

Using Sentinel 2 Data to Guide Nitrogen Fertilization in Central Italy: Comparison Between Flat, Low VRT and High VRT Rates Application in Wheat

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Abstract. The goal of this research was to compare traditional and variable rate technology (VRT) nitrogen (N) fertilization in winter wheat (*Triticum aestivum L.*). The study was developed over two years in two different fields (one field per year). Three different N fertilization approaches applied to the second fertilization were compared by integrating NDVI (Normalized Difference Vegetation Index) data from Sentinel 2 satellites (S2), grain yield, and protein content. In both fields used for the experimentation, the three treatments were defined as follows: 1) a standard rate (Flat-N) derived by an N balance approach; 2) a variable rate based on S2 NDVI, where the maximum rate was equal to the standard rate (Var-N-low); 3) a variable rate based on S2 NDVI, where the average rate was equal to the standard rate (Var-N-high). An inverse linear relationship between NDVI and N-rates was applied to calculate VRT doses on the assumption that NDVI and other correlated VIs, before the second N fertilization, are directly related to crop N nutritional status. Results show that differences between treatments in terms of NDVI, grain yield, and protein content were very low and generally not significant, suggesting that a low-N management approach, even using simple linear models based on NDVI and VRT, may considerably improve the economic and environmental sustainability of N fertilization in winter wheat. Further experiments are necessary to better explore the proposed approaches and compare them, by example, with the NDVI proportional methods that could be more suitable when the crop growth is mainly influenced by limiting factors other than N nutrition status.

Keywords: NDVI · Remote sensing · GIS · Precision farming · Variable rate technology · Yield mapping · Protein content

1 Introduction

Precision agriculture (PA) is mainly aimed at improving economic and environmental sustainability of cropping systems by reducing inputs and increasing temporal and spatial use efficiencies of the main cultivation operation like tillage, irrigation, fertilizers, pesticides and herbicides (see e.g. references [1–3]).

© Springer Nature Switzerland AG 2020
O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12253, pp. 78–89, 2020.
https://doi.org/10.1007/978-3-030-58814-4_6

PA integrates various modern and advanced technologies to achieve a well-timed in-season and between-seasons crop management [4]. These technologies include Geographic Information System (GIS), Global Navigation Satellite System (GNSS), agronomic modeling, variable rate technology (VRT), yield mapping and Remote Sensing (RS) from various platform such us UAVs (Unmanned Air Vehicles), airborne variable rate technology (VRT), yield mapping and advanced data processing.

Remote sensing of vegetation mainly relies on the detection on the green (495–570 nm) and red (620–750 nm) portions of the visible spectrum, the red-edge (680–730 nm), near and mid-infrared bands (850–1700 nm) [5, 6]. A plethora of algebraic formulas are available to combine these bands and calculate several Vegetation Indices (VIs) for investigating vegetation status and define coherent crop management according to more or less advanced approaches (see e.g. references [7–9]). In this context, the most used index, because of its ease of calculation and interpretation, is still the NDVI (Normalized Difference Vegetation Index), a normalized difference between reflectance of Red and Near-Infrared (NIR) spectral bands [10]. It varies between 0 and 1 in vegetated areas, increasing with LAI (Leaf Area Index), chlorophyll content, and plant N-nutritional status (see e.g. references [11–14]). The NDVI has been widely applied to assess wheat N-nutritional status and yield, with encouraging results [15–17].

The Sentinel-2 satellites (S2) are equipped with a multispectral sensor (MSI) including 13 spectral bands, with a spatial resolution ranging from 10 m to 60 m, an average temporal resolution of 5 days, and a radiometric resolution of 12 bit enabling the image to be acquired over a range of 0 to 4095 potential light intensity values with an accuracy error less than 5%. Visible and NIR bands have a spatial resolution of 10 m. Such features make the S2 a very relevant source of Spatio-temporal information for supporting precision agriculture [18].

N is the main nutrient of the vast majority of crops, including wheat. Increasing the N rate generally increases crop yield since it increases the grain number and size [1]. However, increasing the N rates reduces the N uptake efficiency (NUE) and increases the amount of residual N in the soil which is exposed to leaching risks [11, 19] and may cause severe environmental impacts on near-surface and deep aquifers [20]. In this regard, while traditional flat-rate approaches typically tend to over- or under-apply fertilizers, with map-based VRT precision fertilization it is possible to modify and optimize the distribution and improve the economic and environmental sustainability of the crops. A wide number of researches deals with wheat N nutrition and precision N fertilization, but most of them propose quite complex models that result not easily adoptable by PA non-specialists.

