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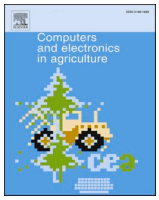

Cost-benefit evaluation of preventive site-specific fungicide spraying for fusarium head blight in wheat

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ABSTRACT

Fusarium head blight (FHB) is a major wheat disease that reduces yield and grain quality. While fungicide application is a key control strategy, conventional uniform-rate (UR) spraying often fails to account for spatial variability in disease risk, leading to inefficiencies, and extra cost. This study evaluates the economic impact of preventive site-specific spraying (PSSS) based on FHB forecasts in three winter wheat fields in Lithuania. A data fusion-based approach was employed to forecast FHB spread and develop recommendations for PSSS, integrating satellite crop data and soil properties. FHB prediction maps were categorized into five management zones (low to high risk), which were used to compare variable-rate (VR) fungicide treatments with conventional UR spraying. Yield data were recorded post-harvest using a combine harvester equipped with a yield sensor. Results indicated that doses of 300, 100, and 120 L ha^{-1} were not recommended due to negative residual effect of crop health, which resulted in lower yields compared to other doses. An increase of 93.12–94.93 € ha^{-1} in gross margin was observed with PSSS compared to UR treatments. However, one field exhibited a loss of 34.20 € ha^{-1}, which was attributed to the very low and high doses (100 and 300 L ha^{-1}, respectively), resulting in significantly lower yields compared to that of UR. These findings suggest that PSSS can be a profitable approach over UR, provided that appropriate fungicide doses are used, avoiding very low and very high doses (e.g., 100 and 300 L ha^{-1}).

1. Introduction

The global demand for wheat (*Triticum aestivum* L.), a staple food crop, emphasizes the importance of maximizing yield and quality (Igrejas and Branlard, 2020). However, wheat production is frequently threatened by several fungal diseases. Fusarium head blight (FHB), a destructive fungal disease primarily caused by *Fusarium graminearum* and other *Fusarium* species, poses a significant threat to wheat production worldwide (Shude et al., 2020). This devastating fungal disease not only reduces yield and quality but also produces mycotoxins, such as deoxynivalenol (DON), posing serious health risks to humans and animals alike (Desjardins, 2006; Meng et al., 2023). As such, effective management strategies are essential to mitigate the economic and health impacts associated with FHB, which is one way to support food security sustainably.

Fungicide application is a cornerstone of FHB management, offering growers a critical tool to suppress fungal growth and reduce mycotoxin contamination in wheat (Meng et al., 2023). Traditionally, fungicides are applied uniformly across entire fields at a fixed rate, regardless of spatio-temporal variations in disease pressure or crop health. While this approach has provided some level of control, it often results in inefficiencies, as it fails to account for the spatial and temporal variability

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inherent in FHB occurrence within fields. Moreover, overreliance on uniform applications can lead to unnecessary fungicide use, increased production costs, and environmental concerns associated with pesticide runoff and resistance development (Dammer, 2010). This is the reason why there is a need for an alternative technological solution that can ensure overcoming these shortcomings in FHB disease control. The spread of fungal diseases, such as FHB, is significantly influenced by soil and crop characteristics, including biomass and surface area (Ekwomadu and Mwanza, 2023). More specifically, denser canopies and poor soil conditions tend to foster a higher incidence of these diseases. This is attributed to the high-density canopy initiated high humidity and warmer micro-environment, which are optimal conditions for the spread of fungal diseases. Therefore, it is crucial to take these factors into account when applying agrochemicals for disease control.

Advanced sensing technologies, such as hyperspectral imaging (HSI), have been used to predict the spatial variability of FHB across fields, with many studies reporting that FHB severity varies significantly within fields (Almoujahed et al., 2025, 2022; Whetton et al., 2018b). This variability is crucial for optimizing fungicide application, as targeting high-severity zones with appropriate fungicide rates can enhance the overall efficacy of FHB management. Adjusting the fungicide application rate based on specific crop parameters – such as plant surface area, leaf area index (LAI), and biomass – measured in each region of a field can lead to more effective disease management (Dammer et al., 2009). For instance, regions with lower biomass and fertile soil conditions may require less fungicide, while areas with denser vegetation and poorer soil may necessitate a higher dosage. This approach may not only ensure optimal disease control but also minimize the amount of unused fungicide that reaches the ground, thereby reducing environmental impact (Khan et al., 2023; Meena et al., 2020). Finding the optimal crop and soil parameters in the calculation of recommendation rate for fungicide application is a point for research, that started already many years ago and continues to be the case in today's farming.

Variable rate (VR) fungicide relies on spatial variability in disease pressure, crop health, and environmental factors for the calculation and application of varying fungicide rates across different zones of a field. This precision approach enables growers to optimize fungicide efficacy, minimize input costs, and reduce environmental impacts associated with excessive chemical use (Dammer, 2010). Moreover, VR holds the potential to improve the overall farm profitability by maximizing yields and enhancing grain quality, thus bolstering the sustainability of wheat production systems (He, 2022). A recent review highlighted the transformative potential of unmanned aerial spraying systems (UASS) integrated with VR spraying technologies to minimize ecological harm from pesticide overuse while maintaining yield. This approach reduces agrochemical overuse by up to 30 %, minimizes environmental impact, and enhances resource efficiency while improving yield outcomes through targeted interventions. Furthermore, UASS-based VRS fosters a transformative agricultural model where sustainability, productivity, and technological progress converge. The review highlighted the advantages of VR spraying as a critical shift toward precision, adaptability, and global sustainability goals (Taseer and Han, 2024). The spatial distribution of plant leaf surface measured by the CROP-Meter sensor, was utilized to apply VR fungicides in real-time on cereals, resulting in an average fungicide saving of 22 % (Dammer and Ehlert, 2006). Another study utilized crop biomass as a key factor adopted for the implementation of real-time VR spraying through camera-sensor measurements for LAI/biomass. This data was then sent to the sprayer to adjust doses based on crop density. This method achieved fungicide savings of up to 45 %, compared to uniform rate (UR) spraying (Tackenberg et al., 2018). Furthermore, another investigation demonstrated that VR spraying technology based on real-time sensors can significantly reduce pesticide use in soybean and maize cultivation without compromising crop yield. This technology, which controls spraying nozzle-by-nozzle, led to a 56.16 % reduction in pesticide application costs by targeting only areas where plant presence was detected. This reduction was especially pronounced during the early growth stages when foliage coverage was limited. Importantly, crop yields remained consistent with historical averages, indicating that this precision method is both economically and environmentally advantageous (Zanin et al., 2022). It is important to note that these studies primarily focused on the environmental benefits of the technology, such as reducing chemical use, which is certainly crucial. Nevertheless, they did not consider the potential economic advantages for farmers, which are equally important for encouraging widespread adoption. While reducing fungicide usage contributes to environmental sustainability, assessing the economic benefits, such as potential cost savings, return on investment, or improvements in crop yield could further incentivize farmers to adopt this technology.

