A low cost approach for site-specific nitrogen application : a use case in viticulture

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Abstract

This paper proposes a low-cost approach for site-specific nitrogen application based on tractor speed variation, which is designed specifically for small-scale farms in viticulture with limited investment capacities. It first describes how to design prescription maps using the spatialized data available on the farm. Then the article proposes a method to operate fertilization using existing equipment and the farmer's personal smartphone. Driver's compliance with speed prescriptions during fertilization have been monitored with a tracking system based on a dual frequency GNSS device, in order to validate the applicability of this low-cost approach. The approach was implemented across all 51 Fields of the vineyard during the 2024 growing season to assess its effectiveness. Results show that the driver was able to apply speed prescriptions.

Keywords: low cost, variable rate, nitrogen application, fertilization, GNSS, viticulture

Introduction

Nitrogen Variable Rate Application (VRA) can reduce input costs while mitigating negative impacts on water quality and greenhouse gas emissions (Guerrero and al, 2021). Although nitrogen VRA offers a particularly promising avenue for improving nitrogen use efficiency, studies examining the adoption of precision agriculture tools and methods indicate that the uptake of this practice remains low. Indeed, a recent study has shown that in France, only 10% of arable crops farms implement variable rate nitrogen application (Bellon-Maurel et al, 2023). While precise figures are unavailable, it is expected that the adoption rate is significantly lower, if not negligible, among smallholder farmers (Van Loon et al., 2018). This low adoption can be explained by the high cost and the technical complexity of purchasing adapted spreaders equipped with GNSS technology and the skills required to implement the entire chain (data processing, integration into the tractor console, adjustment of the appropriate spreader, etc.). Small-scale farms typically face significant challenges in adopting these techniques as they have limited resources.

Wine production in southern France is largely based on small-scale farms. Similar to large-scale crops, and despite the much lower nitrogen rates applied, research demonstrated the interest of nitrogen VRA in viticulture. Indeed, it effectively reduced variability in vine vigor, canopy density, and grape composition over time (Gatti et al., 2018; Gatti et al., 2019) showing the potential of VRA to improve nitrogen efficiency for this crop. This observation underscores the potential benefits, as well as the difficulties associated with the adoption of nitrogen VRA in vineyards undergoing economical constraints. Indeed, to be implemented and adopted in small-scale viticulture, it is essential that it relies on simple, affordable, and user-friendly tools that can be retrofitted to existing equipment, thus avoiding the need for significant financial (new machinery) and human capital investment.

Apart from a few very specific developments aimed at providing low-cost retrofit kits (Van Loon et al., 2018), there are, to the authors' knowledge, very few simple and

inexpensive devices available for implementing VRA in small-scale agriculture. One simple way to adjust fertilizer application using existing farm equipment is to vary the tractor speed while keeping the spreader settings the same. Changing the speed will change the amount of fertilizer applied per unit area which is a simple method for implementing VRA. Nevertheless, its application, especially in small-scale viticulture, poses several challenges. Key questions include: i) what is the practical limit on the number of different speeds (corresponding to different fertilization rates) that can be effectively managed by the tractor driver? ii) what data should be used and how should prescription maps be generated? iii) how can clear and concise instructions be provided to the tractor driver to ensure accurate implementation of the variable speed application? iv) how to ensure/verify that the speed prescriptions are actually properly applied by the tractor driver. This paper aims to address these questions by proposing tools and experimental design to be tested on a whole vineyard estate. The device is designed to be simple and cost-effective, and it will be used to modulate nitrogen application by varying tractor speed.

Materials and methods

The proposed method breaks down into four stages: i) formalization of the agronomic reasoning for fertilization to define fertilization rules based on available data and operational constraints; ii) creation of speed prescription maps based on the previous year's yield (2023), vigor maps of the year (2023) and the expertise of the farm manager; iii) concrete application of the speed prescription maps by the tractor operator in the plots, and iv) analysis to check the compliance of speeds actually applied with the initial prescriptions.

