Producing Mid-Season Nitrogen Application Maps for Arable Crops, by Combining Sentinel-2 Satellite Images and Agrometeorological Data in a Decision Support System for Farmers. The Case of NITREOS

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Abstract. NITREOS (Nitrogen Fertilization, Irrigation and Crop Growth Monitoring using Earth Observation Systems) is a farm management information system (FMIS) for organic and conventional agriculture which aims in enabling farmers to tackle crop abiotic stresses and control important growing parameters to ensure crop health and optimal yields. NITREOS employs a user friendly, web-based platform that integrates satellite remote sensing data, numerical weather predictions and agronomic models, and offers a suite of farm management advisory services to address the needs of smallholder farmers, agricultural cooperatives and agricultural consultants. This paper provides an analysis of different methodologies employed in the nitrogen fertilization service of NITREOS. The methods are based on the determination of the Nitrogen Fertilization Optimization Algorithm for cotton, maize and wheat crops. Available agro-meteorological data on two distinct agricultural regions were used for the calibration and validation of the recommended Nitrogen rates.

Keywords: Nitrogen Fertilization, NITREOS, Earth Observation Data, FMIS

1 Introduction

Geographic information systems technology has been widely used in fertilization research, through the use of decision support systems. Nitrogen (N) management based on remote sensing technologies is one of the most representative examples as N is found to be one of the most critical nutrients for crop growth. Crop N requirement determination and improvement of Nitrogen Use Efficiency (NUE) has been proved efficient through the use of remote sensing tools [1, 2]. Improving NUE reduces fertilizer costs, improves yield and quality and mitigates environmental pollution caused by loss of N due to deep percolation [3]. Operational applications employ Earth Observation (EO) techniques, Vegetation Indices (VIs) and algorithms, enabling farmers to monitor their fields and acquire advices on the application of N fertilizers [4-6].

In this paper, a satellite-based fertilization advisory system is presented. NITREOS (https://business.esa.int/projects/nitreos) offers a number of services to farmers and agricultural consultants, namely irrigation scheduling, variable rate fertilization (VRF),

crop growth monitoring, yield estimation, as well as short term weather prediction. The VRF service provides in-season optimum N rates for maize, cotton and wheat crops. Zones of equal fertilizer recommendation dose per registered parcel are delivered daily from agro-meteorological data, and updated regularly with the use of high-spatial resolution multispectral satellite images. The VRF service offers:

- a personalized in-season fertilization advice, based on calculation of the Nitrogen Fertilization Optimization Algorithm (NFOA), by taking into account the in-field heterogeneity of the sensed NDVI (Normalized Difference Vegetation Index) and Growing Degree Days (GDD), for variable rate applications;
- the Optimum Time Window (OTW), pointing out the appropriate period for in-season N fertilization, allowing the user to decide upon the level of input, the amount and type of fertilizer (conventional and organic) and the time of in-season application;
- timely delivery of the daily calculated N rates, within the OTW, which consists of maps and suggested fertilizer dose per pixel. The information is published on a dedicated webGIS-platform in order to better plan for fertilizer applications and consequently improve NUE.

This paper focuses on the detailed description of methodological approaches and processing chain employed in NITREOS VRF service. It provides an analysis of the algorithms implemented in the operational workflow of NITREOS. The first calibration – validation results under Greek and Serbian farming conditions, are also presented.

2   Materials and methods

In the VRF service of NITREOS, the crop heterogeneity captured by the high resolution Sentinel-2 images is considered a valuable add-on information to identify the variability of soil texture and fertility, plant nutrition, or different performance of cropping systems. The concept of the service is based on two main components:

1. the processing of multi-temporal, high-spatial resolution images (Sentinel-2), provided by the EU's Copernicus Program, to timely monitor the crop growth;
2. the estimation of plant N demands, by taking into account weather data (GDD) and the canopy development (through the sensed NDVI) during the appropriate period for mid-season fertilization.