A simulation study conducted in the UK evaluated the economic viability of VR fungicide spraying for FHB management in winter wheat. The cons-benefit analysis concerned the estimation of the gross margin not only for VR but also for selective harvest (SH), by which wheat grain can be separated into different consuming categories based on disease level. The researchers considered NDVI, LAI, FHB, temperature, and humidity along with soil properties, in a k-means cluster analysis to divide the field into different management zone (MZ) classes, for each of which a different fungicide rate was proposed. The study found that VR allowed for fungicide reductions of 22.24–25.93 %, compared to UR fungicide application. The gross profit of combining SH and VR was 83.35 £ ha^{-1} (96.69 € ha^{-1}) per year, with a total net profit considering the data acquisition costs of 66.85 £ ha^{-1} (77.55 € ha^{-1}) per year (Whetton et al., 2018a). This demonstrates the potential for fungicide reductions and economic viability of the MZ concept in VR, despite this being a simulation work, in which no validation data was provided. Furthermore, the simulation results of Whetton et al. (2018a) were based on measured FHB using a hyperspectral camera during the anthesis stage, which is too late to implement VR in practice. Therefore, there is a need for an economic analysis of VR, whose recommendation rates are calculated based on the forecast of FHB spatial distribution early in the cropping season.

Despite the significant advantages of VR, research on VR fungicide treatments remains limited. Most studies have focused on optimal fungicide application timing and the effectiveness of various fungicides in controlling FHB and reducing DON contamination (D'Angelo et al., 2014; González-Domínguez et al., 2021; Mesterházy et al., 2011). This gap in the literature highlights the need for further research in this area to fully understand the potential benefits and trade-offs of such an advanced smart farming approach. To the best of our knowledge, there are no studies to date exploring how FHB forecast models could be applied to optimize VR for FHB control. This study aims to evaluate the agronomic and economic benefits of preventive site-specific spraying (PSSS), a VR fungicide application strategy, in comparison with conventional UR treatment for managing FHB in wheat. To achieve this, the research integrates a data fusion modelling approach that combines satellite-derived crop data and proximally measured soil properties to generate FHB risk maps, which are used to guide spatially targeted fungicide applications. The economic evaluation is based on gross margin analysis, enabling comparison of cost-effectiveness across treatments. Additionally, the study seeks to identify optimal fungicide dose ranges within the PSSS framework that maximize yield and improve economic return.

2. Materials and methods

2.1. Experimental sites

The study was carried out in the 2022–2023 cropping season in three commercial fields with winter wheat (*Triticum aestivum* L.) located in Kaunas, Lithuania (Fig. 1). The study sites are located in areas with an average temperature of 22 °C, and rainfall of 80 mm during the milking stage of wheat growth (May to July), which is considered the most

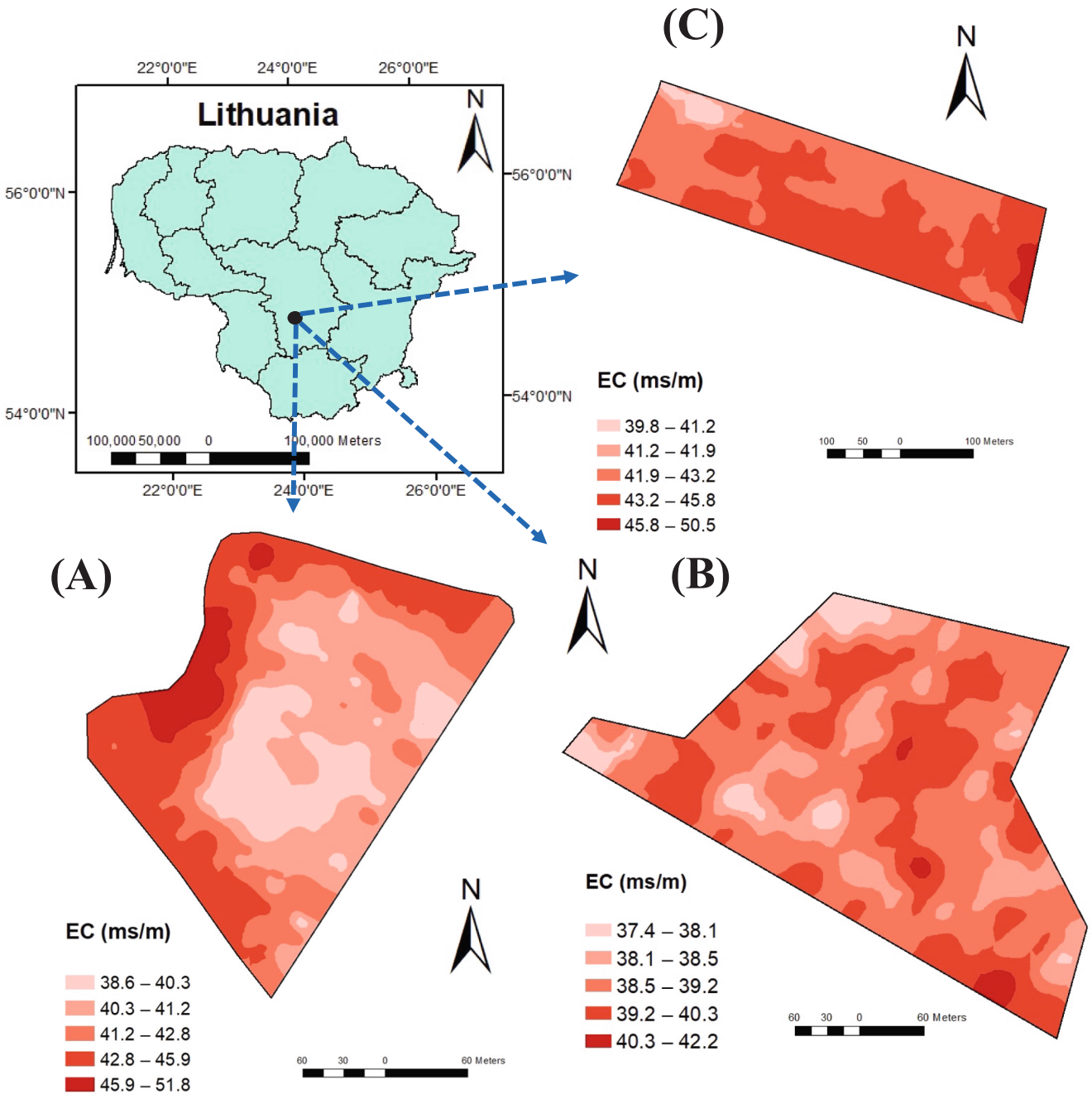

Fig. 1. Apparent electrical conductivity (ECa) maps and the locations of the study fields, in Kaunas, Lithuania. A: Field 1 (5.6 ha); B: Field 2 (7.8 ha); C: Field 3 (9.4 ha).

sensitive stage for fungus disease infection (Whetton et al., 2018b). The crop rotation of this work required to have winter wheat after winter wheat for all the sites.

