Simulation for variable-rate nitrogen fertilization with different application schemes

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Abstract

Optimizing variable-rate nitrogen (N) fertilization (VRNF) is required to minimize input, maximize output, and reduce environmental footprint. This study aims at comparing the amount of N used by traditional uniform N fertilization (URNF) against three VRNF treatments of map-based (MB), sensor-based (SB) and map-sensor-based (MSB) in four commercial fields using a new simulation software. Under the three VRNF treatments, two different application schemes were evaluated: applying more N fertilizer to the more fertile zones (Kings scheme, KS) and more N fertilizer to the least fertile zone (Robin Hood scheme, RHS). Simulations were made after imposing N legislation limits and without imposing them. Finally, VRNF applications were evaluated for a full boom, a section control sprayer and a nozzle control sprayer. Results showed that the VRNF did not exceed the traditional URNF approach, but only if the N limit by legislation is imposed. The RHS consumed 16.4-118.1% less N fertilizer than the KS and 33.3-56.2% less than URNF approach. The best performing RHS-VRNF without imposing N limits was the SB followed by the MSB treatment. However, the KS without N limit always exceeded the applied N fertilizer, compared to the URNF approach, imposing large risks of N leaching. When imposing the N limit, both KS and RHS consumed less N than the traditional URNF approach, except for the MSB under the KS, which used the same N as the URNF. Spatial variability can be observed in the MB approach, temporal variability in the SB approach and both variabilities in the MSB approach. Regarding the spatial variability, no significant differences between section and nozzle control options could be observed, whereas it was minimized when using the full boom control. We concluded that the optimal VRNF is a combination of the RHS and section control, which is expected to result in saving on N fertilizer cost, minimal risk of N leaching, and ensuring N applied is under the set legislation limits.

Keywords: Variable rate N fertilization, simulation, software, uniform rate N fertilization.

1. Introduction

The "application of local resources management in the sense of transferring the site-specific plant nutrient demand into variable rates in dependence on the spatial variability of soil and crop parameters" is defined as site specific or variable rate nitrogen (N) fertilization (VRNF) (Srinivasan, 2007). The core objective of VRNF systems is to optimize economic, environmental and yield factors of the fertilization process. This method has been partially proven to show significant positive differences when compared to uniform rate nitrogen application (URNF) (Basso et al., 2016a; Havlin and Heiniger, 2009; Koch et al., 2004). VRNF systems are divided into map-based (MB) and sensor-based (SB) approaches. When using MB treatment, an assessment of soil fertility is performed by measuring key soil parameters and a fertilization recommendation map is created in advance (offline) with the aim to be implemented by a VRNF machine. In the case of SB approach, the measurements can be done in real-time by using optical reflectance sensors over the crop with the aim to capture information of the crop's nutrient status. This is then used to estimate the nutrient requirements and control the doses in real-time VRNF system (e.g., Commercial Yara System) (Boyer et al., 2011). A new approach of VRNF that accumulates the advantages of MB and SB was recently introduced by Guerrero et al. (2021a), [named map-sensor-based (MSB) VRNF], which merges soil fertility information measured a prior with real-time crop normalized difference vegetation index (NDVI). Through data fusion, different recommendation rates are calculated to supply the right amount of N fertilization that the crop needs at the moment of the application. Additionally, a common concern in VRNF systems is whether to apply more N fertilizer to the most fertile zone [Kings scheme (KS)] or to the least fertile zone [Robin Hood scheme (RHS)]. A study developed by Guerrero et al. (2021b) has partially answered this question by proving that the RHS is a more environmentally responsible and profitable solution, compared to KS or URNF schemes in two commercial fields where barley and wheat were grown. However, further research is required to account for the three VRNF approaches (MB, SB and MSB). The use of URNF might lead to overapplication of N in some parts of a field, which can end up in N-leaching causing several environmental problems. Therefore, in Flanders, Belgium, the Flemish Society of Soil and Land has set the Action Program for the Implementation of the Nitrate Directive 2019–2022 (MAP6), in which strict limits for N fertilization were determined according to the location, the type of soil and the crop to be cultivated. These limits were necessary to avoid the contamination in surface- and groundwaters (Vlaamse Landmaatschappij, 2019b, 2019a). Furthermore, to the best of our knowledge, no literature was found on the evaluation of different VRNF treatments and schemes considering the N limits set by the MAP6. Finally, to fully optimize the performance of VRNF systems, the variable rate machinery resolution plays an important role. In liquid fertilization, the resolution of application can be defined at three levels, namely, individual nozzle, section control and full spray boom control (Grisso et al., 2011). The full boom control option allows for lower resolution spraying, compared to the section and nozzle control options. Section and nozzle control permit more precise spraying of fertilizers adapting to the field variability and crop needs, making them able to increase yield and farm profitability and reduce environmental risks (Chattha et al., 2014). Simulating the effect of control type on N application during VRNF under the different approaches and schemes mentioned above is necessary to avoid overapplication of N, while providing appropriate resolution of N applied at reasonable cost.