Experimental site and data available

The study took place in a vineyard estate located in the south of France, near Montpellier (Villeneuve-lès-Maguelone, WGS84—43.532300° N, 3.864230° E). The area of the vineyard estate is 30 ha organized into 51 different blocks. A block refers to a section of the vineyard with uniform grape variety, rootstock, training system, same date of plantation, etc. A block commonly corresponds to a management unit.
On each plot, yield was precisely measured using a low-cost and retrofit approach as described by Gras et al., 2024. In short, Gras et al. (2024)’s approach involved achieving complete traceability of harvest operations (grape harvester and trailers) through GNSS tracking devices, which allowed the consolidation of parameters such as the harvest weight measured at the winery, linked to geolocation down to an intra-plot level. The process requires minimal investment and leverages the vineyard's existing harvest organization, ensuring the method's applicability. However, the spatial resolution remains relatively low, as it is determined by the maximum capacity of the tanks used to transport the grapes. The yield mapping method used allows for the identification of within field zones of approximately 0.3 hectares (Gras et al., 2024), which can be useful for considering potential variable rate fertilization.
Other available data include vine vigor map in 2023, determined using remote sensing imagery (Oenoview, ICV, France). For several years, the estate manager has been applying uniform nitrogen fertilization across all plots. This nitrogen fertilization aims to offset nitrogen removal from the harvest. In 2023, the average yield was 5 t/ha, which required a nitrogen fertilization rate of 45 units of nitrogen per hectare across the whole estate to be applied.

Agronomic Reasoning For Fertilization

In 2024, based on yield and vigor maps, the estate manager decided to revise the nitrogen fertilization strategy. It was managed in two applications: a uniform organic fertilization of 15 units of nitrogen applied during the winter of 2024, followed by a mineral nitrogen fertilization targeting the remaining 30 units of nitrogen, applied in a site-specific manner during spring 2024. Under the conditions of this study, the estate manager's objective was to restore the exported nitrogen. The estate manager determined that, overall, the plots were well-balanced in terms of grape production and vine vigor. However, this does not exclude the possibility that, under different conditions, the objectives of nitrogen VRA could vary particularly by placing greater emphasis on vine vigor to correct imbalances, such as excessive or insufficient growth in specific areas.

To better tailor the fertilization to the specific needs of each plot while considering technical constraints, it was decided to limit nitrogen variation rate to three distinct rates. This decision, made in consultation with the vineyard manager and the tractor driver, represented a balance between the desired agronomic precision and the technical capabilities of the agricultural equipment. Variable rate fertilization was based on tractor speed adjustments, and overly frequent changes would have significantly complicated operations and potentially compromised the quality of fertilizer application. As a result, three levels of nitrogen rate were defined:

- **When yield was close to the estate's average yield**, i.e., 50 hl/ha (+/- 30%), the target was maintained at 30 units of nitrogen per hectare, applied at the tractor's standard working speed of 7.5 km/h.
- **When yield was significantly below the average yield** (<30%), the target was reduced by 30%, to 20 units of nitrogen per hectare. To apply this dose, the tractor's working speed was increased by 30%, to 10 km/h.
- **When yield was significantly above the average yield** (>30%), the target was increased by 30%, to 40 units of nitrogen per hectare. For this dose, the tractor's working speed was reduced by 30%, to 5 km/h.

Creation of prescription maps

The recommendation maps were created using QGIS software (https://www.qgis.org/) through several steps:

i) **Application of fertilization rules** to zones derived from yield maps using QGIS. By comparing each zone’s yield to the estate's average yield, a nitrogen application recommendation was assigned to each yield zone based on the previously defined rules.
ii) **Adjustment of the prescription map based on field information.** Although the mapping method used to provide yield maps was simple, cost-effective, and easily deployable (Gras et al., 2024), it presents a strong limitation as it cannot account for yield variability along vine row directions. Consequently, the recommendation maps were corrected by the vineyard manager using field knowledge and a vigor map provided by the remote sensing Oenoview® service. The vineyard manager adjusted the initial zones to better account for the variability observed in the field or through vine vigor maps. It should be noted that these corrections were limited to a small number of zones where yield maps were inconsistent with the vineyard manager's knowledge or where vigor maps highlighted a significant change in vigor perpendicular to the vine rows direction.

iii) **Modification of recommendation zones in QGIS** to incorporate the manager's adjustments. At this stage, nitrogen recommendations were converted into speed recommendations based on the previously defined rules.

iv) **Validation of nitrogen and speed prescription maps** with the vineyard manager and the tractor operator responsible for fertilization.

v) **Export of fertilization prescriptions** for the tractor's onboard device. The prescription maps were exported in shapefile format, with each zone represented by a polygon attributed to the corresponding speed recommendation for that zone.

