Evaluation analysis of DSS case studies

Deliverable D4.4

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Deliverable D4.4
Evaluation analysis of DSS case studies

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Abstract

The Deliverable 4.4 of the Horizon 2020 IPMWORKS project (Grant No. 101000339) evaluates the efficacy of Decision Support Systems (DSS) in optimizing Integrated Pest Management (IPM) strategies across European agriculture. The study employs a multi-method approach (meta-analysis, stakeholder surveys, and in-field trials) to compare traditional IPM practices with DSS-based approaches for disease and pest control in key crops: grapevine, potato, wheat, and chickpea.

A meta-analysis of 65 scientific studies revealed that DSS significantly reduced the Treatment Frequency Index (TFI), a measure of pesticide use, by 25% in grapevine, 20% in potato, and 39% in wheat, while maintaining or improving disease control. DSS-based strategies also lowered disease severity by 59% in wheat and 10% in grapevine compared to conventional practices. However, DSS adoption in organic grapevine systems showed no TFI reduction, likely due to limited approved pesticides. Yield impacts were minimal, with slight reductions in wheat (-6%) but comparable or improved results in potato.

A survey of 89 stakeholders (70% farmers/advisors) across 14 European Countries identified barriers to DSS adoption: lack of trust in outputs (21%), perceived complexity (26%), and insufficient crop-specific tools (16%). Conversely, DSS users reported reliability (57%) and utility (63%), though 48% acknowledged reduced pesticide use. The survey highlighted the need for enhanced user-friendliness and targeted outreach to bridge adoption gaps.

In-field trials have demonstrated practical benefits of DSS for achieving a more sustainable and efficient crop protection. In Italian organic vineyards, DSS reduced copper use by 34–62% and costs by 45–56% over two seasons. Chickpea trials in Italy saw yield increases of 29% under DSS guidance. Swedish wheat trials achieved comparable disease control with 1–3 fewer fungicide applications, while Scottish potato farms reduced sprays by 1.7 per season without yield loss. The case studies conducted on BYDV in winter wheat in England demonstrated the possible reduction in insecticide use, decreased applications following DSS suggestion without compromising the final yield; the avoidance of insecticide was tested also in the Netherland where both DSS and delayed sowing time were tested as sustainable practices for BYDV disease and aphid vectors control. An ex-post analysis of 180 Italian vineyards using DSS showed reductions in environmental metrics: 22% in carbon footprint, 36% in chemical exposure (Dose Area Index), and 38–40% in human/eco-toxicity scores.

The study underscores DSS as a viable tool for sustainable pesticide reduction, aligning with EU agricultural and environmental goals. However, wider adoption requires addressing user concerns through improved interface design, farmer training, and demonstration programs. By integrating empirical evidence, stakeholder feedback, and real-world validation, this work provides actionable insights to advance IPM adoption, promoting economic and environmental resilience in European farming.

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1 Introduction

The European Commission supports research and initiatives to implement Integrated Pest Management (IPM) adoption across the EU. As part of the Horizon 2020 project IPMWORKS (Grant number 101000339), an EU-wide network of farmers and advisors has been established to demonstrate and promote cost-effective and sustainable IPM strategies. A key aspect of this approach is the comparison of different management strategies, with a particular focus on reducing plant protection products (PPPs) use while maintaining farm profitability. **The overall objective of the fourth Work Package (WP4)** of the IPMWORKS project was to create and develop the Resource Toolbox to provide easy access to IPM resources for internal and external stakeholders. Behind the Resource Toolbox, **a specific objective was to evaluate on-farm use of IPM Decision Support Systems (DSSs) provided by the "IPM Decisions" platform**, including evaluation of costs and benefits. This specific represents a key bridge between the two sister-projects, IPMWORKS and IPM Decisions (Grant number 817617).