To optimize VRNF, it is necessary to evaluate the aspects mentioned above and all of their combinations, together with different VRNF treatments, schemes, N-limitations and VR dosage at several machine resolutions. However, the evaluation of each of these aspects in VNRF systems in commercial fields, requires intervention in agricultural practices and years of experiments considering several different scenarios. Therefore, a simulation software can be a suitable alternative that can reduce time, effort and costs. The aim of this work is to evaluate three different VRNF treatments (e.g., MB, SB and MSB) using both VRNF schemes (e.g., KS and RHS), based on simulations that consider the soil variability, the crop needs, the N limits set by legislations and the technical specification of variable rate spraying machinery. The study will present the results of a new simulation software which produces VRNF recommendation maps, based on data fusion of soil and crop data acquired at high sampling resolution from four commercial fields in Flanders, Belgium, growing cereal crops.

2. Materials and Methods

2.1. Soil and crop data acquisition

This study was carried out on four commercial fields in three different locations in Flanders, Belgium. Two fields located in Veurne named Beers (12 ha – sandy loam) and Fabrieke (8 ha – loam), one field located in Huldenberg named Kouter (12 ha - silty loam) and a field located in Landen named Gimgelomse (11 ha – loam). The data on soil and crop were collected in 2018-2019 (Kouter) and 2019-2020 (other three fields), with barley grown in Fabrieke and Kouter (2019) and wheat in Beers and Gimgelomse. The soil data was collected by using the online multisensor platform designed and developed by Mouazen (2006), which uses a visible and near infrared (vis-NIR) sensor to produce high resolution data of soil attributes. The detailed description of the sensor and data acquisition can be found in Guerrero et al. (2021b). The historical yield data was only available in Kouter and Fabrieke, where yield was obtained using a combine harvester equipped with a yield sensor. The normalized difference vegetation index (NDVI) data was collected with Sentinel 2 satellite imagery for Beers, Fabrieke and Gimgelomse and by six Green Seeker® sensors installed on a liquid fertilizer spraying machine in Kouter field.

2.2. Data processing and management zone delineation

During online measurements, random soil samples were taken to develop prediction models for soil organic carbon (OC), pH, phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sodium (Na) and soil moisture content (MC). The prediction models were developed after vis-NIR spectra pre-treatment and partial least squares regression (PLSR) analysis in RStudio (RStudio Inc, USA) with open-source libraries (Stevens and Ramirez Lopez, 2014). Principal component analysis (PCA) was done before PLSR to examine similarity or differences between soil samples. A total of 179, 121 and 155 soil samples collected from different fields with similar soil texture in three farms were used to develop three groups of models for Veurne, Huldenberg and Landen farms, respectively. Only leave-one-out cross-validation was possible for the Kouter field (in Huldenberg farm), as limited data from this field was available to support independent validation. Both leave-one-out cross-validation and independent validation were possible in the remaining three fields. To this end, the entire data set was divided into calibration (70%), and validation (30%) sets. The prediction performance of the developed models was evaluated by means of the coefficient of determination (R2), root mean square error (RMSE), and the ratio of performance to inter-quartile distance (RPIQ). Data fusion of yield data (if available), online predicted soil properties and crop NDVI was performed to delineate management zones (MZ) in each field. For Kouter field, yield data collected in 2017, online measured soil properties (excluding MC, Mg, and Na) collected in summer 2018 and NDVI measured in three growth stages of wheat in 2017 were used for MZ delineation. In Fabrieke field, yield data from 2018, online measured soil properties in 2019 and NDVI obtained in spring 2020 were used. For Gimgelomse field, no yield data was available, hence, the delineation of MZ was performed using the online measured K, MC, Mg, OC, P and pH in 2019 and the NDVI obtained from Sentinel 2 satellite imagery in spring 2020. For Beers field, only the online measured properties and the NDVI obtained from Sentinel 2 satellite imagery in spring 2019 were used, as no historical yield was available. The first step for the MZ delineation was a raster analysis, which allowed resampling of the soil, NDVI, and yield data (if available) in a common grid of 5 by 5 m resolution. This was followed by K-means clustering, dividing each field into a limited number of clusters, each having similar soil and crop characteristics. The ranking of the MZ classes into different fertility areas was done according to the online measured soil fertility properties and crop NDVI measurements, in addition to the historical yield information or the farmers experience in case the yield was not available.

2.3. Implementation of simulation software

The maximum effective N rates in kg/ha are generally determined according to area classifications according to MAP6, soil texture and the crop grown. Lands are divided into two subclasses according to soil texture, namely, sandy and not sandy. All four fields in this study were of none-sandy soil textures. MAP6 classifies agricultural soils in Flanders into 4 areas according to run-off potential and dictates additional measures such as the sowing of catch crops after harvest where possible, to achieve the target value of nitrate in agricultural areas in the long term (Vlaamse Landmaatschappij, 2019b). Depending on the area classified by MAP6, strong limitations are required to avoid extra contamination in the soils. Areas 0 and 1 refer to zones where any additional measurements are required while areas 2 and 3 refer to zones where strongest limitations (low effective N dose) need to be applied. Fabrieke, Beers and Kouter are located under area 0, while Gimgelomse is located under area 1. Therefore, according to the Standards and Guidelines of January 2020 (Vlaamse Landmaatschappij, 2020), the maximum allowed effective N rate for non-sandy soils is 175 kg/ha per year for wheat and 125 kg/ha per year for barley. These limits were used to calculate the recommendation of the total N rate by running two fertilization applications along the cropping season. The maximum allowed N fertilizer was 300 kg/ha for wheat (corresponding to 78 kg/ha effective N) and 200 kg/ha for barley (corresponding to 52 kg/ha effective N). In the simulation software, two scenarios were implemented. In the first one the N limits were ignored, and the recommendation doses were calculated based on the VRNF treatments and schemes. In the second scenario, the N limits were implemented, so that the maximum allowed N rate should not exceed these limits, regardless of the calculated VRNF according to treatments and schemes.