The NFOA was initially proposed for the in-season N fertilization recommendation of winter wheat [8-11], and is based on the Predicted Yield potential with zero-N fertilization (YP_0) and the field-specific NDVI-based Response Index (RI_{NDVI}). The basic steps in the determination of the NFOA include:

1. calculation of YP_0 using the relationship between actual grain yield and INSEY,
2. calculation of the Response Index (RI) at harvest ($RI_{Harvest}$) using RI_{NDVI}, computed as the mean NDVI readings of adequate N rate treatment divided by the mean NDVI readings of the pre-plant N rate. To accomplish this step, NDVI measurements should be collected from particular growth stages,
3. the determination of the Yield Potential (YP) using pre-plant N rates YP_N and equation:

$$YP_N = YP_0 \cdot RI_{NDVI} \qquad (1)$$

4. the calculation of the percent N in the grain (PN_G) with a linear relationship between PN_G and YP_N,
5. the calculation of grain N uptake (GN_{UP}) by multiplying YP_N with PN_G,
6. the calculation of canopy N uptake (FN_{UP}) based on an exponential relationship equation between FN_{UP} and NDVI,
7. determination of the in-season N requirement (FNR) using the generalized equation:

$$FNR = \left(GN_{UP} - FN_{UP} \right) / NUE \qquad (2)$$

In the methodology above, INSEY represents the In-Season Estimate of Yield, which is the NDVI divided by GDD and reflects the biomass produced per day for a particular crop [7, 8, 11]. NDVI is calculated with the use of Sentinel-2, Level-2A, Bottom-Of Atmosphere, surface reflectance products. The index is calculated for every parcel registered in NITREOS, through a fully automated procedure, with a spatial resolution of 10 m. NFOA is calculated per pixel and then averaged in four zones of equal treatment. The application offers the choice of downloading geospatial data for variable rate applications. The GDDs or heat summation are computed using the optimum-day method [13], with the equation:

$$GDD = \left[\left(T_{max} + T_{min} \right) / 2 \right] - T_{base} \qquad (3)$$

where T_{max} and T_{min} are the max. and min. daily temperatures (^{o}C). T_{base} refers to a temperature, below which crop growth ceases, equal to 10, 15.5 and 4.4^{o}C for cotton, maize and wheat, respectively. The RI was introduced to quantitatively characterize the crops' in-season likelihood to respond to additional N [13]. The actual harvested crop grain response to applied N is defined as:

$$RI_{Harvest} = yield\ of\ the\ N\ treatment\ /\ yield\ of\ the\ usual\ N\ practise\ treatment \qquad (4)$$

The $RI_{Harvest}$ was well correlated with RI_{NDVI} and was defined as the grain yield from N-adequate plots divided by the yield from the plots receiving the pre-plant N rate [14]. The proposed methodology has been widely applied and confirmed in different agro-climatic conditions and crop types [15-24].

2.1 NFOA for cotton

Previous studies have demonstrated and evaluated the use of NFOA on optimum in-season fertilization on cotton crop [25, 26]. The NFOA for cotton is as follows:

$$NFOA(\ kgha^{-1}\ ) = \left[\left(YP_0 \times RI \right) - YP_0 \right] \cdot percentage\ N\ /\ NUE \qquad (5)$$

where percentage N is the N removed by the crop during the growing season.

For the application of NFOA algorithm, the following steps are followed. Firstly, INSEY, is calculated by dividing the NDVI with the cumulative GDD from planting to sensing (for GDD > 0) [26, 27]. The INSEY value is related to biomass produced per day. Correlation between biomass produced per day and final grain yield has been shown to be highly correlated [7]. Furthermore, NDVI is a good biomass indicator and also implies total N content [28]. In a study for cotton [25], the CumGDD - INSEY was correlated with yield data. Specifically, the CumGDD - INSEY was produced from NDVI readings of cotton, collected between 38 and 90 days after sowing, to produce

empirical equations that predict the cotton yield potential. Lint yield data referred to cotton crops receiving a sum of 0, 50, 100, 150 and 200 kgha^{-1} N rates, in pre-planting and in-season N applications. Crops were sown from the 15th to the 18th of May. The nonlinear regression model produced, is as follows [25]:

$$YP_0 \left(kgha^{-1} \right) = 309.72e^{1295.9 \times INSEY} \qquad (6)$$

Apart from the yield potential, the degree to which a crop will respond to additional N is an equally important component in determining in-season N recommendations [11]. The RI is calculated by dividing the yield of a N-rich strip by the yield of the zero-N plot or farmer's practice, where less preplant N is applied. The RI value calculated using the yield is referred to as $RI_{Harvest}$. RI can also be measured mid-season using NDVI values (RI_{NDVI}) collected from the same areas used to determine $RI_{Harvest}$. It has been found that RI_{NDVI} collected midseason is a good predictor of $RI_{Harvest}$ [14]. A linear regression model to describe the relationship between RI_{NDVI} and $RI_{Harvest}$, was proposed as follows:

$$RI_{Harvest} = 0.7324 \cdot RI_{NDVI} + 0.238 \qquad (7)$$

Another study [26] calculated the RI_{NDVI}, by dividing the highest NDVI reading of N-rich strips in the field, by the average NDVI. The average NDVI was received by an area in the field, where the typical farmer's N application practice was followed.

NFOA implementation for cotton in NITREOS. NFOA is used in NITREOS to deliver in-season fertilization of cotton. For the calculation of RI_{NDVI} in NITREOS, values were collected from 29 cotton fields registered in the Crop Growth Monitoring Service of AgroApps P.C. (Greece). In the selected crops, cotton was sown from the 10th to the 25th of April 2018 and the sensing day of NDVI was the 18th of June. The highest NDVI value was considered representative of a N-rich treatment of cotton, while the lower NDVI value was calculated as the average of the remaining measurements. Fig. 1 presents the NDVI sensed at the 18th of June per different sowing date.
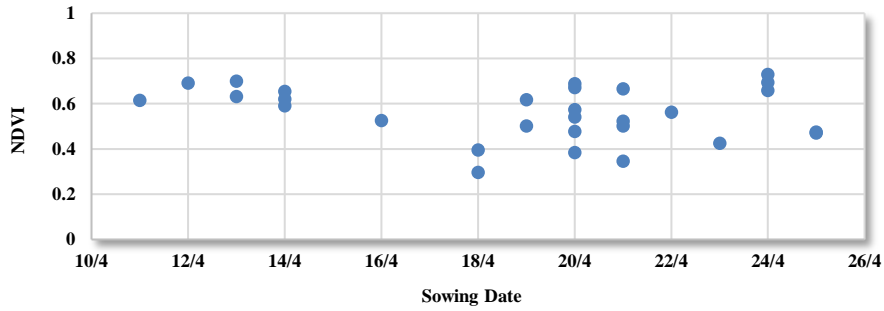

Figure 1. NDVI at the 18th of June per sowing date of cotton.

Based on the sensed values, the highest NDVI is 0.730 and the average of the readings (excluding 0.730) is 0.553. Dividing the highest NDVI with the average NDVI, results in RI_{NDVI} equal to 1.320, while based on Eq. 7, $RI_{Harvest}$ is 1.205. The RI_{NDVI} is limited at values lower than 2.0 as in-season applications of N would unlikely lead to yield potential being more than two times greater than baseline YP_0 [8].

It is considered that 90 g N per kg of lint and seed, is removed by the cotton crop during harvest, thus the percentage N is set at 0.09 [25-27]. The NUE levels for cotton reported in the literature range from 25 to 60% [25], while 50% is a representative value, since side-dress application of N is expected to be at the higher end of the recorded NUE range [25-27]. Based on the previous calculations and assumptions, the equation providing the optimized, in-season nitrogen fertilization rate (Kgha^{-1}), used in NITREOS, is as follows:

$$FNR = \left[\left(1.205 \times 309.72 e^{1295.9 \times INSEY} - 309.72 e^{1259.9 \times INSEY} \right) \times 0.09 \right] / 0.50 \qquad (8)$$

It is evident from Eq. (8) that the N recommendation rates change daily with the new calculated CumGGD and newly sensed NDVI values. A daily change is expected due to the nature of the cotton plant having an optimum time for N uptake. In the literature, the maximum N uptake in cotton has been observed between 49 to 71 days from sowing [25, 26, 29, 30]. In NITREOS, the OTW for in-season N application lasts from 38 to 90 days after planting. During that time, recommendations are provided. Fig. 2 provides the NITREOS user interface and the fertilizer recommendation dose per zone of equal treatment for a registered cotton field in Greece.