Use of a smartphone application for site-specific fertilization.
The choice of a terminal and associated software to display working speed prescriptions to the driver was based on the following specifications: a) allow maps to be loaded (shape files generated in QGIS), b) easy-to-use application to be installed on the driver's smartphone c) display of the various information required for operation, such as current speed, geolocalization in the plot, speed prescribed and distance to next speed change, and d) limited cost of use. It should be noted that this application is only a support to visualizing the prescriptions, as the tractor driver manually manages his tractor's forward speed.
Several services have been examined to address this need: Mergin maps (London, UK), Vineview (Halifax, Canada), Topcon (Tokyo, Japan), etc. A call to the international precision farming community failed to identify any other solutions that met our specifications.
The Vineview company was chosen because a) it met all the required criteria, b) cost was limited to 280€/year for a vineyard of 10 to 50 ha. It should be noted, however, that the loading of the prescription maps (.shp file containing polygons with speed prescriptions) into the web platform was forced by the customer advisor. Once the maps are loaded, the speed prescriptions are displayed in real time on the smartphone application (as described in the results section).

Validation method of site-specific fertilization application.
Validation of the approach consisted in verifying that the speed variation was realistic and effectively applicable to the entire vineyard (51 plots), and that the information given to the tractor was sufficiently relevant and precise to enable speed changes in line with the instructions. These two aspects were validated by measuring the tractor's actual speed during the work. The tractor was therefore equipped with a dual-frequency GNSS geolocation tracking device (Samsys, Lille, France). This sensor recorded the tractor's location, time and exact speed every second throughout the fertilization operation. At the end, the data was downloaded via the solution's API (Application Programming Interface) and uploaded into the QGIS project for spatial analysis.
Average speed calculations were performed based on the recorded dated locations. In order to eliminate speed change phases corresponding to plot entrances and exits, as well as intra-plot zone changes, an internal buffer of 5m was implemented around each zone . For each management zone, it was then possible to compare the actual average speed with the target speed.

Results

Three classes of speed prescriptions were defined (5, 7.5 and 10 km/h) for all the plots on the estate, each corresponding to a recommended nitrogen dose. Figure 1D shows the

example of three plots covering a surface area of 3.72 ha, with different colors corresponding to level of speed prescriptions: red 5 km/h, blue 7.5 km/h, green 10 km/h. This prescription map results from the methodology described in the material and method section which takes into account vine 2023 vigor (Figure 1B) and map of vine 2023 yield (Figure 1C). Given the resolution of the initial data and the constraints set by the tractor operator in terms of speed changes, the variable rate zones are large (of the order of 0.3 ha to 1 ha). The majority of zones correspond to entire rows, which is logical given the resolution of the observation sources used to design the maps. However, figure 1D presents an exception on the south-western part of the plot. At this point, a change in speed takes place along the row (the direction of the rows can be seen in the image in figure 1A).

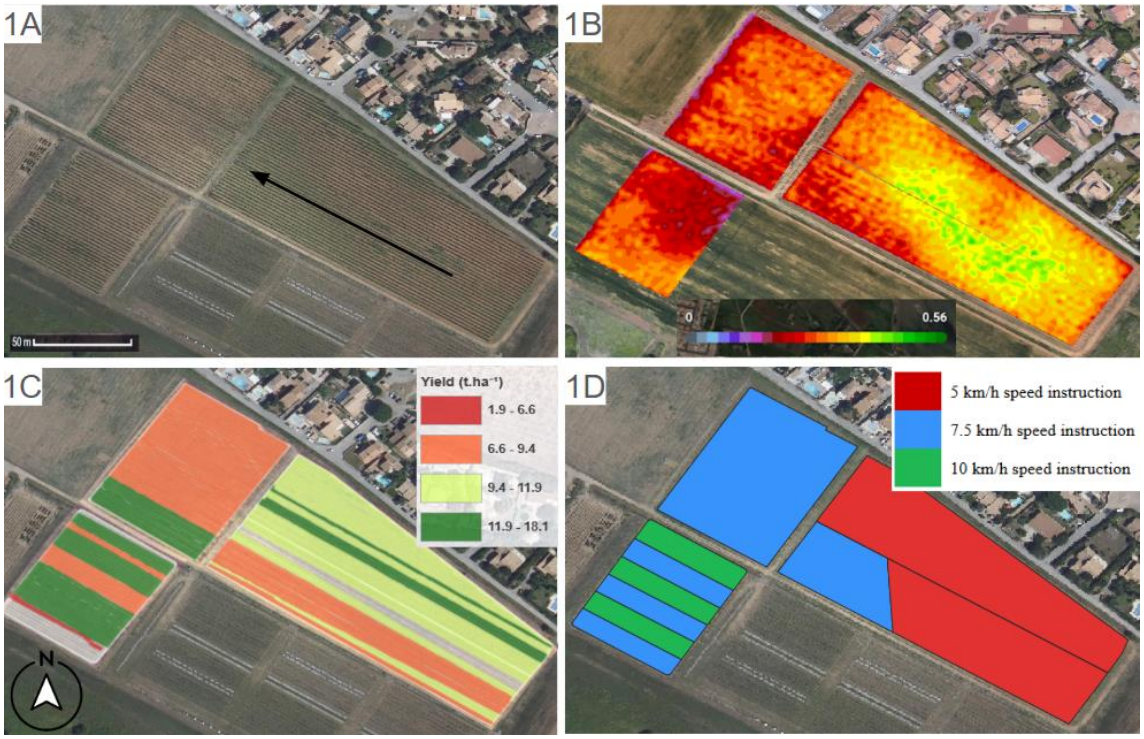
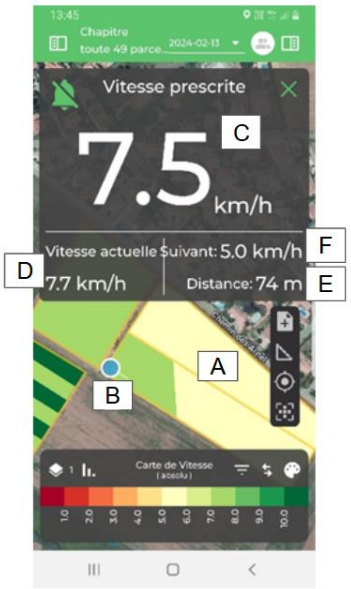