Two different schemes are evaluated in this study to understand which approach is the optimal application for VRNF. The RHS applies more fertilizer to the least fertile zones and less fertilizer to the most fertile zones while the KS applies more fertilizer to the more fertile zones and less fertilizer to the less fertile zones. In the VRNF treatments, N rates oscillated between +50% and -50%, depending on RHS or KS scheme that is being used (Table 1). The VRNF treatments of MB, SB and MSB were compared with the traditional URNF treatment.

The recommended N rate was provided by the farmer according to his experience, traditional soil analysis and guidelines of the nitrate directive. This recommended rate was used as URNF treatment. The MB treatment is based on the MZ delineation and the variation of recommended rate percentages was determined according to the fertility class (high, medium high, medium low or low) and the VRNF scheme. In the SB treatment, NDVI obtained from Sentinel 2 satellite images was used to calculate the N rates, dividing the NDVI value in four groups, under the RHS or KS schemes (Table 1). Since the new proposed MSB combines the MB and SB treatments, the in advance determined fertility zones by MZ maps and the NDVI values measured in real-time were combined to calculate the N recommendation rates. Table 1 details the calculation of N rates for each of the four treatments.

In this work three sprayer control options, namely, full boom, section and nozzle control were evaluated. The full boom control is the application of the same rate along the entire spraying boom (33 m or 39 m depending on the commercial machinery). The section control, divides the entire boom into sections of 3 m, where the same rate is applied along the section but varies between sections. Finally, the nozzle control allows to cover 0.5 m and different doses can be applied at higher resolution. The VRNF machine automatically adjusts the rate while driving along the field by using the geo-localized variable-rate map. However, the VRNF machinery requires a stabilization time (lag time) while changing between doses. This period is a lapse in time that the nozzles require to adjust and achieve the next desired rate. For a regular sprayer, driving at an average speed of 8 km/h, the stabilization period is approximated 30s or 15m driving distance. In the simulation software, the N dose will be maintained for this 15m before changing to a new N dose.

The simulation software was designed using Labview programming language (National Instruments, USA). The software performed several tasks: 1) prediction of online soil properties using online collected raw spectra, 2) development of maps of soil and crop parameters, 3) implementation of clustering analysis for MZ delineation, and 4) calculation and simulation of recommendation maps for VRNF treatments (MB, SB, MSB and URNF), under both RHS and KS schemes. The software also allows to impose or ignore the legislative N limits while setting the desired control option (full boom, section control or nozzle control). The system inputs are georeferenced online collected soil spectra, and satellite Sentinel 2 data or proximal sensor measured NDVI. To create an application map for VRNF, the software interface allows the user to indicate the tramline direction, crop type and select the width of sprayer and its control option. The simulation output included the calculated N fertilizer in kg per field, the calculated N fertilizer in kg per MZ and recommendation maps for each option of VRNF. Since N fertilization was performed in two applications (two different dates) along the cropping season, then the final N rate in each VRNF treatment is calculated and compared with the final N rate of the URNF. The traditional URNF treatment designated as the control rate (CR) treatment in this study, corresponds to the recommended rate (obtained from soil analysis) that a crop would receive if only URNF scheme was used. The calculated rates for the URNF were 104 kg/ha effective N for barley and 156 kg/ha effective N for wheat. The final N rates per field and per MZ for the MB, SB and MSB treatments were calculated by adding the amount of N applied in the two applications (assuming equal rates of 50% each).

Table 1. Calculation of nitrogen (N) rate (in %) for map based (MB), sensor based (SB) and map sensor based (MSB) treatments, presented for the Robin Hood (apply more on poor zones) and Kings (apply less on fertile zones) schemes under 3 and 4 management zones (MZ) and differentiated by fertility classes. Each N Rate presents the value for Robin Hood scheme (RHS) followed by the value of Kings scheme in blue color: RHS/KS

VRNF Scheme	Number of MZ	MB treatment		SB treatment		MSB treatment				
		Fertility Class	**N Rate (%)**	**NDVI**	**N Rate (%)**	**Fertility Class**	**NDVI**			
							0 - 0.34	**0.34 - 0.67**	**0.67 - 1**	
Robin Hood Scheme / Kings Scheme	**3**	Low	50/-50	0 - 0.25	50/-50	Low	50/-50	25/-25	0*/0*	
		Medium	0*/0*	0.25 - 0.5	37/-37	Medium	25/-25	0*/0*	-25/25	
		High	-50/50	0.5 - 0.75	-37/37	High	0*/0*	-25/25	-50/50	
				0.75 – 1	-50/50					
							0 - 0.25	**0.25 - 0.5**	**0.5 - 0.75**	**0.75 - 1**
	4	Low	50/-50	0 - 0.25	50/-50	Low	50/-50	44/-44	0*/0*	-25/25
		Med low	25/-25	0.25 - 0.5	37/-37	Med low	44/-44	37/-37	-25/25	-37/37
		Med high	-25/25	0.5 - 0.75	-37/37	Med high	37/-37	25/-25	-37/37	-44/44
		High	-50/50	0.75 – 1	-50/50	High	25/-25	0*/0*	-44/44	-50/50

*Refers to the same N rate applied for the URNF.