In PA, grain yield mapping is possible thanks to combines equipped with GNSS and yield tracking systems [21]. To produce yield maps, the harvested quantities are georeferenced and linked with the corresponding reference area on the ground calculated by multiplying the working width by the area length (working speed * time interval). Yield mapping accuracy is very variable and is mainly influenced by flow sensor calibration, combined speed changes, grain flow variations, and grain moisture. Despite many limitations and possible spatial and quantitative inaccuracies [22], this technology provides interesting information about the spatial heterogeneity of yields.

Grain protein development is physically based on the deposition of plant N and its translocation to grain during the filling process and the N content at the anthesis stage was found to be indicative for the final grain protein content [23]. Consequently, optimal N-fertilization management results very important for both quantitative and qualitative properties of yield.

While many studies have combined VIs (derived from various remote or proximal sensors) and VRT crop fertilization, only a small quantity of research integrates yield mapping sensors, and, to our knowledge, probably very few studies have combined VIs, VRT fertilization, and yield mapping in a PA case study and, in particular, to assess the effects of different variable N-rate treatments on winter wheat.

In this framework, this study carried out over two years and in two different experimental fields, was aimed at comparing two different VRT N fertilization treatments (based on Sentinel 2 and easily-applicable approaches) versus a traditional standard flat N rate in terms of crop NDVI trend, grain yield, and protein content. The research also investigates the possible relationships existing between quantitative and qualitative features of yield and the NDVI to assess its forecasting potential.

2 Materials and Methods

2.1 Study Areas

The experiments were carried out over two consecutive cropping seasons, in two different fields owned by two farms: in 2017–2018 on a 14 ha plain field in Tiber valley, near Deruta, Umbria, Italy (170 m a.s.l., 42°95'07" N, 12°38'18" E) owned by the FIA – "Fondazione per l'Istruzione Agraria" farm (Fig. 1, Field 1) and in 2018-2019 on a 10 ha plain field in Mugnano, Umbria, Italy (227 m a.s.l., 43°04'57" N, 12°21'74" E) (Fig. 1, Field 2) owned by the "Sodalizio di San Martino" farm. Both fields are characterized by a soil gradient related to proximity to a stream (located at the east of the Field 1 and at the west of Field 2).

The climate is the Mediterranean, characterized by a dry season between May and September and a cold and rainy season from October-November to March-April. The cropping season 2017–2018 was unusually rainy in December and March, while temperatures were generally higher than the poly-annual trend except for a very cold end of February (Fig. 2a). The cropping season 2018–2019 was particularly favorable for crops, with winter rainfall in the seasonal average and temperatures above the average (Fig. 2b).

The experimental crop was rainfed winter wheat (*Triticum aestivum L.)* sown in the first half of November. The previous crop had been pea (*Pisum sativum Asch et Gr*) in Field 1 and sunflower (*Helianthus annuus L.*) in Field 2. The crop was managed according to ordinary practices, while weeds and diseases were controlled chemically.

2.2 Experimental Design

The experiments were based on the comparison in terms of NDVI trend, yield, and protein content, of three different N fertilization, approaches applied to the second fertilization in wheat. In both fields used for the experimentation, the three treatments