The aim was to collate field comparisons between standard IPM agricultural practices, normally used by farmers, and advanced IPM (DSS-based) strategies for diseases and pests control, similarly to the trials conducted and reported in D3.7 (Francis, C., Dearlove, E., Jones, I., and Ramsden, M. (2025). *Report on the approach for implementation of 'in- field' comparisons of IPM strategies. Deliverable 3.7 of the Horizon 2020 project IMPWORKS (GA number 101000339)*, published on the project web site in April 2025: https://ipmworks.net/category/public-deliverables/). In particular, since few cases studies already reported in D3.7 also had a specific focus on DSS evaluation, they have been analyzed in both Deliverables. Farmers within the Farmer Hubs were encouraged to allocate small portions of their fields for these trials over the course of the project. The idea was to utilize the DSS and models freely available on the "IPM Decision" platform (https://platform.ipmdecisions.net/), which was developed during the sister project IPM Decision and made available for public consultation in September 2022.

Since the aim of Task 4.4 was to investigate the current implementation of IPM DSS by farmers, three specific objectives were addressed:

1) Assess the benefits of IPM DSS consultation on pest infestation severity, pesticide use (as measured as TFI), and yield across three key European crops (wheat, potatoes and grapevine) considering pest management, crop performance, and profitability;
2) Assess farmers motivations for consulting or not consulting DSS **within IPMWORKS and associated/not associated networks**;
3) Combine outputs from objectives 2 & 3 to develop a short series of IPM DSS Evaluation Case Studies, extending or supplementing demonstrating activities in WP3.

To achieve the abovementioned goals, a multi-step approach was developed:

i) A meta-analysis study was conducted to compare the two practices (Standard and DSS-based), based on the results of already published papers. This approach allowed us to summarize existing knowledge from scientific literature on the use of DSS and models in IPM, providing us the basis for the next steps to reach WP4 goals. The results of this analysis are presented in **Chapter 2 "Meta-analysis"** of this D4.4, quantifying the effects of DSS-based crop protection on pest or disease severity, treatment frequency index (TFI), and crop yield, through a systematic literature review and a network meta-analysis approach applied to three major crops—grapevine, wheat, and potato;

ii) A survey was carried out to investigate the reasons behind the adoption or not of DSS by farmers and advisors. **Chapter 3 "Short survey on DSS"** presents components, main drivers,

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barriers and perceived value of DSS tools by different stakeholders. The results of this survey contribute to understand adoption patterns and opportunities for improving DSS implementation in practice;

iii) Together with voluntary farmers, field trials comparisons were performed on different crops and in various areas across Europe, assessing the impact of DSS-based strategies under real farming conditions. **Chapter 4 "IPM DSS case studies"** focuses on field demonstration, aiming to compare the performance of standard crop protection practices with DSS-supported approaches, evaluating not only pest and disease control, but also economic aspects, environmental indicators, and overall sustainability in several agricultural contexts.

Collecting data from these trials, along with insights from the meta-analysis and survey, provided valuable evidence on the benefits of DSS and/or other Decision Tools (DTs) in IPM supporting wider adoption and encouraging farmers and advisors to integrate these tools into their crop protection strategies. Indeed, numerous tools have been developed to aid in decision-making across strategic, tactical, and operational levels in crop protection. These tools, which include models of population dynamics and epidemiology, risk assessment algorithms, intervention thresholds, decision rules, and decision support systems (DSSs), focus on predicting the behavior of organisms detrimental to crops and guiding their management. (Rossi et al., 2019). In particular, a modern DSS for crop management and protection can be described as computer platforms that can be used via the Internet, and consist of four main components: 1) an integrated system for collecting data that characterize the crop environment (e.g., data measured by weather or soil sensors, collected by satellites or drones, cameras installed in the crop, monitoring activities, or insect traps, etc.); 2) the use of mathematical models to analyze the data; 3) their interpretation in the light of expert knowledge; 4) the formulation of agronomic advice, alerts, or other information useful for decision-making (Caffi et al., 2018).

In this Deliverable a distinction is made (if and when possible) between modern DSSs, built as described above according to Caffi et al., 2018, and other DTs, where only a component such as a model is present. By the way, it is implicit that the overall scope of both DSSs and DTs for IPM is to support knowledge-based management of harmful organisms in agriculture. All DTs help decision-makers in solving complex problems while reducing the time and the resources allocated for analyzing the available information and selecting the best solution (Rossi et al., 2019).