3. Results and Discussion

3.1. Accuracy of prediction models and management zone delineation

Results results for cross-validation presented high prediction accuracies for OC and MC in Huldenberg, MC in Landen and pH, Mg, Ca and Na in Vernue (R2 > 0.80) and moderate to good prediction for the rest of soil properties (R2 > 0.52). For online prediction using the prediction set, high prediction accuracies (R2 > 0.80) were obtained for MC in Landen and pH, Mg, Ca and Na in Vernue, while moderate to good prediction accuracies were observed for the rest of soil properties (R2 > 51). Veurne models obtained the best prediction results for both cross-validation and online-validation. The fusion of online predicted soil properties, with crop yield and NDVI developed by the k-means cluster analysis explained the spatial variability of the fields by dividing them in three (Kouter and Fabrieke) or four classes (Beers and Gimgelomse) as can be observed in Figure 1. The ranking of the fertility classes in Kouter and Fabrieke were determined mainly based on the historical yield while in Beers and Gimgelomse a meeting with the farmer was held to determine the proper classification.

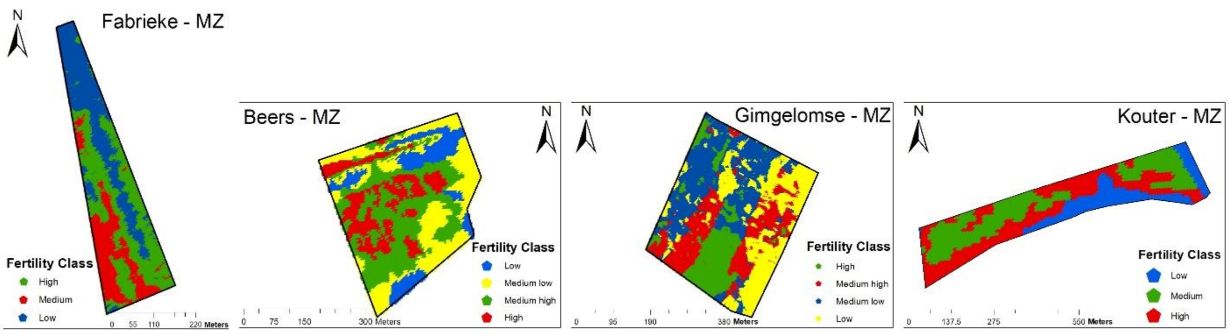

Figure 1. Management zone delineation and fertility classes per field obtained from the K-means clustering analysis.

3.2. Simulation results

3.2.1. Application rates

The output of the simulation software regarding the calculated N rates for each field is presented in Figure 2 for MB, SB, MSB and URNF and under both RHS (Figure 2a) and KS (Figure 2b). VRNF treatments exceed the URNF in the majority of cases (especially for the KS), when the N limit is not considered (Figure 2). When the N limits were imposed all RHS-VRNF treatments presented lower N rates than the CR treatment. Nevertheless, the N rates exceeded the CR for all KS-VRNF treatments in Kouter and for MSB in Fabrieke and MB in Beers. The published literature based on field experiments in commercial farms have proven to have the potential to improve N fertilization practices by reducing the amount of fertilizer applied (Basso et al., 2016b; Colaço and Molin, 2017; Guerrero et al., 2021b; Kitchen et al., 2010; Link et al., 2006). However, results presented for VRNF when the N limit is not imposed and particularly under KS imply that not always VRNF lead to the reduction of amount of fertilizer but on the contrary might lead to an over-application with both economic and environmental costs. SB treatment seems to have less influence on MSB than MB, since the latest two have the same tendency (Figure 2), which is different than that of the SB. This can be explained by the effect of spatial variability of soil and crop properties, as soil data and subsequently the MZ maps were of higher resolutions. The rates of all VRNF treatments fluctuated along the fields, this can be attributed to the degree of spatial and temporal variability affecting the degree of fluctuation in respect to the URNF. Consequently, the spatial and temporal variability in soil and crop needs to be understood by using proximal and remote sensing tools to be able to capture the interactions between soil-plant-environment, which permits the optimization of VRNF systems (Amaral et al., 2017; Basso et al., 2016c) and can result in both economic and environmental benefits (Kitchen et al., 2010).