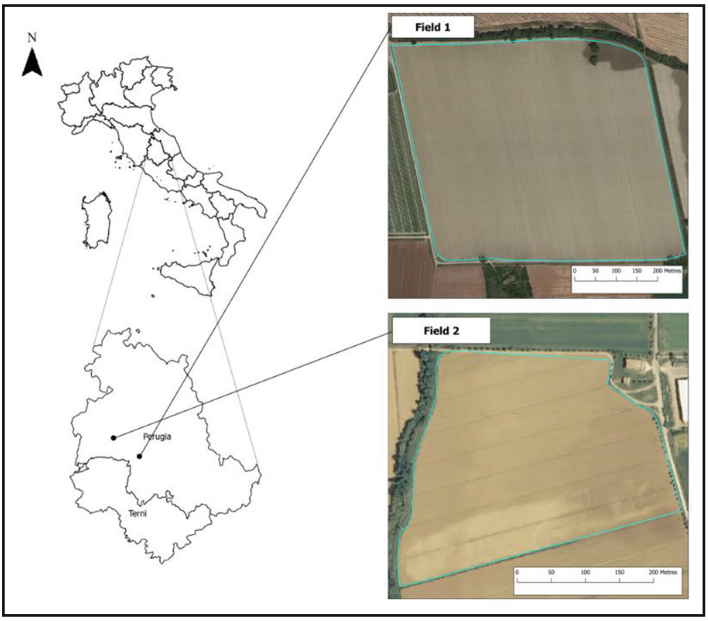

Fig. 1. The geographical location of the study areas.

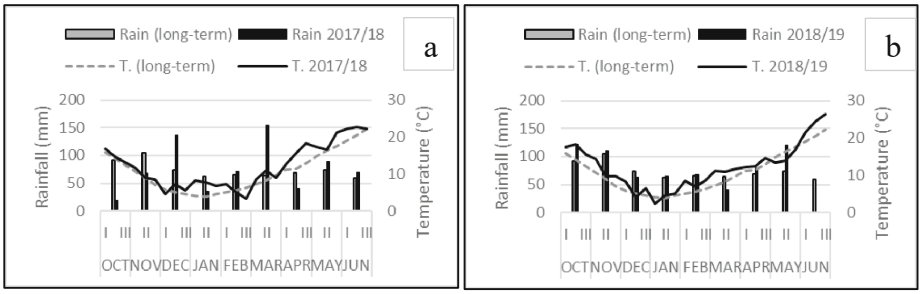

Fig. 2. Monthly cumulated rainfall and average temperatures per decade during the wheat growing season 2017–2018 (a) and 2018–2019 (b), and in the long term (temperature 1951–2018, rainfall 1921–2018).

under investigation were defined as follows: 1) a standard rate (Flat-N) derived by an N balance approach; 2) a variable rate based on S2 NDVI, where the maximum rate was equal to the standard rate (Var-N-low); 3) a variable rate based on S2 NDVI, where the average rate was equal to the standard rate (Var-N-high). An inverse linear relationship between NDVI and VRT N-rates was adopted both in Var-N-low and Var-N-high on the assumption that NDVI and other correlated VIs (e.g. NIR/Red simple ratio), before the second N fertilization (7–8 Feekes' stage), are directly related to crop N nutritional status [12, 16, 24]. For both fields, to calculate the VRT rates, a Level 2A Sentinel-2 image, collected before the second fertilization (respectively March 22nd, 2018 for Field

1 and March 3, 2019 for Field 2) and georeferenced according to WGS84-UTM32, was downloaded from The Copernicus Open Access Hub. NDVI, calculated from bands 4 and 8 using QGIS Raster Calculator, was used for the N rates calculation. A linear relationship was imposed between the average NDVI value calculated for all experimental units and fertilizer-N rates where the 5° percentile of NDVI value corresponded to the maximum fertilizer-N rate and the 95° percentile of NDVI value corresponded to the minimum fertilizer-N rates. All the data processing and analysis were carried out using QGIS software, version 3.10 64 bit [25], and MS Excel 2016. Average NDVI values were calculated using the SAGA "grid statistics for polygons" tool included in the QGIS processing framework. All the three treatments, for both fields, were merged in a single prescription map in shapefile format subsequently used for the N fertilization with the VRT fertilizer spreader. All the precision on-field operations were performed using a tractor equipped with a GNSS automatic guide device connected to a Real-Time Kinematic (RTK) network. The variable rate treatments were performed using a Sulky 40+ (ECONOV) VRT fertilizer spreader linked through ISOBUS (a widely used software protocol compliant to ISO 11783 standard) to the Topcon system console.

To monitor and compare the crop growth related to the experimental treatments, all relevant level 2A Sentinel-2 images with no cloud cover were collected for the two study areas from the second N fertilization to the beginning of the senescence. In total, 7 images were collected for Field 1 and 10 images for Field 2. Average NDVI values and standard deviations were then calculated for each plot using the SAGA "grid statistics for polygons" tool included in the QGIS processing framework.

Protein content was analyzed in both fields according to a grain sampling scheme based on NDVI classes. All samplings were analyzed according to the official Kjeldahl method, a widely used chemical procedure for the quantitative determination of protein content in food, feed, feed ingredients, and beverages [26].

