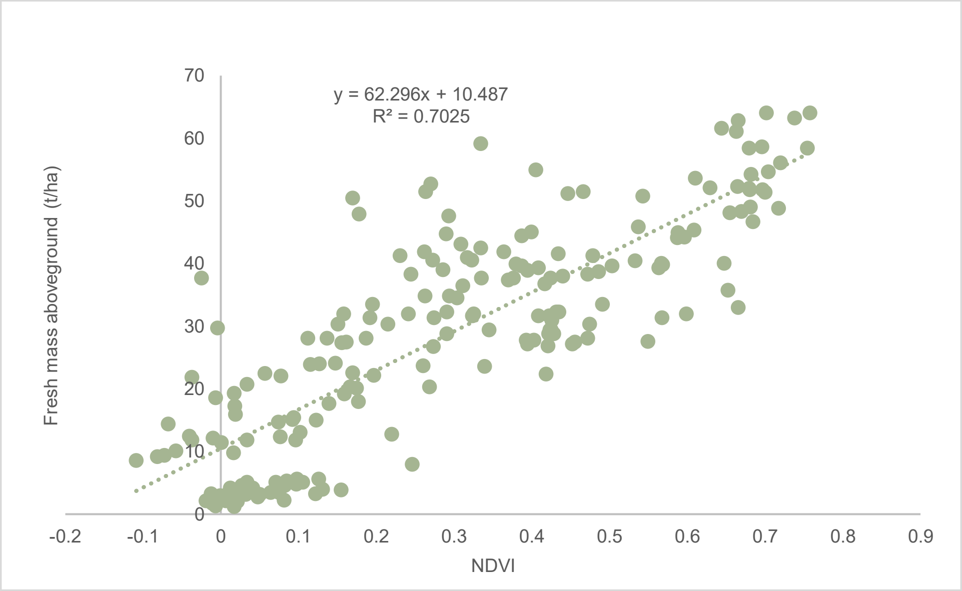


Figure 34: Linear graph representing the relation between bulb fresh biomass and leaves fresh biomass.

The graph in Figure 35 here below illustrates the relationship between NDVI and vegetation parameters, specifically the crop biomass and the leaf nitrogen content. Regarding the biomass, it was found a positive linear relationship between NDVI and that estimated in leaves, explaining 70% of total variability. Regarding the relationship between NDVI and N content (%), a negative powered relationship was found, indicating a dilution in the N content in leaves as the NDVI increases, i.e., as the vegetation is growing and the biomass is increasing. The model used N% in the logarithmic scale, and well described the N content dynamic as already observed in many other crops, and also in onion (Geissler et al., 2022).



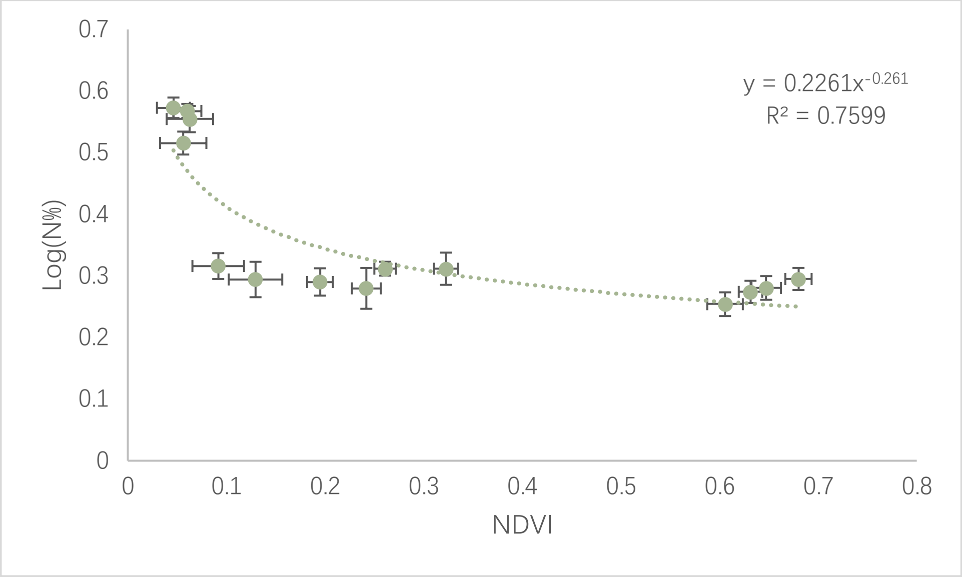


Figure 35: Scatter plot of plant biomass and NDVI.

6. CONCLUSIONS

In conclusion, this study demonstrated the effectiveness of precision agriculture techniques in improving nutrient management and increasing onion yields. The main findings highlight the benefits of real-time crop monitoring and targeted fertilizer application using drones and NDVI analysis. By adopting precision agriculture techniques, farmers can thus optimize nutrient use, reduce environmental impacts, and improve overall crop yields also in crops where precision farming technology has been so far rarely applied.

The results of the study showed that there was no significant difference in harvest yields at the fertilizer meter doses of N150, N180, N200, and N220 in the control group in the onion field, so we can recommend that farmers obtain higher yields by applying the smallest doses to save costs and reduce environmental impact. Enabling farmers to tailor fertilizer application rates to the specific nutrient needs of each plant, ensuring optimal nutrient uptake and minimizing nutrient waste.

Variable rate fertilization provides a more efficient and environmentally friendly approach to nutrient management. By reducing the excessive use of fertilizers, farmers can reduce nutrient runoff and its negative impact on water bodies. It also helps minimize greenhouse gas emissions associated with nutrient leaching.

Future research directions in the field of precision agriculture for onion production should focus on several areas. First, there is a need to further explore the optimal amount of fertilizer to be applied in order to achieve the highest yield without compromising environmental sustainability. Studying the upper limit of fertilizer usage and its impact on onion yield and quality will provide valuable insights for developing precise fertilization guidelines. In addition, the integration of advanced technologies such as artificial intelligence and machine learning can improve the precision and automation of nutrient management practices. The development of predictive models that incorporate environmental factors, crop growth patterns, and soil properties can help optimize fertilizer rates and timing of applications, resulting in higher onion yields. In addition, expanding the scope of precision agriculture to other aspects of crop management, such as pest and disease detection, irrigation optimization, and weed control, will provide a more comprehensive approach to sustainable onion production. Integration of multiple data sources, including satellite imagery, weather data, and field sensors, could further enhance decision making and support precision agriculture practices.

This study demonstrated the significant benefits of variable rate fertilization in improving nutrient management and increasing onion yield. The results of the study highlight the potential of using drones, combined with multispectral cameras, to estimate NDVI and to find suitable relationships with vegetation parameters, and targeted fertilization in revolutionizing onion cultivation in open field conditions. By adopting precision agriculture practices, farmers can achieve sustainable and efficient nutrient management that increases crop yields, reduces environmental impacts, and improves food security.

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