2.2. Measurements of soil electrical conductivity

The apparent electrical conductivity (ECa) was measured using an EM38-MK2 conductivity scanner (Geonics Ltd.), following Kazlauskas et al. (2021) protocol. ECa measurements were saved as a CSV file using a Convert EM38-MK2 software, enabling the creation of an ECa map (Fig. 1) in ArcGIS (ESRI ArcGIS v10.7, Redlands, CA, USA). The map delineated five zones with distinct ECa levels, from which soil samples were taken, and key soil characteristics—such as texture, pH, levels of phosphorus (P), potassium (K), magnesium (Mg), and organic matter content—were analyzed.

2.3. Recommendation for preventive site-specific fungicide spraying (PSSS)

To optimize the control of FHB, a science-based calculation of recommendations for PSSS of fungicides is needed. For this, a data fusion-based approach was adopted to forecast FHB early in the cropping season, which integrated satellite data on crop growth characteristics (e.g., normalized difference vegetation index [NDVI], LAI and chlorophyll [Chl]) with soil properties (e.g., pH, Mg, and ECa) and microclimate conditions (e.g., relative humidity, and temperature) to generate precise forecasts of FHB spread (Morellos et al., 2025). The forecasting modelling compared three machine learning algorithms, namely, random

forests (RF), least squares support vector machines (LS-SVM), and multilayer perceptrons (MLP). Among them, MLP demonstrated the best results. The MLP architecture consisted of an input layer (number of neurons equal to the input features), two hidden layers with 64 and 32 neurons, respectively, and an output layer. The rectified linear unit (ReLU) activation function was applied to the hidden layers, while the output layer used a linear activation function for regression tasks. The model was trained using the Adam optimizer with a learning rate of 0.001 and a mean squared error (MSE) loss function. For validation, two distinct approaches were employed: (1) a cross-field validation (training on two fields and testing on the third) and (2) a field-specific validation (training and testing on subsets of the same field). The field-specific approach achieved superior performance, with MLP yielding R^2 values of up to 1.00 and residual prediction deviation (RPD) values of 25.63, alongside Kappa coefficient values of 0.91–0.97, indicating near-perfect agreement between predicted and observed FHB spatial distributions. The training data (70 % of the dataset) and validation data (30 %) were partitioned randomly within each field, ensuring spatial and temporal representativeness. The model was initially calibrated using data from three experimental winter wheat fields in Lithuania during the 2021–2022 season and validated across the same fields in the 2022–2023 season (Morellos et al., 2025). The results of the MPL forecasting model of FHB were used in this study.

To capture crop health and growth characteristics, high-resolution satellite imagery (3 m by 3 m) was acquired from RapidEye (https://www.planet.com) before fungicide treatment. Remote sensing parameters including NDVI, LAI, and Chl were derived from this imagery. NDVI was calculated on May 7, 2023, the day before spraying, to assess the crop condition and guide management decisions. The NDVI values were directly extracted from the satellite data, while LAI and Chl were estimated using empirical relationships based on NDVI. The satellite data served as the foundation for generating NDVI, calculated using equation (1) (Sellers, 1985):

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

where NIR is the near infrared band, and RED is the red band.

From the NDVI, the following empirical models were employed to estimate LAI and Chl. To derive empirical equations for LAI and Chl, we conducted calibration experiments using a CropCircle active sensor (Holland Scientific, Lincoln, NE, USA), which measures NDVI, LAI, and Chl directly. We scanned the winter wheat crop canopy in the previous cropping season (2022) and developed empirical correction equations. The resulting relationships were used to estimate LAI [mg/m^2] and Chl from NDVI, based on Equations (2) and (3):

$$LAI = 0.57*\exp(2.33*NDVI) \quad (2)$$

$$Chl = 2.92265*NDVI - 0.9149 \quad (3)$$

These remote sensing parameters (NDVI, LAI, Chl), along with the soil variables, were fed into the forecasting model (Morellos et al., 2025) to predict the distribution of FHB.

After the successful prediction of FHB using the forecasting model, the geotagged prediction dataset containing GPS coordinates was used for the development of FHB forecasted maps. High-resolution maps were created by first fitting a semi-variogram model to the FHB data, which describes the spatial correlation of FHB incidence across different distances. A spherical model was chosen for the semi-variogram due to its suitability for datasets with moderate spatial autocorrelation, where values become less similar with increasing distance up to a certain threshold (the range). In this model, spatial dependence diminishes smoothly until reaching a maximum distance beyond, which no correlation is observed (the sill). Once the semi-variogram model was established, ordinary kriging (OK) was applied in ArcGIS (ESRI ArcGIS v10.7, Redlands, CA, USA) to interpolate the data and generate the FHB forecasted maps. Kriging uses the spatial structure defined by the semi-variogram to estimate values at unsampled locations, resulting in smooth, continuous surface maps.

2.4. Management zone (MZ) delineations and recommendation maps

To calculate the application rate of fungicide, FHB forecasted maps were categorized into five levels of risk: Low (L), Medium Low (ML), Medium (M), Medium High (MH), and High (H), each of which should be assigned a recommendation rate to ensure the most effective treatments overall. Based on these site-specific FHB risks, as well as the available fungicide products, a combination of Priaxor [0.5 L ha^{-1}] and Curbatur [0.5 L ha^{-1}] was recommended in a 200 L water solution for the uniform treatment. For the PSSS treatment, the obtained maps from the forecasting model of the FHB distribution were divided into parallel strips each having a vertical spacing (e.g., strip length) of a minimum of 10 m, while the horizontal spacing (e.g., strip width) varied depending on the width of spraying machine used. For this reason, the horizontal spacing was decided to be 24 m, the width of the spraying machine used in this work.

In Field 1 the strips were alternately treated with the UR and PSSS applications, following a pattern where every other strip received a different treatment. The remaining two fields were divided into two halves, with one half accommodating the UR treatment strips and the other half accommodating the PSSS treatment strips. In the PSSS treatment, each strip was divided into several plots, the length of each is equal to the risk zones shown in Fig. 2A, B & C. For the simplicity of the fungicide application, the following assumptions were considered. In the cases of high spatial variability only, when having two plots with the same spraying rate and a small plot in between having a different class, then the three blocks are merged into one, which was given the label of the class with the highest recommendation dose. For example, if between two plots categorized as ML, there is a small plot that is categorized as L, the three blocks will be merged, and labeled as ML. Likewise, if the middle plot was ML resided between two L plots, then the merged block would be labeled as ML. This is to ensure that sufficient fungicide is applied, against underapplication that may lead to risk for poor prevention of FHB.