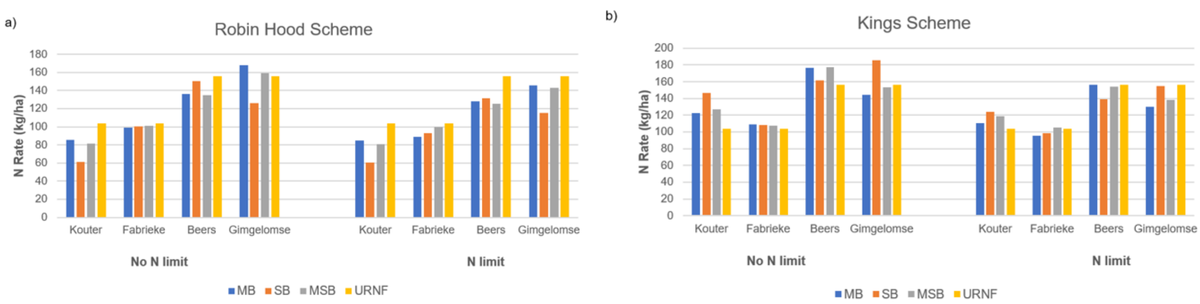

Figure 2. Fertilizer rates applied in each field according to a) Robin Hood scheme and b) Kings scheme. MB: Map-based treatment. SB: Sensor-based treatment. MSB: Map-sensor-based treatment. URNF: Uniform rate nitrogen fertilization. Barley was assumed in Fabrieke and Kouter and wheat in Beers and Gimgelomse.

The calculated N rate of KS-VRNF when the N limits are ignored exceeded the maximum allowed rate of effective N of 125 kg/ha per year for barley and 175 kg/ha per year for wheat. In Beers field, the MB and MSB treatments slightly exceeded the limit (total of 176.41 kg/ha and 177.44 kg/ha per year respectively); in Gimgelomse, the SB treatment exceeded the limit (185.88 kg/ha per year) and in Kouter field, the MSB treatment exceeded it as well (126.86 kg/ha per year). Nevertheless, as expected the calculated N rates did not exceed the maximum allowed N rates for neither RHS or KS, when the legislative N limits were imposed. By imposing the N limits on the VRNF (KS in particular), one can guarantee that the N applied does not exceed the legislative limits and that the nitrate target of 50 mg/l proposed in the nitrate directive can be achieved, which is important since the nitrate target proposed in the nitrate directive is still exceeded in practice in some sand regions (Van Grinsven et al., 2016).

3.2.2. Application maps

The VRNF application maps obtained from the simulation software are presented in Figure 3 for RHS and in Figure 4 for KS. It is clear that in both cases, MB and MSB treatments allow detailed spatial variability which is attributed to the high-resolution data obtained during the soil online scanning. In the case of SB treatment, the application maps are less detailed compared to the MB and MSB maps, and reflect the temporal variability associated with NDVI captured at two different growth stages of the crop (SB_1 and SB_2 maps in Figure 6 and Figure 7). The resolution of the online measurements with the multi-sensor platform (1 m by 12 m) is different than that of satellite images (10 m by 10 m), a difference that is eliminated during the delineation of the MZ by the raster analysis by constructing a common grid of 5 m by 5 m. In the SB treatment no MZ was used hence the sampling resolution was 10 m by 10 m, which is bigger than both the MB and MSB (e.g., 5 m by 5 m). The different resolution may partially explain the coarser resolution of the SB maps. Moreover, more detailed maps are reported to be necessary for more accurate management of within-field variability (Pantazi et al., 2015). But, it is important to note that the resolution of the application map should match or at least not exceed the machine dimension. Still it is true that the SB solution based on crop NDVI data only is not ideal, as no soil data was included in the analysis and recommendation establishment. The fusion between proximal soil sensing and crop remote sensing (in case of MB and SMB) is important not only to evaluate spatial variability and define crop yield limiting factors but to improve within field management of farming input resources (Nawar et al., 2017; Shaddad et al., 2016).

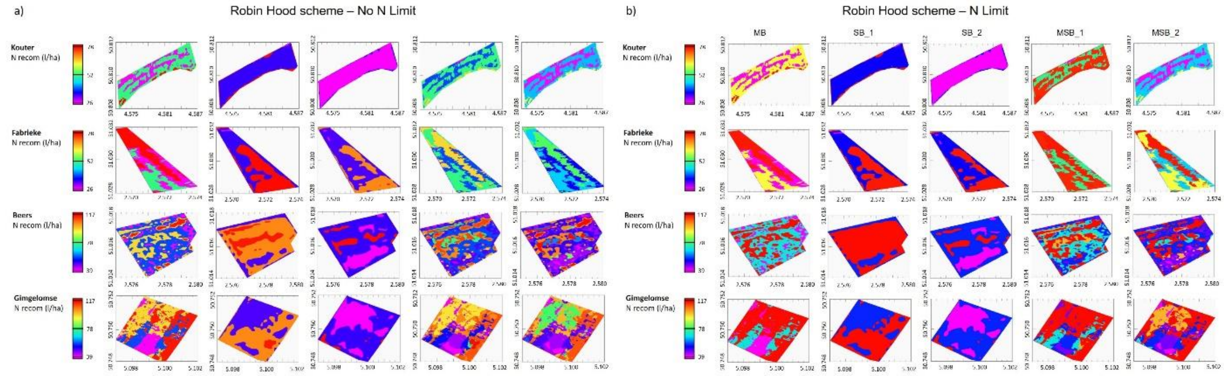

Figure 3. Nitrogen fertilization recommendation (N recom) maps (in l/ha) under Robin Hood scheme per variable-rate treatment. a) Maps ignoring the nitrogen legislative limit. b) Maps considering the nitrogen limit imposed. MB: Map-based treatment. SB_1: Sensor-based treatment first application. SB_2: Sensor-based treatment second application. MSB_1: Map-sensor-based treatment first application. MSB_2: Map-sensor-based treatment second application.