Figure 1. Cluster of several blocks illustrating the different steps involved in creating a nitrogen (tractor speed) prescription maps, with a) image of the block showing the direction of the rows b) vigor map of year 2023 showing very vigorous zones in green and low vigour zones in red (source Oenoview 2023) c) low resolution yield maps 2023 (t/ha) and d) speed prescription map for three plots of the estate. Photo background : IGN - Photothèque Nationale - 2021

These choices are justified by the high spatial variability in vigor observed along the vine rows. Indeed, Figure 1B clearly shows this south-western zone marked by lower vigor. In order to gain precision, the estate manager decided to take this zone of lower vigor into account by lowering the nitrogen input over this zone. This results in a change of nitrogen rate application by changing the speed along the row. Compared to nitrogen recommendation maps typically used in large-scale crop production with geo-referenced and automated fertilizer spreaders, the recommendation map as presented in Figure 2 may appear simple. However, it should be noted that management zones remain relatively small throughout the vineyard (approximately 0.3 ha). Moreover, to ensure the success of the initial implementation across the entire domain, it was necessary to convince the

tractor driver and to avoid significantly increasing the difficulty of his work or slowing him down during operations. In this context, it was sometimes decided to limit speed changes along the rows or even to simplify the recommendation map to ensure it was applicable for the tractor driver.
Vineview application (Figure 2) is installed on a smartphone placed in the tractor cabin. During the fertilization operation, the application helps the driver to correctly follow the speed prescriptions, ensuring changes in the applied fertilizer dose and thus enabling variable rate fertilization.



Lexical

Vitesse prescrite: speed set
Vitesse actuelle: actual speed
Suivant: next
Distance: distance
Carte de vitesse: speed prescription map

Figure 2. Screenshot of the smartphone application displaying at work, a) the speed prescription map, b) the tractor's position on the map, c) the prescripted speed for the zone where the tractor is located on, d) the tractor's actual speed measured by the smartphone's GNSS receiver, e) the distance to the next speed change zone, f) the speed to be applied in the next zone.

One of the key benefits of the application is the display of the distance to the next speed change zone along with the speed to be applied there. This feature allows the driver to better anticipate speed changes, facilitating optimal speed adjustment between the different zones of the field.
Other useful information is provided to the tractor driver to ensure an efficient operation: the different map zones (1A), the real-time position of the tractor (1B), the prescribed speed at a given moment (1C), the current actual speed (1D), the distance to the next zone change (1E), and the next prescribed speed (1F).



Figure 3. Example of the geolocated path of the tractor during the fertilization operation on three plots of the estate. In (a), the different zones are shown, each with an associated speed prescription. In (b), the geolocated points represent the tractor's path, with the corresponding speed class displayed.