Figure 2. NITREOS in-season fertilizer recommendation zones of a cotton parcel.

2.2 NFOA for maize

A modification of the NFOA has been proposed for maize [20], as follows:

$$NFOA(kgha^{-1}) = \left[YP_0 \cdot \left(RI_{NDVI} - 1 \right) \cdot percentage\ N \right] / NUE \qquad (9)$$

In this approach, INSEY was calculated by dividing NDVI readings by the number of days from planting to sensing, and was correlated with grain yield data in order to produce empirical equations that predict the maize grain yield potential. Maize yield data referred to plots treated with fixed rates of 0, 67 and 134 kgha^{-1} N, applied in split, pre-plant or side-dress. Crops were sown from the 28th of March to the 12th of April. The nonlinear regression model produced in this case was:

$$YP_0 \left(kgha^{-1} \right) = 1333 e^{122.5 \times INSEY} \qquad (10)$$

The RI was calculated by an adjusted equation of the form:

$$RI_{NDVI} = \left(1.64 \cdot NDVI_{N-Rich} \ / \ NDVI_{Farmer}\right) - 0.528 \tag{11}$$

The equation is derived by dividing the NDVI of a high-N plot by the NDVI of a zero-N plot or farmer's practice. In this study [20] the NDVI readings were collected within the time period of 38 to 60 days after sowing. The highest NDVI value of 0.830 was reported for that period, as well as values of RI equal to 1.43±0.42.

NFOA implementation for maize in NITREOS. The NFOA proposed for maize [20] is used in NITREOS to deliver in-season fertilization. For the calculation of RI_{NDVI} in NITREOS, values were collected from 23 maize fields registered in the Crop Growth Monitoring Service of AgroApps P.C. (Serbia). In the selected crops, maize was sown from the 31st of March to the 4th of May 2018. The highest NDVI among the values was considered representative of a N-rich treatment of maize, while the lower value was calculated as the average of the remaining measurements. Fig. 3 presents the sowing date and the NDVI sensed at the 2nd of June 2018, for the 23 maize fields.
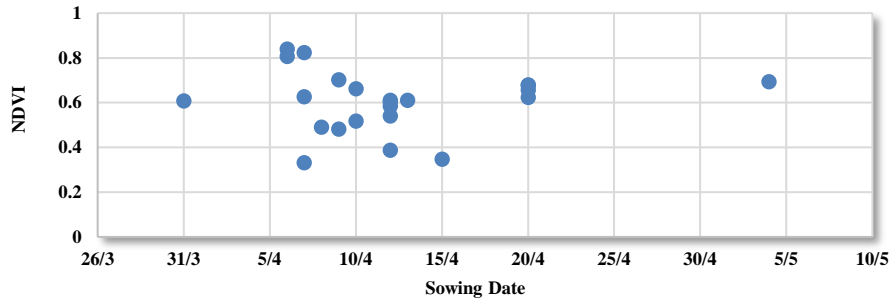

Figure 3. NDVI at the 2nd of June per sowing date of maize.

Based on NDVI sensed on the 2nd of June, the highest is 0.839 and the average of the readings (excluding 0.839) is 0.594. Therefore, based on the adjusted Eq. (11), RI_{NDVI} is equal to 1.788. The NUE levels reported in the literature for maize range from 33 to 70% [1, 11, 31]. In NITREOS, NUE for maize is set at 0.56 and the N content in grain is 0.0125 kg N per kg grain [20]. Therefore, the general equation providing the optimized, in-season nitrogen fertilization rate in NITREOS, is as follows:

$$NFOA(\ kgha^{-1}\ ) = \left[\ 0.788\left(1333e^{122.5 \times INSEY} \times 0.0125\right)\right] / \ 0.56 \tag{12}$$

Maize N uptake is significant between the 50th and 85th day after sowing. Therefore, the half or one third of the total N fertilizer should be provided in preplant applications, while the rest should be provided in-season. In NITREOS, the OTW for in-season N application lasts from 38 to 90 days after sowing.