Different combinations of fungicide dosages were used to identify the optimal rate for PSSS. Different fungicide dosage strategies were applied in the three fields intentionally, to compare and evaluate which dosage adjustment method would be most effective under different risk and environmental conditions. Since there was no established standard or prior study for optimal dose modulation across FHB risk levels, each field was treated as a separate trial to explore a range of plausible strategies. The map of Field 1 was divided into nine strips, five of which were sprayed uniformly with the recommended fungicide dose provided by the farmer (0.5L Priaxor + 0.5L Curbatur [total 1.0 L] in a 200-liter water solution per ha). The remaining strips used the PSSS approach, allowing fungicides to be applied according to each zone's specific needs based on the level of the forecasted FHB risk in each area. For zones with medium (M) risk, the recommended fungicide dose (1.0 L ha^{-1} in a 200-liter water solution) was applied uniformly. In zones with ML and L disease risks, the fungicide dose was reduced by 25 % and 50 %, respectively, whereas for MH and H risk zones, the dose was increased by 25 % and 50 %, respectively.

The Field 2 was divided into two halves for fungicide application (Fig. 2E). One half was uniformly sprayed, while the other half was sprayed using the PSSS approach. For the PSSS half, the fungicide dose was customized based on the level of FHB risk identified in each area. For zones categorized as ML and L risk, the fungicide dose was reduced by 50 % and 25 %, respectively, while for zones categorized as MH and H risk, the fungicide dose was increased by 15 % and 30 %, respectively, in respective to the recommended rate by the farmer.

Likewise, Field 3 was divided into two halves (Fig. 2 F), with one half uniformly sprayed, while the other part was sprayed using a PSSS

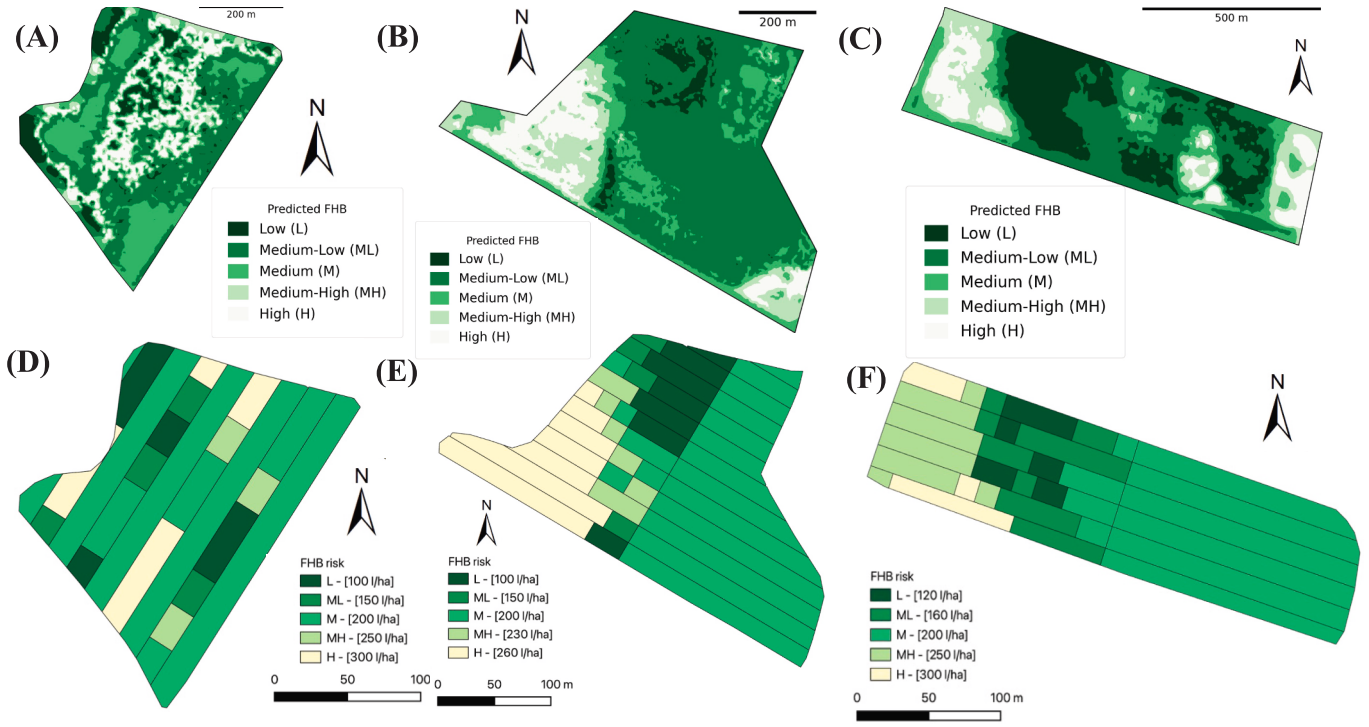

Fig. 2. The spatial distribution of fusarium head blight (FHB) forecast in Fields 1, 2, and 3, shown in A, B, and C, respectively. The variable-rate fungicide spraying maps, shown in D, E, and F for Fields 1, 2, and 3, respectively, are based on the forecast map shown in A, B, and C, respectively.

approach. For the PSSS strips, the fungicide dose was customized based on the level of Fusarium FHB risk identified in each area. For zones categorized as ML and L risk, the fungicide dose was reduced by 20 % and 40 %, respectively, while for zones categorized as MH and H risk, the fungicide dose was kept at 25 % and 50 %, respectively, in respective to the recommended rate by the farmer (0.71 L ha^{-1} in a 200-liter water solution). The application of fungicide took place on 11 May, which was the date of spraying. As a result of the dry weather, the risk of FHB infection was minimal, thus no further applications were deemed necessary.

2.5. Crop yield measurement

At the end of the cropping season, on the 2nd of August 2023, the grain yield of winter wheat was harvested using a combine harvester (CLAAS LEXION 670, CLAAS Group, Germany), equipped with a yield monitoring system. The system estimated the grain yield by measuring mass flow (throughput) in tons per hectare (t ha^{-1}) at a constant travel speed. Geo-referenced data was provided through a global navigation satellite system (GNSS), allowing the yield to be recorded at each spatial point within the field. Yield data collected from the combine harvester were aggregated into a yield layer, representing the spatial variability of the wheat production across the field. This yield layer was subsequently merged with the pre-established FHB risk MZ layers using the spatial join function in ArcGIS (ESRI ArcGIS v10.7, Redlands, CA, USA). This tool enabled the accurate association of yield data points with their corresponding MZs. The average yield for each MZ was calculated by aggregating the yield data points within each zone, allowing for an accurate evaluation of yield variability across the field. These averaged yield values were then used in the subsequent cost-benefit analysis for economic performance evaluation.

2.6. Cost-benefit analysis

A cost-benefit analysis was conducted to calculate the gross margin of PSSS against UR fungicide spraying, assuming the fungicide cost as input cost and the market price of grain yield as output revenue. All operational costs, such as tillage machinery and crop management, were assumed to be equal for both UR and PSSS treatments. The fungicide price (1.0 L ha^{-1} = 25 € ha^{-1}) was the same for both treatments; however, the cost for each MZ under the PSSS treatment was calculated based on the amount of fungicide applied in each zone. For instance, in high-risk (H) zones, where 50 % more fungicide was applied (1.50 L ha^{-1}), the cost was 37.50 € ha^{-1}. Conversely, in low-risk (L) zones, where 50 % less fungicide was applied (0.50 L ha^{-1}), the cost was reduced to 12.50 € ha^{-1}. The average revenue per MZ class (€ ha^{-1}) was determined by multiplying the average wheat grain yield (t ha^{-1}) with the market price (240 € t^{-1}). Gross margin i.e., benefit to fungicide spraying cost, was calculated after subtracting fungicide cost from the revenue, and the percentage increase of gross margin in comparison with UR was also calculated.