To investigate the possible relationships existing between quantitative and qualitative features of yield and to assess the NDVI forecasting potential a final correlation analysis was performed comparing yield quantities, protein contents, and NDVI multi-temporal data.

The two experimental fields were agronomically managed considering the differences in terms of soil properties, fertilization practices, and the harvest machines available in the two farms.

2.2.1 Field 1

To account for the possible unknown spatial actors, the 14 ha experimental area of the field was divided into 168 plots of about 700 square meters each (35 m long, 21 m wide) grouped in 28 zones. Thus, the three treatments were laid down according to a randomized design with 2 replicates per treatment in each zone for a total of 56 replicates per treatment in the whole study area (Fig. 3).

N fertilization (as urea) was split into two applications. The first application occurred on 18 January 2018 with 30 kg N ha^{-1}, while the second one, occurred on 26 March 2018 and, according to the general methodology, was managed according to the three experimental theses: 1) a standard rate of 120 kg N ha^{-1} (Flat-N) derived by an N balance (the relatively high rate is justified by the very rainy winter); 2) a variable rate of 60 to

120 kg N ha^{-1}, calculated using the linear model applied to S2 NDVI of 22 March 2018 (i.e., four days before the second fertilization), where the maximum rate was equal to the standard rate (Var-N-low); 3) a variable rate of 90 to 150 kg N ha^{-1}, based on S2 NDVI, where the medium rate was equal to the standard rate (Var-N-high).

Harvest was carried out on 26 June 2018 for the Field 1 using a combined harvester Claas Lexion 630 equipped with a Topcon YieldTrakk system (processing data from the optical sensor measuring grain mass flow and moisture sensors), which produced a georeferenced yield map as an ESRI polygon shapefile. The combine harvester had a cutting width of 7.50 m and was equipped with a tilt sensor to correct the effect of slope on the sensor readings. Initial on-field calibration was performed on the combine to adjust for the actual working width and measure the unit weight of grain, which was used by the system to convert the measured mass flow (l/s) to Mg. The shapefile generated by the yield tack system was overlapped in QGIS on the experimental units to calculate the average yield values. This averaging procedure and the subsequent averaging to calculate a mean yield value for each treatment type, attenuated the possible inaccuracies generated by the yield track system.

Protein content was measured on 20 June 2018 (i.e., six days before the final harvest). To reduce the number of samples, the sampling scheme was defined according to three classes of NDVI for a total of 36 field samples, then merged two by two to obtain 18 lab samples.

2.2.2 Field 2

In this field, due to the lack of a harvester equipped with a yield track system, larger experimental units were defined. To account for the possible, not measured spatial factors, the three treatments were laid down in 14 experimental units according to a randomized design with 4 replicates per treatment (Fig. 3). N fertilization (as urea) was split into three applications. The first application occurred on 16 January 2019 with 40 kg N ha^{-1}, while the second N fertilization, occurred on 18 March 2019 and, according to the general methodology, was managed according to the three experimental treatments: 1) a standard rate of 100 kg N ha^{-1} (Flat-N) derived by an N balance; 2) a variable rate of 50 to 100 kg N ha^{-1}, calculated using the linear model applied to S2 NDVI of 2 March 2019 (i.e., three days before the second fertilization), where the maximum rate was equal to the standard rate (Var-N-low); 3) a variable rate of 85 to 115 kg N ha^{-1}, based on S2 NDVI and calculated using the AGROSAT model, where the medium rate was equal to the standard rate (Var-N-high). The VRT N rates were calculated on a sub-scheme basis including 120 plots of about 460 square meters each (22 m long, 21 m wide) within the 14 experimental units. The last N application was made on 6 May 2019 with 30 kg N ha^{-1}.

To measure yield, harvest, carried out on 8 July 2019, was performed separately collecting and weighing the yield by each experimental unit. This procedure, even though very time-consuming, allowed us to obtain very accurate yield data for each experimental unit and treatment.

To measure protein content, 28 samplings (each consisting of 4 sub-samples), two for each experimental unit, were collected on 26 June 2019 (i.e., twelve days before final harvest).