2.3 NFOA for wheat

NFOA has been used to estimate the in-season N fertilizer rates for wheat [11]. In this case, INSEY was calculated by dividing NDVI readings with the number of days from sowing to sensing. Including only the days, where GDD > 0, is necessary in order

to remove days where growth is not possible in winter wheat. INSEY was correlated with wheat yield data in order to produce empirical equations that predict the potential yield. The model proposed to predict wheat grain yield [10], is:

$$YP_0 \left(kgha^{-1} \right) = 992.26e^{142.67 \times INSEY} \tag{13}$$

In this model, the INSEY was produced from NDVI readings of wheat, collected between 99 to 146 days after sowing. Wheat was sown from the 10th of October to the 20th of November [10]. An improved fit of a linear-linear regression model to describe the relationship between RI_{NDVI} and $RI_{Harvest}$, based on the evolution of RI_{NDVI} values was proposed [20] for wheat. In this case the RI_{NDVI} was calculated by dividing the highest NDVI reading of N-rich strips in the field, by the average NDVI of the farmers practice area. The model is as follows:

$$RI_{Harvest} = \begin{vmatrix} 1.69 \times RI_{NDVI} - 0.70 & RI_{NDVI} < 1.72 \\ 0.45 \times RI_{NDVI} + 2.20 & RI_{NDVI} > 1.72 \end{vmatrix} \tag{14}$$

NFOA implementation for wheat in NITREOS. In NITREOS, INSEY for wheat is calculated by dividing NDVI readings by the number of days from planting to sensing, where GDD > 0. For the calculation of RI_{NDVI}, values were collected from 15 wheat fields registered in the Crop Growth Monitoring Service of AgroApps P.C. (Serbia). Wheat was sown from the 3rd to the 31st of October 2017 and the sensing day of NDVI was the 20th of April 2018. The highest NDVI value was considered representative of a N-rich treatment of wheat, while the lower value was calculated as the average of the remaining measurements. Fig. 4 presents the NDVI sensed at the 20th of April per sowing date. Based on the sensed NDVI values, the highest was 0.883 and the average of the readings (excluding 0.883) was 0.614. Dividing the highest NDVI with the average NDVI, results in RI_{NDVI} equal to 1.438, while based on Eq. 14, $RI_{Harvest}$ is 1.730.
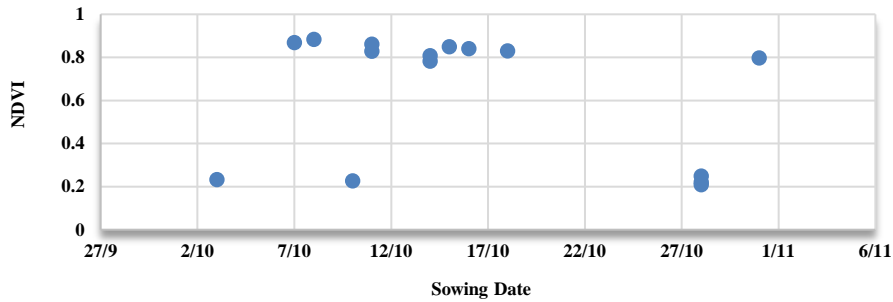

Figure 4. NDVI at the 20th of April per sowing date of wheat.