A complete list of the abbreviations used in this deliverable (D4.4) is reported in Annex 1 (Table 1).

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2 Meta-analysis

2.1. Summary

A systematic literature search was conducted using the PRISMA flow diagram to gather relevant studies from major scientific databases. The research focused on studies that compared Decision Tools (DT) driven solutions with standard agricultural practices in disease and pest control for three main crops covering different agricultural sectors: grapevine, wheat, and potato. A total of 65 papers were selected as eligible, and a total of 433 comparisons on severity and 645 on treatment frequency index (TFI) were identified, in different proportions for each crop. When available, even yield (t/ha) was used.

To conduct the analysis, a network meta-analysis approach was adopted, to evaluate the effects of the different treatments (DT-based and Standard), expressed as the effect size using standardized mean differences (SMD). Results showed that DT-based strategy showed a significantly reduced severity compared to the Standard, achieving a reduction up to 59% and 10% in wheat and grapevine, respectively. In potato, DT-tools and Standard reached the same control. Moreover, TFI in DT-based was generally reduced in the three crops compared to the Standard, by 25%, 20% and 39%, for grapevine, potato and wheat, respectively. Thus, results indicate a reduction in pesticide use without compromising disease or pest control. Yield (t/ha) was comparable (potato) or slightly reduced (wheat) in DT-based management compared to the standard.

The study concludes that Decision Tools can optimize plant protection products use, reducing TFI without negatively affecting disease control. Efforts to involve farmers in demonstration events and small-scale trials could help increase the use of DT in agriculture.

2.2. Introduction

Chemical pesticides have contributed to avoid and reduce potential yield losses due to diseases and pests for several crops, but also led to potential negative effects on the environment and human health (Lamichhane et al., 2016; Deguine et al., 2021). According to IPM principles, alternative strategies should be used before chemicals, that should represent the last resource and should be apply when economically and environmentally justified (Lamichhane et al., 2016; Rossi et al., 2019; Deguine et al., 2021). However, many diseases and pests control is difficult to achieve totally avoiding plant protection products. In this context, Decision Support Systems (DSSs) may represent a viable alternative.

DSSs integrate several models to help farmers make informed crop protection decisions, aiming to reduce and optimize pesticide use and minimize environmental and health risks (Rossi et al., 2012; Lazaro et al., 2021). Various DSSs exist for different crops, such as grano.net® for cereals (González-Domínguez et al., 2021), NegFry for potatoes (Eremeev et al., 2006), and vite.net® for grapevine (Rossi et al., 2014). These systems rely on models that vary in complexity and accuracy, with mechanistic models proving more robust under diverse conditions than empirical models (Caffi et al., 2007; Salotti et al., 2021).

However, DSS adoption among farmers remains limited due to several barriers (Deguine et al., 2021; Rossi et al., 2012; Lazaro et al., 2021). The objective of this study was to analyse the impact of IPM DSS consultation on diseases and pests severity, pesticide use (as measured as TFI), and yield, on three key European crops: wheat, potatoes and grapevine. To address this, a network

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meta-analysis was conducted on the consolidate existing knowledge on DSS effectiveness, comparing the standard agricultural practices, typically used by farmers, and DSS-based strategies for disease and pest control.

Thus, this study aims to provide quantitative evidence of DSS benefits for pest control by analysing literature data on grapevine, potatoes, and wheat.

2.3. Methods

A systematic literature search was performed following the PRISMA flow diagram (Fig. 1) in the main scientific databases, using the query: "decision support system" AND ("empirical" OR "mechanistic") AND ("model") AND ("forecast") AND ("grapevine" OR "vineyard" OR "potato" OR "wheat") AND ("disease control" OR "disease management" OR "crop protection") AND ("Plant protection product") AND ("sustainable disease management" OR "integrated pest management").