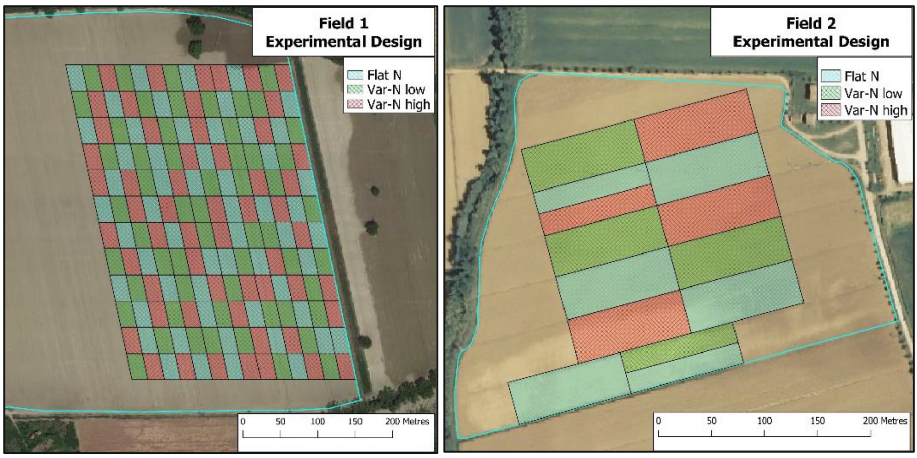

Fig. 3. Experimental layout. Flat-N (derived by an N balance), Var-N-low (variable-rate with the maximum rate equal to the standard rate), Var-N-high (variable-rate with the medium rate equal to the standard rate)

3 Results and Discussion

3.1 VRT Treatments and NDVI Trends

The NDVI and the prescription maps used for the VRT treatments of the second N fertilization in the two fields are shown in Fig. 4. In both cases can be observed an NDVI spatial trend (with a more relevant range in the Field 1) apparently related to the textural gradients of the two fields (Fig. 5). In all the field portions, both where the NDVI was high before N fertilization and where it was low, the index showed a further moderate increase up to nearly or over 0.9, highlighting a very good crop vigor. After the second fertilization, the trend of NDVI was slightly affected by fertilization treatments only in the second field while no differences can be observed in Field 1. This could indicate that the nitrogen rate was probably above the crop requirements in all the treatments, highlighting a potential N excess in the higher dosage theses, and probably that the field heterogeneity was not due to a real nitrogen nutritional deficiency but to intrinsic factors of the fields. This could explain the same NDVI trend of the three treatments in both fields, apart from slight differences which decrease with the crop growth in the Field 2).

3.2 Grain Yield and Quality

The yield map for Field 1, exported from the yield-track system, and the yield map for Field 2, showing the yield quantities measured in each experimental unit, are reported in Fig. 6. The relevant yield difference between the two fields can be related, besides the different soil features, to the meteorological trend of the two years (Table 1). This was characterized, in the first year, by intense rainy events during March (which generated considerable stress during the most important crop growth stage) and, in the second year, by very favorable and mild temperatures together with a good quantity and well-distributed rains which determined a very high yield in all over Central Italy. Concerning