In NITREOS, the topdress N requirement for wheat, is calculated as follows [21]:

$$FNR \left(kgha^{-1} \right) = 0.0239 \frac{1.73 \cdot 992.26e^{142.67 \times INSEY} - 992.26e^{142.67 \times INSEY}}{0.55} \tag{15}$$

where 0.0239 is the percentage of N contained in wheat grain. Published studies report the recovery of applied N at sowing ranging from 30% to 55% while that applied at flowering, ranging from 55% to 80%, thus the NUE is set at 0.55 [9]. Wheat early

season N uptake is significant between 123 to 163 days after sowing (leaf sheaths lengthen through first node of stem visible). In NITREOS, the OTW for in-season wheat N application lasts from 100 to 163 days after sowing.

3   Results and Discussion

3.1   NFOA Application for Cotton

The calculation of N rates using NFOA was applied in crops registered in the Crop Growth Monitoring Service of AgroApps P.C. For cotton, a Greek region was selected. Data from three cotton crops were used in the calculation of NFOA. The selection criteria were based on the different planting dates for each crop. Cotton was sown on the 8th of April, the 24th of April and the 17th of May, 2018. For the calculation of GDD, max., min. and average temperatures for the region were derived from the Meteorological Service of Agroapps P.C. (1st of April to the 31st of August). The NFOA was calculated from sowing to harvest. The results were produced by averaging the NFOA pixel values of the registered fields in Fig. 5.
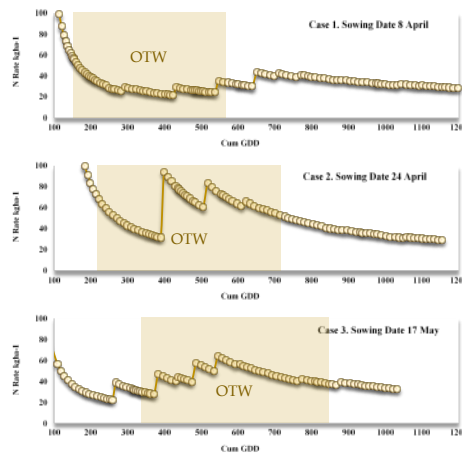

Figure 5. Recommended N rates with NFOA. Three cotton fields are presented. OTW denotes the Optimum Time Window for the beginning of NFOA calculations (38-90 days after sowing).

It is evident from Fig. 5 that the N recommendation rates change daily due to INSEY and peak values are mainly influenced by the newly sensed NDVI. Based on the calculations of the NFOA, the highest rates were 53.1, 94.2 and 64.4 kg N ha^{-1} with cotton sowing dates 8-April, 24-April and 17-May, respectively. Only the rates in the OTW (38-90 days after sowing) were taken into account. The difference between the predicted doses is attributed mainly to the combination of the sensed NDVI values and the CumGDD. Cotton N requirements have been reported to be highly variable, with a range from 67 to 255 kg N ha^{-1} [29]. In a previous study the use of NFOA on cotton predicted a range of in-season N rate between 26.88 and 51.52 kg N ha^{-1} [25].

3.2   NFOA Application for maize

For maize, a Serbian region was selected. Data from three registered fields were used in the calculation of NFOA. Maize was sown on the 12th, the 20th of April and the 4th of May, 2018. For maize fields, NFOA was calculated from sowing to harvest. The results of the calculations are provided in Fig. 6.
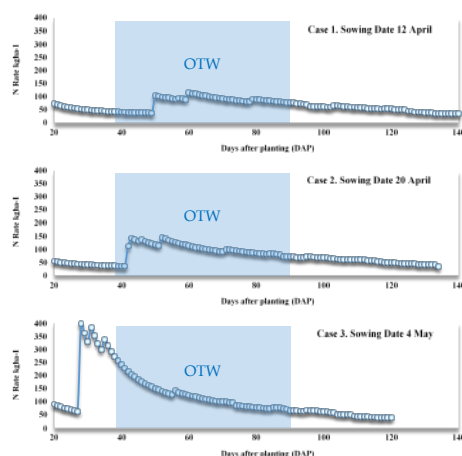

Figure 6. Recommended N rates with NFOA. Three maize fields are presented. OTW denotes the Optimum Time Window for the beginning of NFOA calculations (38-90 days after sowing).