3. Results and discussion

3.1. Fusarium head blight forecasted maps and corresponding application maps

The distribution of the predicted FHB within the fields is shown in Fig. 2. The predicted maps showed considerable spatial variability, justifying the need for VR management of farming input using precision agriculture technology. The predicted map of Field 1 (Fig. 2A) showed that there is a higher chance of having FHB at the borders near the roads as well as the center and towards the northeastern part of the field, while in the case of Fields 2 and 3 (Fig. 2B and C, respectively) the maps showed that there is a higher chance of FHB presence at the borders nearby the roads of the fields which is aligned with the findings of Whetton et al. (2018b) and Almoujahed et al. (2025), reporting higher FHB spatial distribution at the edges of the field. This can be explained by the fact the *Fusarium* pathogens can survive in soil and plant debris occurring in the hedgerows of a field, acting as a source of inoculum for the following cropping season (Champeil et al., 2004), which is a clue to confirm the forecasting model ability to predict FHB spatial distribution

over the field. These spatial variations emphasize the importance of employing VR technology to enhance disease management practices. Overlaying the FHB forecast maps with the parallel strip experiment assigned for each of the three fields resulted in the application maps shown in Fig. 2 D, E, and F. We hypothesize that the customized doses for each treatment and plot within each strip (specified above) can improve FHB control, by reducing fungicide use in areas with lower risk, and increasing yield in zones receiving overapplication by the traditional UR fungicide spraying. This will provide evidence in support of the economic and environmental benefits of precision fungicide applications.

3.2. Yield maps

The spatial variability of wheat yield across the three studied fields was analyzed, revealing spatial differences in yield patterns within each field (Fig. 3). In Field 1, the yield ranged from 4.38 to 10.9 t ha^{-1}. The north western part of the field, where the highest and the lowest doses were applied (Fig. 2 D), showed the lowest yields, ranging from 4.38 to 6.66 t ha^{-1}. This suggests that the H and L PSSS treatments in these regions did not effectively control disease leading to significant reductions in yield (Fig. 2 A). Proximity to the road may have introduced environmental factors, such as altered microclimatic conditions, further impacting yield outcomes. In contrast, the central part of the field, which was predicted to have a higher FHB risk and received a M to MH doses of fungicide (Fig. 2 A, and D), produced the highest yields, ranging from 8.5 to 10.9 t ha^{-1}. This indicates that these areas benefited from the VR fungicide strategy, leading to improved disease control and higher grain yields. The results indicate that the PSSS treatments did not consistently outperform the UR approach. While targeted applications in the ML to MH risk zones improved yields, areas with the highest and lowest fungicide doses underperformed compared to the UR treatment. This suggests that other factors such as soil conditions, microclimate, or inappropriate dosage calibration might have influenced the outcomes. Fine-tuning the PSSS strategy and incorporating additional field data, such as soil health and microclimatic variations, could help improve the precision of disease control and yield outcomes in future applications.

Field 2 exhibited even greater yield variability, ranging from 6.12 to 11.4 t ha^{-1}. The central part, treated with lower PSSS doses aligned with lower predicted FHB risk, produced the highest yields (9.2–11.4 t ha^{-1}). However, the west southern corner, which received the highest dose (260 L ha^{-1}) for high FHB risk, yielded only 7.9–8.22 t ha^{-1}. The north side, treated with a low dose (100 L ha^{-1}), also underperformed compared to the UR treatment, yielding 6.12–7.9 t ha^{-1}. Field 3 showed moderate yield variability, with values between 5.13 and 9.53 t ha^{-1}. The central-western area, treated with PSSS in zones of moderate to medium–low FHB risk, achieved the highest yields (8.06–9.53 t ha^{-1}). In contrast, the northwestern and southeastern ends, despite receiving high doses, produced lower yields (5.13–6.60 t ha^{-1}).

Overlaying the yield maps with soil ECa data revealed an inverse relationship in all three fields. Higher ECa zones, indicating greater soil salinity (Corwin and Lesch, 2005; Rhoades, 1996), coincided with lower yield. For instance, in Field 1, the highest ECa zones (up to 50 mS/m) in the western corner matched the areas with the lowest yields. Field 3 illustrated this trend with lower ECa in the western half corresponding to superior productivity. While the inverse relationship between ECa and yield was less pronounced in Field 2, the pattern was still observable, suggesting that soil salinity may have contributed to yield reductions in combination with suboptimal fungicide dosing (H and L). These spatial patterns indicate that PSSS treatments were effective in moderate-risk zones but not consistently across all areas. The quantitative yield responses to different fungicide rates and the underlying mechanisms are discussed in section 3.3.

3.3. Crop yield response to variable rate fungicide spraying

To evaluate the impact of fungicide application rates on crop performance, yields were calculated for various treatments across three fields (Fig. 4). The results demonstrate a clear variation in yield response among the different fungicide treatments.

In Field 1, the UR treatment resulted in a yield of 7.47 t ha^{-1}, which is lower than the yields from the MH, M, and ML treatments. The MH treatment produced the highest yield of 7.81 t ha^{-1}, reflecting a 4.55 % increase over the UR treatment. However, the H and L treatments yielded 7.09 t ha^{-1} and 6.89 t ha^{-1}, respectively, both underperforming compared to the UR treatment. The total PSSS treatment average was 7.26 t ha^{-1}, representing a 2.8 % reduction compared to UR. This reduction can be attributed to the negative impact of the extreme doses (H and L) applied, which either oversupplied or undersupplied fungicide, leading to suboptimal FHB management and, consequently, lower yields. Excessive fungicide application has been shown to negatively affect crop physiology. Liu et al. (2021) found that high doses of triazole fungicides trigger reactive oxygen species accumulation, reduce chlorophyll content, and impair photosynthetic electron transport in wheat,