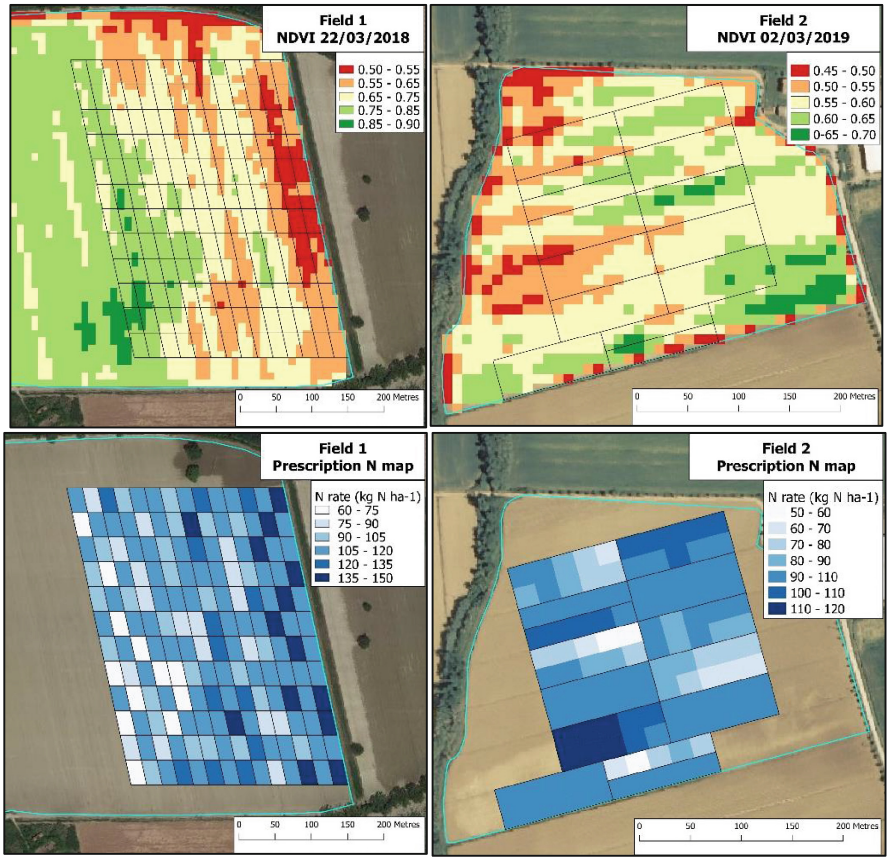

Fig. 4. NDVIs calculated from Level 2A Sentinel-2 image and N prescription maps developed by integrating the three different experimental treatments.

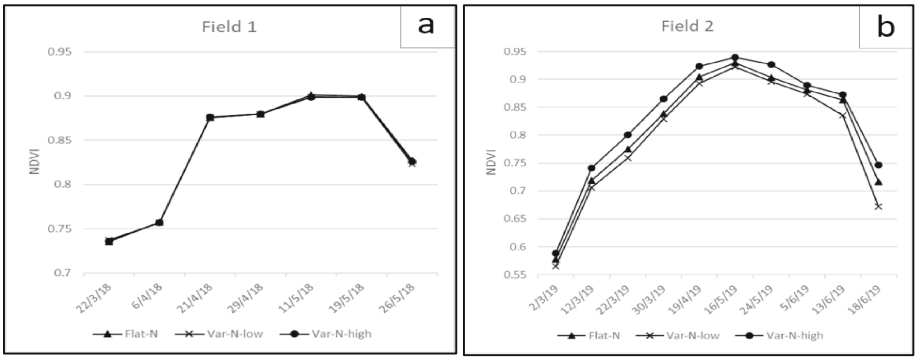

Fig. 5. NDVI time series analysis for the three N fertilization treatments in the two experimental fields

the three treatments under investigation, In Field 1, they did not differ significantly for total yield (Table 1), and no relationship was found between the N rate and yield ($R^2 = 0.087$). Similarly, no correlation was found between N treatments and protein content ($R^2 = 0.001$). Even though the slight difference in protein content of Flat-N and Var-N-low treatments was statistically significant ($p = 0.02$), it did not appear relevant from the agronomic viewpoint. Similarly, in Field 2, no evident relationship was found between the N rate and yield ($R^2 = 0.174$), and no correlation was found between N treatments and protein content ($R^2 = 0.150$). Finally, in both fields, grain yield was very weakly correlated to NDVI only in Field 1 at any time of NDVI measurements (Table 2).

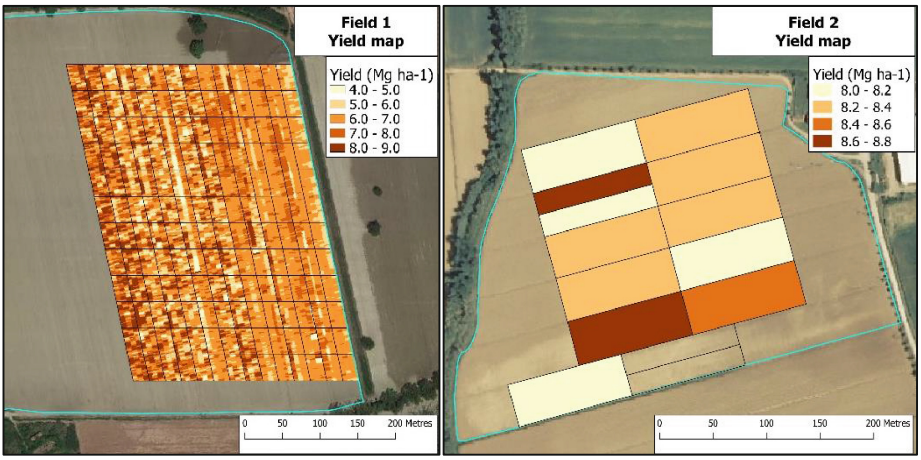

Fig. 6. Yield maps of the two experimental fields.