Thus, we included into the analysis not only DSS, but also the use of empirical and mechanistic models (later referred to as Decision Tools, DTs), compared to standard practice. Furthermore, we selected three different crops: grapevine, wheat and potato, in order to cover different cropping sectors, characterized by different managements. The abovementioned crops were chosen also based on the number of scientific papers available for the analysis. Following the PRISMA flow diagram a total of 65 papers were selected based on the eligibility criteria, that were: i) a comparison between DT-based, the standard farmer practice, and untreated control; ii) an evaluation, at least one in the season, of pests (diseases or insects) as incidence or severity; iii) the inclusion of the sample size, mean and standard deviation, or a measure of variability allowing to calculate the within study variance as described by González-Domínguez et al. (2019).

Among the 65 papers, 53 reported the comparison as described above, thus comparing pests control practices as incidence or severity, while 57 reported the comparison as TFI, thus they were maintained comparing the practices in terms of TFI. The TFI is the treatment frequency index as defined by Gravesen (2003) and Pingault (2007). When available, even the yield (t/ha) was included.

Each paper could include more than one comparison. A comparison was defined between the two management systems (DT-based and standard) and the untreated control, in the same season and place. A total of 433 comparisons were identified, 76 for wheat, 155 for potato and 202 for grapevine, as pests severity or incidence. A total of 645 comparisons on TFI were considered, 131 on wheat, 299 on potato and 215 on grapevine.

The treatment type was categorized as either: i) untreated control (UTC); ii) farm-based (Standard); iii) DT-based, when treatments were scheduled by using a DT, that recommend products application based on forecasting (e.g., Pellegrini et al., 2010) or DT output that provides a direct alert to farmers or advisors (e.g. Rossi et al., 2014); or iv) expert-based (EX-based), when treatments were applied based on disease monitoring (e.g., Jermini et al., 2003) or critical growth stages of the crop (e.g., Kast and Bleyer, 2011).

The meta-analysis was conducted using the software R (R version 4.2.1) (Viechtbauer, 2010; Balduzzi et al., 2019; Wickham et al., 2019). Specifically, a network meta-analysis was conducted to evaluate the effect of the different treatments; the analysis was first performed separately for grapevine, potato, and wheat studies, and then for all crops. The arithmetic mean ($\bar{x}$) and standard deviation (s) of the severity in each treatment and comparison were used to calculate a metric per treatment and across all studies called "effect size". Effect sizes are measured to capture the direction and the magnitude of the relationship between two groups. Following a

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series of criteria (Higgins et al., 2019), the standardized between-group mean difference (SMD) was held to calculate the difference between the different treatments and the untreated control. SMD is the difference in Standard deviation units between treatment and untreated control. SMD > 0.2, 0.5, 0.8, and 1.0 are considered to represent small, medium, large, and very large effects, respectively (Ojiambo and Scherm, 2006). In order to compare treatments, the ratio ($1-SMD_{t1}/SMD_{t2}$), with t1 and t2 being treatment 1 and 2, respectively, has been used. To account for the effect sizes variance, the heterogeneity between studies τ^2 was estimated (Hedges and Vevea, 1998; Borenstein et al., 2021); the Higgins and Thompson's I^2 statistic was used to quantify this heterogeneity (Higgins and Thompson, 2002). To examine if one treatment produces more effect than another, a χ^2 (Chi-squared) test was used to assess whether the variability in effect sizes between subgroups is significant.

The TFI data were analyzed by using the non-parametric W-Mann-Whitney test, and yield data by using the non-parametric χ^2- Kruskal-Wallis's test. For grapevine TFI data were analyzed separately for organic and IPM vineyards. Yield was analyzed only for potato and wheat because data for grapevine were often not reported in papers.

2.4. Results

2.4.1 Severity

In grapevine, all treatments were significantly different from the untreated control (Tab. 1). The heterogeneity test resulted in I^2 = 36%, indicating low heterogeneity within the dataset, and the χ^2 test for subgroup between-groups differences was significant (p=0.03). Considering the ratio between SMD values of different treatments ($1-SMD_{t1}/SMD_{t2}$), the DT-based treatment had on average a disease severity 10% lower than the Standard, and 25% lower than the EX-based. In addition, the Standard had an average disease severity lower by 17% with respect to EX-based (Fig. 2A).