Figure 3 shows how the driver applied the speed guidelines on the same group of three fields as already shown in Figure 1 and Figure 2. It shows that, apart from the maneuvering areas at the ends of the rows of the fields where the observed speeds were low (< 3 km/h) and apart from the road traffic where the speed was higher (> 11 km/h), the tractor driver applied the prescripted speeds, thus demonstrating the relevance of the application and the proposed approach to consider site specific nitrogen application. In order to assess the applicability of this approach to all 51 plots on the estate, the measured speeds were collected for each prescription zone (Figure 4).

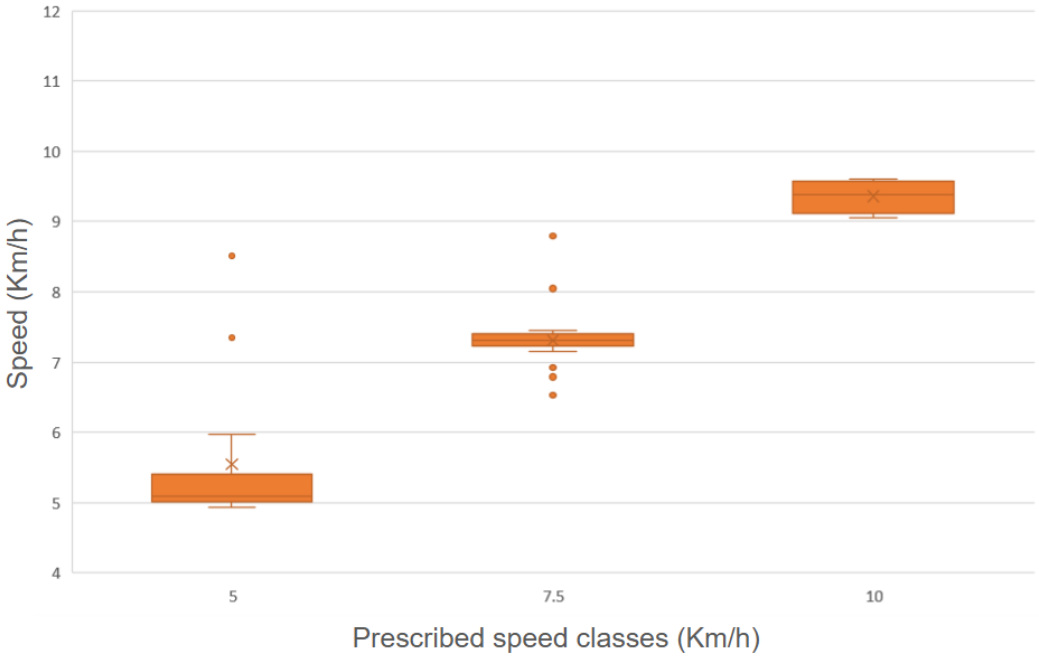


Figure 4. Boxplots showing the distribution of average speeds recorded by prescribed zones during the application. All zones of the 51 fields estate are considered.

The analysis reveals that, on average, the speed prescriptions were followed for the 5, 7.5, and 10 km/h speed classes, taking into account a tolerance of 1.25 km/h around the threshold. These results demonstrate that this approach is realistic for tractor drivers at the whole estate level. It demonstrates that it is possible to implement variable-rate fertilization across an entire vineyard by adjusting tractor speed. However, the average actual speeds recorded for the zones with prescriptions of 7.5 and 10 km/h were all below the target speed, with averages of 7.2 and 9.3 km/h, respectively. The observed differences are due to practical considerations made by the driver when selecting engine speed and tractor gear ratio to optimize the performance of the tractor and the towed spreader. These practical considerations were not fully accounted for during the initial definition of application speeds. Consequently, application rates were slightly higher (lower speeds) than intended, regardless of whether the zones were designated for 10 km/h or 7.5 km/h speeds.

Conclusions

The study demonstrates that variable rate fertilization can be implemented at an intra-plot level using a low-cost approach for small-scale viticulture. The method for variable rate fertilization through speed using a standard spreader and a smartphone application in the tractor cabin to assist the tractor driver by displaying speed instructions was shown to be relevant. The results show that the prescribed instructions were generally followed during the operation. However, the creation of speed prescription maps requires, on one hand, spatially referenced data such as yield and vigor maps and and on the other hand, data processing skills to create prescription maps. Above all, practical issues related to engine speed and tractor gear ratio have to be accounted for to define relevant speed maps. The main limitation of this approach is that, from a practical standpoint, it is difficult to

consider more than three nitrogen application rates, which limits the precision of the method.

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