Based on the calculations of the NFOA for the Serbian fields, the highest rates were 116.5, 144.9 and 273.6 kg N ha^{-1} for the maize crops sown on the 12-April, 20-April and 4-May, respectively. Only the rates in the optimum time window (38-90 days after sowing) were taken into account. For the same period, the average rates were 80.5, 99.8 and 126.6 kg N ha^{-1} for the maize crops sown on the 12-April, 20-April and 4-May, respectively. Optimum N fertilizer rates for maize are highly variable. In a study, optimum N rates for maize, in 198 site-years of published data in the United States (1958–2010), were found to be significantly variable, with an average low of 62 ± 44 kg N ha^{-1} and an average high of 173 ± 55 kg N ha^{-1} [32]. NFOA was appplied in plots of maize and the recommended N rates ranged from 20 to 201 kg N ha^{-1} [20], according to the resolution of the sensed NDVI, the year and the site.

3.3   NFOA application for wheat

For wheat, a Serbian region was selected. Data from three wheat crops were used in the calculation of NFOA. Wheat was sown on the 3rd, the 28th and the 31st of October 2017. For the calculation of GDD, max., min. and average temperatures for the region were derived from the Meteorological Service of Agroapps P.C. (1st of October to 31st of July). NFOA was calculated from sowing to harvest. The results of the calculations are provided in Fig. 7.
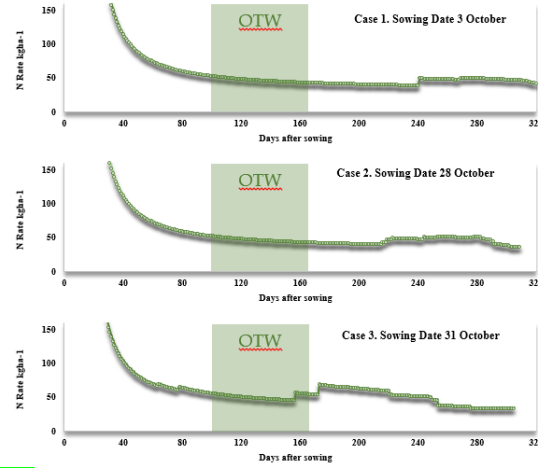
Figure 7. Recommended N rates with NFOA algorithm. Three wheat fields are presented. OTW denotes the Optimum Time Window for the beginning of NFOA calculations (100-163 days after sowing).

Based on the calculations of the NFOA for the Serbian fields, the highest rates were 52.7, 52.1 and 56.2 kg N ha^{-1} for the wheat fields sown on the 3rd, 28th and 31st of October, respectively. Only the rates in the optimum time window (100-163 days after sowing) were taken into account. For the same period, the average rates were 47, 46.6 and 50.2 kg N ha^{-1}, respectively. NFOA has been applied to winter wheat in previous studies where reported estimated N rates ranged between 5.4 to 72.3 kg N ha^{-1} [33].

4   Summary and conclusions

NITREOS is a farm management information system for organic and conventional agriculture which aims in enabling farmers to tackle crop abiotic stresses and control important growing parameters to ensure crop health and optimal yields. Among the services of NITREOS, a nitrogen fertilization advisory module is included for the estimation of mid-season N fertilizer rates for cotton, maize and wheat. This paper presents the algorithms for the calculation of plant N demands, by taking into account weather parameters and canopy development, through the use of Sentinel-2 optical imagery. The methodologies are based on the Nitrogen Fertilization Optimization Algorithm (NFOA). The NFOA was calibrated with the use of agro-meteorological data in two distinct agricultural regions (Greece and Serbia) in order to derive crop and site specific parameters, and was validated against actual crops' data, with different sowing dates. The results of the NFOA in terms of N doses, are in agreement with the values reported in the literature, regarding previous studies on NFOA application, under field conditions. Furthermore, the Optimum Time Window (OTW) provided by NITREOS to

point out the appropriate period for mid-season fertilization, falls well within the periods reported in the literature for optimum N uptake, thus leading to maximum crop utilization of in-season applied N.

Acknowledgments

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