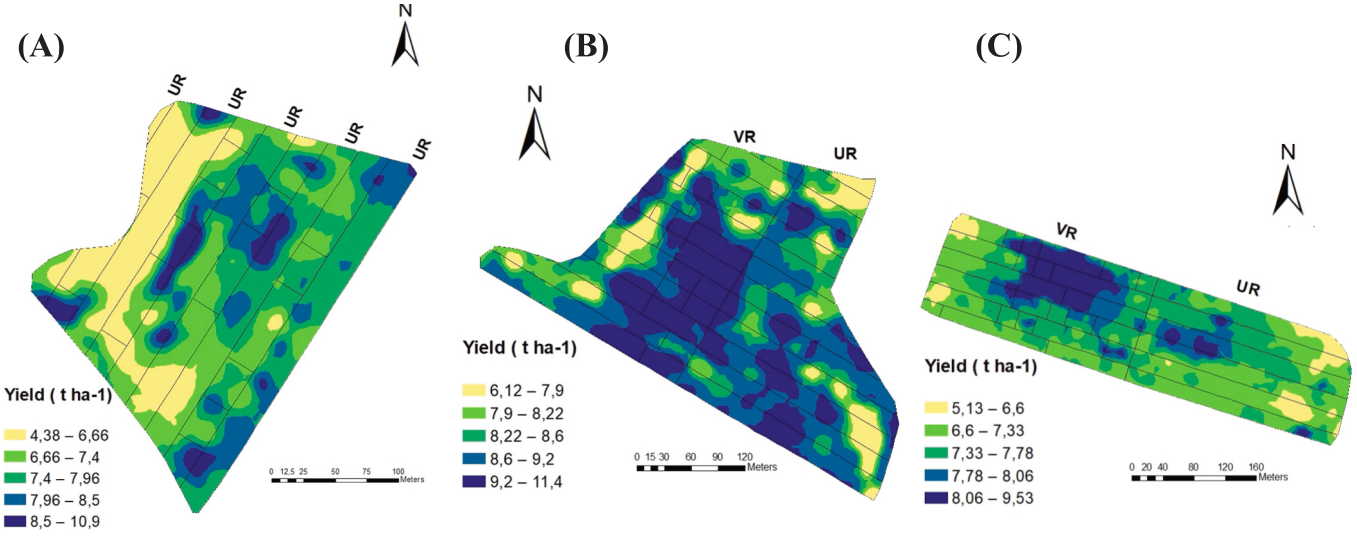

Fig. 3. Wheat yield maps generated by a combine harvester equipped with a yield monitoring system for A) Field 1, B) Field 2, and C) Field 3. PSSS (preventive site-specific spraying) strips are overlaid on the yield maps to compare variable rate (VR) of PSSS treatments with uniform rate (UR) treatments for more precise yield analysis. In Field 1, only UR strips are highlighted, while alternate strips represent VR (PSSS). For Fields 2 and 3, both VR and UR treatments areas are highlighted.

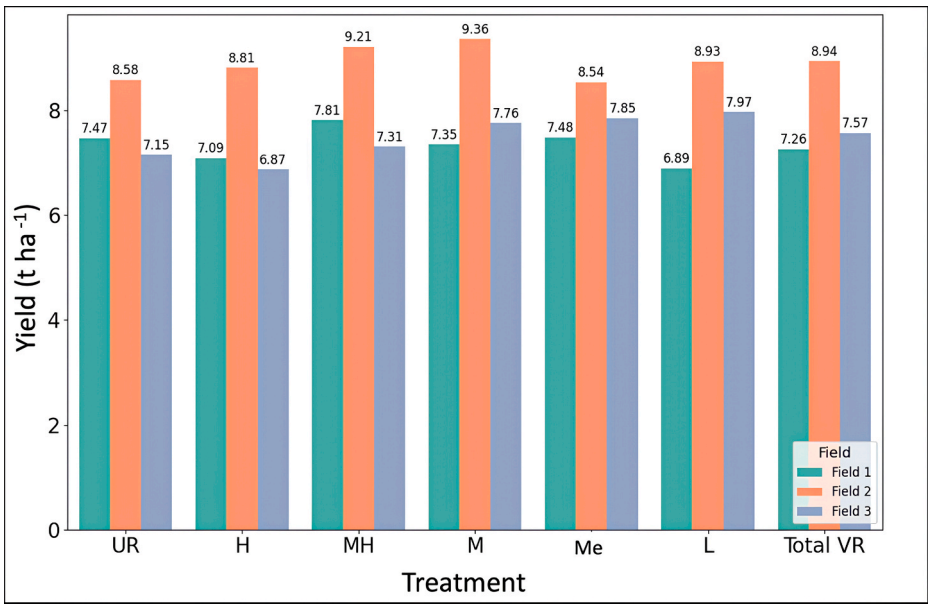

Fig. 4. Crop yield calculated for the uniform rate (UR) treatment and the per individual management zone (MZ) preventive site-specific treatment (PSSS) with five levels of fusarium head blight (FHB) disease risk: Low (L), Medium Low (ML), Medium (M), Medium High (MH), and High (H). The total VR represents the average of the variable rate (VR) of PSSS treatments.

resulting in diminished grain fill and yield. Similarly, Dias (2012) and Petit et al (2012) documented that overapplication can compromise photosynthetic efficiency, while Ruske et al. (2003) and Klix et al. (2007) reported phytotoxic effects such as chlorosis and stunting under high doses. Beyond direct plant damage, excessive fungicide use may disrupt beneficial soil microorganisms, such as arbuscular mycorrhizal fungi, critical for nutrient uptake and plant resilience (Hage-Ahmed et al., 2019; Pu et al., 2021; Gong Cheng et al., 2014). Additionally, environmental factors such as temperature, humidity, and rainfall significantly influence fungicide efficacy in controlling FHB. For instance, González-Domínguez et al. (2021) found that fungicides were more effective when applied shortly before or at the time of infection, which is influenced by warm, rainy, and moist spring conditions favorable for *F. graminearum*. In their experiments, years with higher rainfall led to increased FHB incidence and severity, emphasizing the need for timely applications based on weather forecasts. Similarly, Freije and Wise. (2015) demonstrated that rainfall and temperature during flowering affect *F. graminearum* inoculum availability, with timely fungicide applications being critical for effective control. All these factors could be contributing to the observed decrease in benefits at 300 L ha^{-1}. On the other hand, insufficient fungicide rates compromise disease suppression. Friskop et al. (2018) observed that lower-rate treatments in spring wheat trials led to disease outbreaks and net negative returns under low-pressure scenarios, aligning with our L treatment outcomes. Reimann and Deising. (2005) further noted that under-dosing can allow pathogen proliferation and potentially select tolerant strains, exacerbating yield losses.

In Field 2, the UR treatment yielded an average yield of 8.58 t ha^{-1}, while the overall PSSS treatments increased the yield by 4.19 %, achieving 8.94 t ha^{-1}. The M and MH zones yielded the highest yield, at 9.36 t ha^{-1} and 9.21 t ha^{-1}, respectively, whereas the L treatment still performed well, with a yield of 8.93 t ha^{-1}, outperforming the UR treatment. The H treatment yielded 8.81 t ha^{-1}, which was slightly higher than UR but lower than the medium treatments, highlighting the inconsistency in the response to extreme application rates.