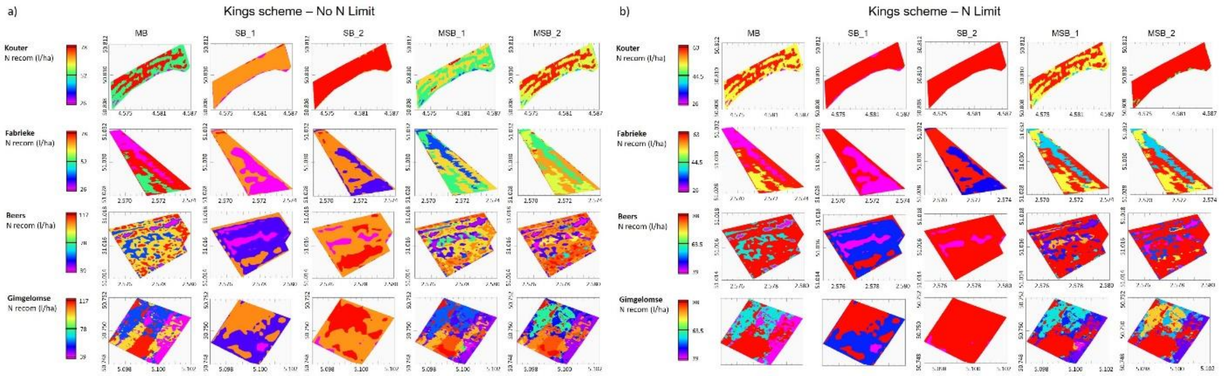

Figure 4. Nitrogen fertilization recommendation (N recom) maps (in l/ha) under Kings scheme per variable-rate treatment. a) Maps ignoring the nitrogen legislative limit. b) Maps considering the nitrogen limit imposed. MB: Map-based treatment. SB_1: Sensor-based treatment first application. SB_2: Sensor-based treatment second application. MSB_1: Map-sensor-based treatment first application. MSB_2: Map-sensor-based treatment second application.

In general, if the N limit is ignored, the fertilization rates exceeded the limit without losing variability in the case of MB and MSB, with the latter showing the lowest N recommended rate (Figure 3). Moreover, in RHS, the maximum rates (red color zones) are observed in SB and slightly less in MB treatment. In contrast, after imposing the N limit, the maximum rate was calculated in large parts of the field in almost all treatments. This can be observed when comparing the variability of the maps when the limit is ignored (Figure 3a) and considered (Figure 3b). Still, the maximum recommended N decreased from 78 to 63 l/ha in Kouter and Fabrieke and from 117 to 88 l/ha in Beers and Gimgelomse, after imposing the legislative N limit (including the RHS). This indicates that even if the N limit is applied and it leads to decrease the maximum rate, the spatial variability is affected in the sense that the rates has the tendency to be uniform limiting the full benefit of the agronomic-optimal VRNF scheme. There are visible larger differences in some areas of KS which are receiving the maximum N rate before and after imposing the limit in comparison with RHS (Figure 4a). Nevertheless, using KS and imposing the N limit, the total areas that should receive the maximum rate increased considerable comparing with the corresponding maps using RHS. This means that the VRNF will be more restricted by KS than RHS, since it will increase the uniformity after imposing the N limits. Some examples of this uniformity in the N application rates can be observed in Kouter and Gimgelomse (Figure 4b). The relative use of N by VRNF treatments compared to the URNF treatment can be analysed by calculating the % of per field recommended N rate in VRNF divided by that of URNF (Table 2). Higher values mean that more fertilizer was used. The relative N use can go over 100%, if the VRNF is larger than that of the URNF. It can be observed that RHS consumed 16.4-118.1% less N fertilizer than the KS and 33.3-56.2% than URNF treatment. As explained before, all the RHS scenarios under-applied N rate compared to the URNF treatment, except in two cases in the Gimgelomse field (Table 2). Additionally, in the KS, the application rates were lower than those of URNF in two cases (e.g., MB and SB with N limit) only the Gimgelomse field (Table 2). The KS consumes more fertilizer than the RHS for both imposing or ignoring the N limits. The KS with the limits, led to increases in N recommended over the URNF treatment for MB, SB and MSB in Kouter; for MSB in Fabrieke; for MB in Beers and never in Gimgelomse. This means if VRNF treatments are implemented without imposing the legislative N limits, KS will always result in over application compared to the URNF, a result which is supported by the finding of Guerrero et al. (2021b). The RHS will be always an environmentally friendly treatment, as it will result in reducing the amount of N applied per field with or without imposing the legislative N limits.