In potato, both Standard and DT-based treatments were significantly different from the UTC (Fig. 2B). The heterogeneity test resulted in I^2 = 55%, indicating a moderate heterogeneity within the data. The test for subgroup differences was not significant (p=0.93), indicating that the two treatments (DT-based and Standard) had the same effect size (Tab. 1).

In wheat, both Standard and DT-based treatments were significantly different from UTC (Fig. 2C). The heterogeneity test resulted in a I^2 = 84.9%, indicating a high heterogeneity between studies, and the test for subgroup differences was significant (p=0.0006) (Tab. 1). Comparing the ratio between SMD of the two treatments, the DT-based had 59 % disease severity lower than Standard.

When data of the three crops were pooled, comparing the effect size of each treatment to the untreated control, both treatments (Standard and DT-based) were significantly different from UTC (Fig. 3). The heterogeneity test resulted in a I^2 of 76%, indicating a high heterogeneity between studies, and the test for subgroup differences (p=0.0001) was significant (Tab. 1). Considering the ratio between SMD values of different treatments, the disease severity was 36% lower in DT-based compared to Standard.

2.4.2 TFI

In grapevine, a significant difference (p=0.0001) was found between the TFI in Standard (average TFI=5.1) and DT-based treatments for both organic (TFI=5.4, 6% higher than the Standard) and IPM viticulture (3.8; 25% less than the Standard) (Fig. 4A). The TFI of EX-based treatment was not significantly different from the Standard (p= 0.156, data not shown).

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In potato and wheat, the TFI of DT-based was significantly lower ($p=0.0001$) than that of Standard, with 20% and 39% reduction, respectively (Fig. 4B and 4C, respectively).

Then, the TFI of the three crops together was considered, finding no significant difference between the Standard and the DT-based treatments, being on average 4.2 and 4.1, respectively (Fig. 4D).

2.4.3 Yield

In potato, the yield in DT-based plots was not significantly different from Standard ($p=0.23$), with an average of 43 t/ha in DT-based and 42 t/ha in Standard plot (Fig. 5A). In wheat, the Standard yielded significantly ($p<0.05$) more grains than DT-based treatment, with averages of 11.7 and 11.0 t/ha, respectively (Fig. 5B).

2.5 Discussion and conclusions

Based on a large dataset covering several producing areas across the world and considering two of the most cultivated crops (wheat and potato) (FAO, 2023) and one of the most treated one (grapevine) (Perez et al., 2023) our results showed how decision tools (DT) may be fundamental to optimize PPPs applications, by reducing the TFI and at the same time maintaining or, in same case, improving the disease control, in accordance with the results of Lazaro et al. (2021).

DT-based treatment exhibited the best overall performance in the three crops, achieving a reduction in severity up to 59% and 10% in wheat and grapevine, respectively. Moreover, even TFI was reduced in the three cropping systems thanks to the adoption of DTs, indeed TFI was lowered by 25% in conventional grapevine, by 20% in potato and by 39% in wheat, as found by Lazaro et al. (2021) that indicated a decrease even higher following DSSs indications for several crops. Similar results were found in grapevine by Delière et al. (2015) that indicates a reduction between 30 and 50% in the TFI; in potato by Schepers et al. (2004) a reduction between 8 and 62%. In wheat, Prahl et al. (2022) showed that DSSs can reduce up to 50% the PPPs applied.

On the other hand, in our study, the worst result was reached when PPPs were applied following the EX-based strategy that led to the highest disease severity. This indicates that treatments reduction based only on field monitoring or phenological stages of crops, and not on models or forecast systems, can be risky, leading to uncertainties in disease control.

Our results indicated that in organic grapevine the TFI was not reduced in DT-based strategy, probably due to the higher complexity of the organic cropping systems that often involve a higher number of sprays, with the few allowed products (Commission implementing regulation (EU) 2021/1165), to effectively control diseases (Lazaro et al., 2021). However, other studies demonstrated that, even in organic farming, DSSs may effectively reduce TFI (Fouillet et al., 2022, Perez et al., 2023, Rossi et al., 2014).