In Field 3, the UR treatment yielded 7.15 t ha^{-1}, while the total PSSS treatment outperformed UR with an average yield of 7.57 t ha^{-1} reflecting a 5.87 % increase. The ML and M treatments were the most effective, producing yields of 7.85 t ha^{-1}and 7.76 t ha^{-1}, respectively. However, the H treatment once again showed a lower yield (6.87 t ha^{-1}) than the UR treatment, while the L treatment performed better, yielding 7.97 t ha^{-1}. This highlights the variability in crop response to extreme treatments and suggests that more moderate applications are more reliable in preventing decreases in yields due to toxicity in case of overapplication (e.g., in H risk areas) and preventing decreases in yield due to poor control of disease in underapplication rates (e.g., L risk), receiving low fungicide rate of 100 7.97 L ha^{-1}. Overall, Fields 2 and 3 exhibited better responses to PSSS treatments compared to UR, with yield increases of 4.19 % and 5.87 %, respectively. The better performance of moderate application treatments (MH, M, and ML) across all three fields suggests that precise fungicide management, tailored to predicted FHB risk, is an effective strategy to enhance yield. However, the inconsistent performance of the H and L treatments across fields indicates that extreme adjustments to fungicide rates (both over- and under-applications) may lead to suboptimal outcomes.

The spatially heterogeneous yield response supports the hypothesis that fungicide rates should align with local canopy and disease conditions. Sensor-based VR systems, as demonstrated by Tackenberg et al. (2018) achieved spray savings of 8–45 % without sacrificing yield or efficacy. In our study, medium- to high-rate zones (MH, M, ML) consistently outperformed extreme rates of 100 and 300 L ha^{-1}, reinforcing the added value of precision applications of fungicides. Similarly, Dammer and Ehlert (2006) found that tailored spraying boosts crop performance by avoiding unnecessary application. However, Vučajnk et al. (2024) reported contrasting results, with a high rate of 320 L ha^{-1}, DON concentrations were reduced and kernel weight of durum wheat were increased, while a low rate of 80 L ha^{-1} led to poor coverage and decreased the grain yield. This discrepancy with our findings may stem from differences in crop variety, disease pressure, or environmental context. Therefore, future studies should aim to explore the underlying causes of this phenomenon, including the role of disease pressure, soil and climate conditions, and potential phytotoxic effects to refine precision fungicide strategies, supporting sustainable wheat production. Overall, PSSS treatments enhance yields when rates are carefully calibrated, minimizing toxicity and ensuring effective FHB control.

3.4. Cost-benefit assessment of preventive site-specific fungicide spraying

The cost-benefit analysis of PSSS across three fields revealed clear differences in yield, and gross margins, highlighting the potential of this precision agriculture approach. In Field 1, the UR treatment achieved a gross margin of 1730.10 € ha^{-1} with a yield of 7.47 t ha^{-1}, while the overall PSSS treatment resulted in a slightly lower gross margin of 1695.90 € ha^{-1}, a net decrease of 34.20 € ha^{-1} (Table 1). The H and L zones of the PSSS treatments, receiving 50 % more and 50 % less fungicide than the UR treatment, respectively, were the main contributors to this reduction, as they both showed reduced yields (7.09 t ha^{-1} for H and 6.89 t ha^{-1} for L) and lower gross margins (1628.72 € ha^{-1} for H and 1607.47 € ha^{-1} for L). On the other hand, the MH and ML zones performed more favorably, achieving yields of 7.81 t $ha^{-1}$and 7.48 t ha^{-1}, respectively, with gross margins close to the UR treatment. By excluding the H and L treatments from the cost-benefit calculation, the overall PSSS approach in Field 1 would have been more profitable than the UR treatment with a relative gross margin of 18.32 € ha^{-1}. The results indicate that the H and L treatments, which involved applying 50 % more and 50 % less fungicide than the UR treatment, respectively, led to the lowest yields and gross margins consistently. The over-application of fungicide in the H treatment likely caused phytotoxicity and disrupted plant physiology, while the under-application in the L treatment resulted in inadequate disease control and higher disease pressure (Petit et al., 2012). These factors combined led to reduced plant health and yield. On the other hand, the MH and ML zones, which applied moderate variations of fungicide, performed more favorably, achieving yields and gross margins larger or close to those of the UR treatment.

Incorporating precision agriculture technologies, such as VR, into crop management practices proved to allow growers to optimize input use based on real-time, site-specific data (Cheema et al., 2023). Indeed, VR ensures that each area of the field receives exactly what it needs, reducing waste, enhancing efficiency, and improving profitability (Mani et al., 2021; Saleem et al., 2023). This aligns with the findings from Field 2, where PSSS demonstrated a clear advantage achieving a gross margin of 2084.49 € compared to 1991.37 € ha^{-1} for the UR treatment, representing a relative increase of 93.12 € ha^{-1}. The M treatment produced the highest yield (9.36 t ha^{-1}) and gross margin (2173.45 € ha^{-1}), outperforming all other zones, including UR. The MH and H zones also yielded higher than UR, with gross margins of 2135.72 € ha^{-1} and 2037.73 € ha^{-1}, respectively, further supporting the effectiveness of PSSS in this field. Even the L treatment, which applied the least fungicide, resulted in a solid yield of 8.93 t ha^{-1} and a gross margin of 2086.41 € ha^{-1} (Table 1).

Field 3 demonstrated a similar trend to that of Field 2, with PSSS outperforming UR in terms of profitability. The PSSS approach yielded a total gross margin of 1749.14 € ha^{-1}, compared to 1654.21 € ha^{-1} for UR, a relative increase of 94.93 € ha^{-1}. The M and ML zones were the most successful, with yields of 7.76 t ha^{-1}, and 7.85 t ha^{-1}, respectively, and corresponding gross margins of 1798.78 € ha^{-1} and 1824.84 € ha^{-1}. Interestingly, the L risk zone also outperformed expectations, yielding 7.97 t ha^{-1} and generating a gross margin of 1858.27 € ha^{-1}, while the H treatment underperformed, with a yield of only 6.87 t ha^{-1} and a gross margin of 1576.47 € ha^{-1}. These findings suggest that extreme fungicide applications (particularly the H rate) may not yield additional benefits and could even reduce profitability, possibly due to over-application or crop stress.

Across all three fields, these results highlight the potential of PSSS to optimize fungicide use and enhance profitability, particularly when extreme dosages (H and L) are avoided. Moreover, this approach aligns with findings from Whetton et al. (2018), who demonstrated that VR could increase gross margins by an average of 8.8 £ ha^{-1} (10.2 € ha^{-1}) per application compared to uniform spraying, emphasizing its financial benefits in precision agriculture. Similarly, Dammer and Ehlert (2006), explored the use of a pendulum real-time crop sensor to measure plant biomass density, whose output readings were then used to apply fungicides at variable rates, e.g., the larger the biomass the larger the rate and vice versa. The results showed that VR fungicide applications could save up to 22 % of fungicides without reducing yields, suggesting that precise application can optimize fungicide use and maintain crop yields (Dammer and Ehlert, 2006).