Table 2. Comparison of % relative fertilizer use by different variable rate nitrogen fertilization (VRNF) treatments and schemes, compared to the uniform rate (URNF) application.

	Robin Hood Scheme - No N Limit	**Robin Hood Scheme - N Limit**	**Kings Scheme - No N Limit**	**Kings Scheme - N Limit**
Map-based (MB)	66.7%	56.3%	142.9%	72.7%
Sensor-based (SB)	46.7%	43.8%	157.1%	90.9%
Map-sensor-based (MSB)	53.3%	50.0%	171.4%	100.0%
Uniform rate (URNF)	100.0%	100.0%	100.0%	100.0%

3.2.3. Effect of variable rate machinery

Recommendation maps for RHS developed for a full boom application (33 m in Kouter and Gimgelomse and 39 m in Beers and Fabrieke), section control (3 m) and nozzle control (0.5 m), are presented in Figure 5. It can be observed that the resolution in application between section (3 m) and nozzle (0.5 m) control are not significant (Figure 5), and these are of much finer resolution than that of the full boom control. It is noteworthy that in SB there are no spraying pattern differences, particularly in Kouter and to a smaller extend in Beers. This can be attributed to the spatial resolution of the NDVI obtained from satellite imagery (10 m by 10 m), which turned out to be larger than the width of the spray boom. Nevertheless, in Fabrieke and Gimgelomse, there are clear differences in SB applications between the three control options. It can be observed that the lapse between two successive rates is highly visible in the recommendation maps. During these laps the crop will not receive the accurate dose of N, which is a limiting factor with large negative effects for the full boom control option, as larger area will be receiving the incorrect amount of N fertilizer compared to the nozzle and section control options. This might lead to over- or under-application and possible agronomic and environmental negative consequences. Nevertheless, the simulation results show that MSB and MB can be implemented in variable rate machinery and that it will match the detailed spatial variability of soil and crop parameters by using section and nozzle control which will guarantee high precision spraying.

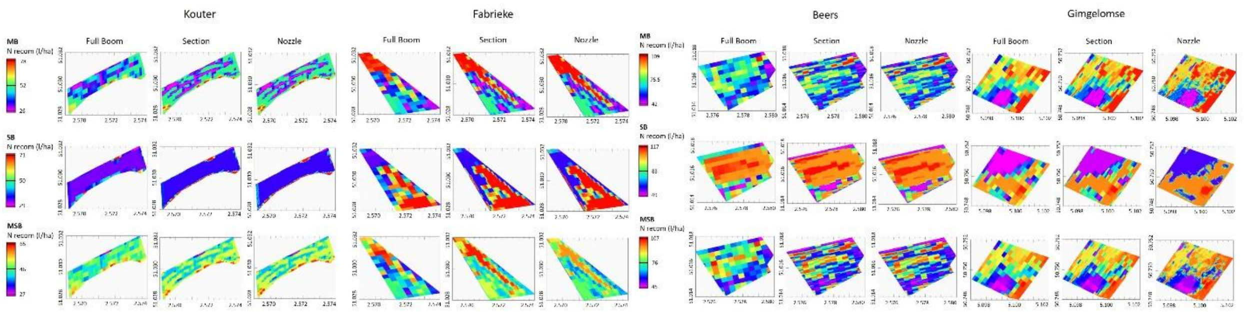

Figure 5. Comparison of Robin Hood scheme with nitrogen limit of variable rate nitrogen fertilization patterns between sprayer three control options demonstrated for the four different fields and variable-rate treatments of MB: Map-based treatment, SB: Sensor-based treatment and MSB: Map-sensor-based treatment. N recom: Nitrogen recommendation.

4. Conclusions

A new software to simulate VRNF under different variable rate scenarios, treatments and spray boom control width was established and used to set the optimal solution from the environmental, economic, and technical points of view. The simulation was carried out using soil and crop data collected at high sampling resolution from four commercial wheat and barley fields. Simulations were also done for the cases of imposing and neglecting the legislative N limit. Results allowed the following conclusions to be drawn: 1) Both VRNF schemes consume less amount of N if the legislative N limit is imposed, with KS consumes consuming more fertilizer than RHS. If the limit is not considered, the fertilizer use in general was higher with KS than with both RHS and URNF. The N limit should be imposed in all scenarios of KS treatment to prevent over-application of N with potential negative environmental consequences. Although in RHS it is not necessary to impose the legislative N limit, as the field VRNF used less N than the recommended URNF in the top majority of cases, it is recommended to impose them to eliminate any risk of over-application of N above the legislative limits. 2) Spatial variability was optimally managed by the MB treatment, temporal variability by the SB treatment and both variabilities by the MSB treatment. 3) Both the section and nozzle control provided similar spatial resolution of N recommendation maps, while using the full boom control was of poor resolution. 4) The combination of RHS (with or without N limit) with section control is the best VRNF solution, as it minimizes the use of N and subsequently environmental impacts, while maximizing precision of application to best manage within-field variability. Future study should validate the proposed optimal solution under field experimental conditions to allow the evaluation of the crop responses. This will be necessary for full economic, agronomic and environmental evaluation of the VRNF. Development in the hardware and software might be necessary to minimize the lapse time between each pair of successive recommendation rates.