Table 1. Grain yield, protein content, and Nitrogen Use Efficiency (yield) for the three N fertilization treatments in the two fields: Flat-N, Var-N-low, and Var-N-high. NRA: Average N rate, YA: Average Yield, YSD: St. Dev. Yield, PCA: Average Protein Content; PCSD St. Dev. Protein Content, NUE: Nitrogen Use Efficiency.

Field	Treatment	NRA (Kg ha^{-1})	YA (Mg ha^{-1})	YSD (Mg ha^{-1})	PCA (%)	PCSD (%)	NUE (Kg Yield/Kg N rate)
1	Flat-N	120	6.74	0.36	9.4	0.31	56.2
	Var-N-low	90	6.73	0.39	8.9	0.37	74.8
	Var-N-high	121	6.76	0.38	9.2	0.48	55.9
2	Flat-N	100	8.41	0.29	13.88	0.50	84.1
	Var-N-low	76	8.18	0.16	13.53	0.98	107.6
	Var-N-high	101	8.33	0.21	14.18	0.43	82.5

Table 2. Correlation between yield and NDVI (at any time of measurement) plotted over all the 168 plots of Field 1 and over all the 12 plots of Field 2.

Field 1		Field 2	
Date	R^2	Date	R^2
22 Mar	0.29	05 Mar	0.12
6 Apr	0.26	22 Mar	0.04
21 Apr	0.24	19 Apr	0.05
29 Apr	0.19	16 May	0.10
11 May	0.19	05 Jun	0.00
26 May	0.27	13 Jun	0.06
31 May	0.26	18 Jun	0.02

In the two case studies, the N rate increase did not translate in an NUE (Nitrogen Use Efficiency) increase as this was probably limited by the other factors. This would indicate that, in some cases, the N rate could be conveniently and more efficiently directly related to the NDVI [27], on the assumption that lower NDVI values could indicate that other soil features, besides N availability, are limiting factors for obtaining higher yields. The similar NDVI trend observed in all the three treatments and in both fields (Fig. 4), could also support this evidence, or at least, indicate that the 20 kg N ha^{-1} of difference among treatments was not significant for NDVI analysis. In this view, VRT nitrogen fertilization can only partially mitigate the heterogeneity of production determined by environmental factors such as soil nitrogen and water availability. Thus, the alternative approach of providing a nitrogen supply proportional to the crop NDVI deserves to be considered when factors other than N nutrition status, as it is with sandy soils where NDVI and yield may be limited by low N availability and water retention [28].

4 Conclusions

Our study compared two VRT N fertilization treatments (based on Sentinel 2 NDVI) with a standard flat N rate in terms of crop NDVI trend, grain yield, and protein content. Results suggest that a VRT approach with a lower overall N rate may be more efficient, producing the same grain yield and comparable protein content with a lower N input. Var-N-low treatment in some cases could determine a lower protein grain content. In this regard, the economic trade-off between lower N fertilization costs and decreased yield value due to lower grain protein content should be determined by the farmers. This evidence is consistent with the result of Raun et al. [29] which reports that the VRT technique improves the NUE by 15% in average compared to the standard flat rates. In specific contexts, the N-rate reduction results environmentally and economically very relevant since it could reduce water pollution (still a critical issue in Umbria and all over the world). However, further experiments are necessary to further explore the proposed approaches and compare them, by example, with the NDVI proportional methods that

may result more suitable when the crop growth is mainly influenced by other limiting factors different than N nutrition status.

Acknowledgements. This research was developed within the project "*RTK 2.0 - Prototipizzazione di una rete RTK e di applicazioni tecnologiche innovative per l'automazione dei processi colturali e la gestione delle informazioni per l'agricoltura di precisione*" – RDP 2014–2020 Umbria – Meas. 16.1. The authors wish to thank the farms "Fondazione per l'Istruzione Agraria" (Casalina di Deruta, province of Perugia, Italy) and "Sodalizio San Martino" (Mugnano, Province of Perugia, Italy) for their valuable support during all the experimental stages.

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