However, one key limitation in our study was the decision to apply fungicide at rates higher than the normal application rate (200 L ha^{-1}), with treatments exceeding this threshold by 15 % to 50 % (which differ from one field to another and MH to H). This might explain why no direct profit was observed from fungicide savings when applying PSSS in this case. If the normal rate (200 L ha^{-1}) had been considered as the maximum for areas predicted to have high FHB risk, with variable rates applied below this threshold, the economic benefit from fungicide savings could have been more pronounced. In such a scenario, profits would

Table 1
Results of cost-benefit analysis of the strip experiment comparing the preventive site-specific fungicide spraying (PSSS) with uniform rate fungicide application (UR) treatments.

Field	Treatment	Area (ha)	Fungicide suspension (L ha^{-1})	Fungicide dose (L ha^{-1})	Fungicide cost (€ ha^{-1})	Cost per treatment (€)	yield (t ha^{-1})	Revenue (€ ha^{-1})	gross margin (€ ha^{-1})	Relative gross margin (€ ha^{-1})
Field 1	UR	2.58	200	1	25	64.5	7.47	1755.1	1730.1	
	H	0.54	300	1.5	37.5	20.27	7.09	1666.22	1628.72	
	MH	0.26	250	1.25	31.25	8.15	7.81	1835.43	1804.18	
	M	0.73	200	1	25	18.21	7.35	1726.23	1701.23	
	ML	0.32	150	0.75	18.75	6.01	7.48	1756.63	1737.88	
	L	0.5	100	0.5	12.5	6.21	6.89	1619.97	1607.47	
	total PSSS	2.35			25	58.84	7.26	1706.22	1695.90	**−34.2**
Field 2	UR	4.8	200	1	25	120.09	8.58	2016.37	1991.37	
	H	1.83	260	1.3	32.5	59.35	8.81	2070.23	2037.73	
	MH	0.6	230	1.15	28.75	17.3	9.21	2164.47	2135.72	
	M	0.47	200	1	25	11.83	9.36	2198.45	2173.45	
	ML	0.31	150	0.75	18.75	5.72	8.54	2007.92	1989.17	
	L	1.16	100	0.5	12.5	14.5	8.93	2098.91	2086.41	
	total PSSS	4.37			23.5	108.7	8.94	2100.38	2084.49	**93.12**
Field 3	UR	3.8	200	1	25	94.99	7.15	1679.21	1654.21	
	H	0.47	300	1.5	37.5	17.59	6.87	1613.97	1576.47	
	MH	1.15	250	1.25	31.25	35.9	7.31	1718.58	1687.33	
	M	0.46	200	1	25	11.6	7.76	1823.78	1798.78	
	ML	1.19	160	0.8	20	23.71	7.85	1844.84	1824.84	
	L	0.55	120	0.6	15	8.26	7.97	1873.27	1858.27	
	total PSSS	3.82			25.75	97.06	7.57	1780.03	1749.14	**94.93**

UR: uniform rate, H: high, MH: medium-high, M: medium, ML: medium-low, L: low

not only stem from higher yields, due to better disease management but also from the reduction in fungicide use, which would simultaneously lower input costs and reduce environmental impact. In contrast, our study's PSSS application rates averaged out to be almost equivalent to the UR treatment, negating the environmental benefits of reduced fungicide usage. This outcome highlights the importance of ensuring that the highest application rate does not exceed the standard in future studies, which would allow VR to generate both economic and environmental gains. For example, based on a simulation work, Whetton et al. (2018b) found that using 100 % of the standard fungicide rate in UR, while adjusting doses based on disease probability as: 75 % for ML areas and 50 % for L zones, resulted in a 22.24 % reduction in fungicide use through VR. Such an approach not only reduced the environmental impact, by minimizing soil and water contamination and decreasing greenhouse gas emissions but also improved profitability by enhancing yield and increasing field efficiency. This highlights an important direction for future work for optimizing the dosage strategy within VR to achieve agronomic, economic and environmental win–win. It is important to note that the findings presented here are based on data from a single growing season. While the trends observed provide valuable insights into the effects of VR strategies, environmental variability across seasons, including weather patterns, disease pressure, and soil moisture, could significantly influence the yield outcomes. Therefore, future studies should aim to validate these findings using multi-year experiments to ensure the robustness and broader applicability of the conclusions.

4. Conclusion

The implementation of PSSS for FHB management in three winter wheat fields has shown promising results in terms of both yield enhancement and economic return by 93.12–94.93 € ha^{-1}, when compared to UR fungicide applications in two out of three fields. Advanced ML algorithms for FHB forecasting based on remote sensing crop data and proximal soil sensing data proved to be highly effective in tailoring the fungicide application to disease risk across management zones, reducing the inefficiencies associated with UR applications. The PSSS approach, particularly when avoiding extreme fungicide doses (100, and 300 L ha^{-1}), has exhibited the potential for increased profitability while maintaining effective disease control. However, the variability in responses to high and low fungicide application rates suggests that future VR strategies should focus on moderate rate adjustments (MH, M, ML) to achieve consistent yield benefits. PSSS demonstrated its capacity to enhance yield and profitability, improve disease management, and pave the way toward more sustainable wheat protection.

While this study primarily focused on yield and economic outcomes, it highlights the potential environmental benefits of optimized fungicide use, especially in reducing chemical inputs, although the latter was not proved the case for the current work. The results suggest the need for further investigating both the economic and environmental impacts of PSSS across various cropping systems and geographical regions. Additionally, incorporating soil data, and long-term data, such as historical yield trends and disease occurrence, will refine PSSS recommendations and further enhance its efficacy. These considerations could enable PSSS to play a critical role in sustainable production, balancing the need for disease control, economic viability, and environmental sustainability.

CRediT authorship contribution statement

Muhammad Baraa Almoujahed: Writing – original draft, Methodology, Data curation, Visualization, Investigation, Conceptualization, Writing – review & editing, Validation, Formal analysis. **Orly Enrique Apolo-Apolo:** Writing – original draft, Methodology, Writing – review & editing, Validation, Data curation, Visualization, Conceptualization. **Antonios Morellos:** Visualization, Methodology, Conceptualization, Writing – original draft, Formal analysis, Writing – review & editing, Validation, Data curation. **Xanthoula-Eirini Pantazi:** Writing – review & editing, Resources, Investigation, Conceptualization, Visualization, Software, Formal analysis, Writing – original draft, Validation, Methodology, Data curation. **Marius Kazlauskas:** Software, Methodology, Writing – original draft, Data curation, Writing – review & editing, Resources, Formal analysis. **Zita Kriaučiūnienė:** Writing – review & editing, Validation, Software, Project administration, Formal analysis, Writing – original draft, Supervision, Investigation, Conceptualization, Visualization, Resources, Methodology, Data curation. **Egidijus Šarauskis:** Writing – review & editing, Validation, Methodology, Data curation, Writing – original draft, Supervision, Resources, Investigation, Visualization, Software, Project administration, Formal analysis, Conceptualization. **Abdul Mounem Mouazen:** Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Data curation, Writing – review & editing, Validation, Formal analysis, Visualization, Software, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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