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References

Amaral, L.R., Trevisan, R.G., and Molin, J.P. (2017). Canopy sensor placement for variable-rate nitrogen application in sugarcane fields. Precis. Agric. 1–14.

Basso, B., Dumont, B., Cammarano, D., Pezzuolo, A., Marinello, F., and Sartori, L. (2016a). Environmental and economic benefits of variable rate nitrogen fertilization in a nitrate vulnerable zone. Sci. Total Environ. 545–546, 227–235.

Basso, B., Fiorentino, C., Cammarano, D., and Schulthess, U. (2016b). Variable rate nitrogen fertilizer response in wheat using remote sensing. Precis. Agric. 17, 168–182.

Basso, B., Dumont, B., Cammarano, D., Pezzuolo, A., Marinello, F., and Sartori, L. (2016c). Environmental and economic benefits of variable rate nitrogen fertilization in a nitrate vulnerable zone. Sci. Total Environ. 545–546, 227–235.

Boyer, C.N., Wade Brorsen, B., Solie, J.B., and Raun, W.R. (2011). Profitability of variable rate nitrogen application in wheat production. Precis. Agric. 12, 473–487.

Chattha, H.S., Zaman, Q.U., Chang, Y.K., Read, S., Schumann, A.W., Brewster, G.R., and Farooque, A.A. (2014). Variable rate spreader for real-time spot-application of granular fertilizer in wild blueberry. Comput. Electron. Agric. 100, 70–78.

Colaço, A.F., and Molin, J.P. (2017). Variable rate fertilization in citrus: a long term study. Precis. Agric. 18, 169–191.

Van Grinsven, H.J.M., Tiktak, A., and Rougoor, C.W. (2016). Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. NJAS - Wageningen J. Life Sci. 78, 69–84.

Grisso, R.B., Alley, M., Thomason, W., Holshouser, D., and Roberson, G. (2011). Precision Farming Tools : Variable-Rate Application. Virginia Coop. Ext. 1–16.

Guerrero, A., De Neve, S., and Mouazen, A.M. (2021a). Current sensor technologies for in situ and on-line measurement of soil nitrogen for variable rate fertilization – A review. Adv. Agron.

Guerrero, A., Neve, S. De, and Mouazen, A.M. (2021b). Data fusion approach for map-based variable-rate nitrogen fertilization in barley and wheat. Soil Tillage Res. 205, 104789.

Hassan, M.A., Yang, M., Rasheed, A., Yang, G., Reynolds, M., Xia, X., Xiao, Y., and He, Z. (2019). A rapid monitoring of NDVI across the wheat growth cycle for grain yield prediction using a multi-spectral UAV platform. Plant Sci. 282, 95–103.

Havlin, J.L., and Heiniger, R.W. (2009). A variable-rate decision support tool. Precis. Agric. 10, 356–369.

Kitchen, N.R., Sudduth, K.A., Drummond, S.T., Scharf, P.C., Palm, H.L., Roberts, D.F., and Vories, E.D. (2010). Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. Agron. J. 102, 71–84.

Koch, B., Khosla, R., Frasier, W.M., Westfall, D.G., and Inman, D. (2004). Economic Feasibility of Variable-Rate Nitrogen Application Utilizing Site-Speicific Management Zones. Agron. J. 96, 1572–1580.

Kuang, B., and Mouazen, A.M. (2011). Calibration of visible and near infrared spectroscopy for soil analysis at the field scale on three European farms. Eur. J. Soil Sci. 62, 629–636.

Link, J., Graeff, S., Batchelor, W.D., and Claupein, W. (2006). Evaluating the economic and environmental impact of environmental compensation payment policy under uniform and variable-rate nitrogen management. Agric. Syst. 91, 135–153.

Mouazen, A.M. (2006). Soil Survey Device. International publication published under the patent cooperation treaty (PCT). World Intellectual Property Organization, International Bureau. International Publication Number: WO2006/015463; PCT/BE2005/000129; IPC: G01N21/00; G01N21/0.

Nawar, S., Corstanje, R., Halcro, G., Mulla, D., and Mouazen, A.M. (2017). Delineation of Soil Management Zones for Variable-Rate Fertilization: A Review.

Pantazi, X.E., Moshou, D., Mouazen, A.M., Alexandridis, T., and Kuang, B. (2015). Data fusion of proximal soil sensing and remote crop sensing for the delineation of management zones in arable crop precision farming. CEUR Workshop Proc. 1498, 765–776.

Shaddad, S.M., Madrau, S., Castrignanò, A., and Mouazen, A.M. (2016). Data fusion techniques for delineation of site-specific management zones in a field in UK. Precis. Agric. 17, 200–217.

Srinivasan, A. (2007). Handbook of precision agriculture: Principles and applications. Euphytica.

Stevens, A., and Ramirez Lopez, L. (2014). An introduction to the prospectr package. 1–22.

Vlaamse Landmaatschappij (2019a). Overzicht wijzigingen MAP 6.

Vlaamse Landmaatschappij (2019b). 6de actieprogramma in uitvoering van de nitraatrichtlijn 2019-2022.

Vlaamse Landmaatschappij (2020). Normen en richtwaarden 2020. 1–19.