These results are interesting because, even if TFI was generally reduced, DT use never determined an increase in the disease or pest level. Actually, in two out of three cases, the severity was even lower, and in the other one comparable, highlighting how those technologies can really optimize the plant protection products applications, as found by Caffi et al. (2010), Carisse et al. (2009) and Valdés-Gómez et al. (2017) in grapevine; by Eremeev et al. (2006), Liu et al. (2017) and Abuley (2019) in potato; and by El Jarroudi et al. (2014) in wheat.

Concerning crop yield, in accordance with Liu et al. (2017) and Abuley (2019) results, the adoption of Decision tools did not determine a reduction in potatoes, despite TFI reduction, meaning that the treatments missed based on DT were unnecessary. Our results indicated a yield reduction of about 6% in wheat, in agreement with Burke & Dunne (2008) who

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hypothesized that yield reduction can be related to a too early or too late spray application, thus the control may be sub-optimal compared to the Standard.

This study showed how Decision Tools may have the potential to reach a good reduction of PPPs, but it is needed to communicate to farmers the usefulness of this technology, being still low adopted (Rossi et al., 2019, Perez et al., 2023, Gent et al., 2013). Indeed, many farmers still perceive models riskier (Prahl et al., 2022, Möhring et al., 2020), or they prefer an additional spray application instead of a potential yield loss (Möhring et al., 2020). However, this study demonstrates the benefits of DTs. Increasing the adoption of DT in agriculture would require to involve farmers in several activities, such as demonstration events or testing DT-based strategy in small scale in their farms (Perez et al., 2023).

2.6 Figures and Tables

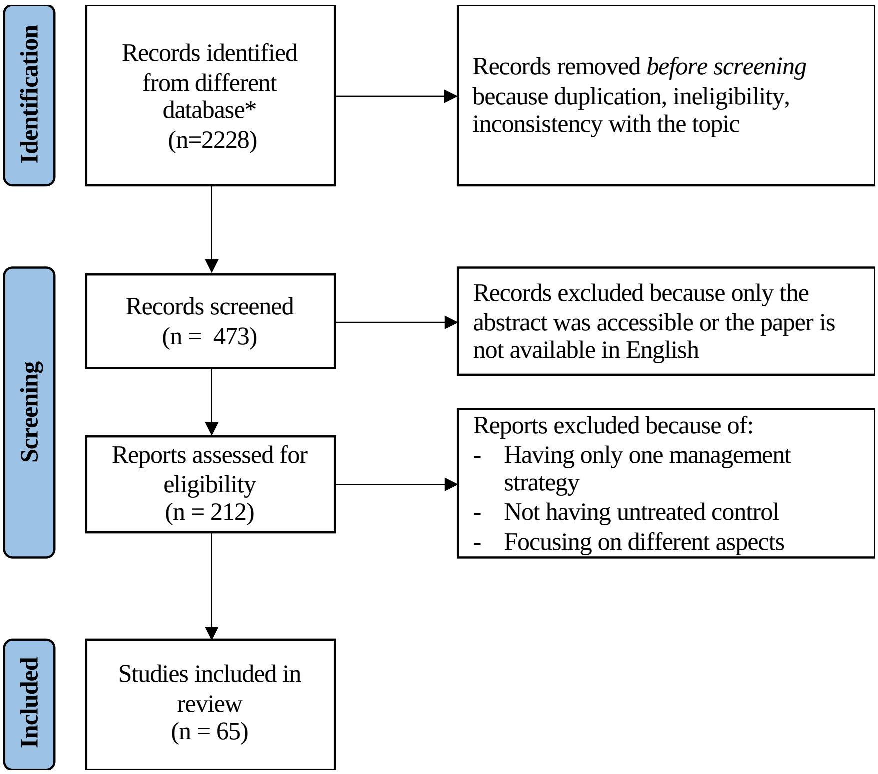

Figure 1. PRISMA flow diagram of paper selection process used in this study: the symbol (*) refers to the database accessed for retrieving papers and, in particular: Scopus, Web of Science, MDPI, PubMed, CABI and Google Scholar.

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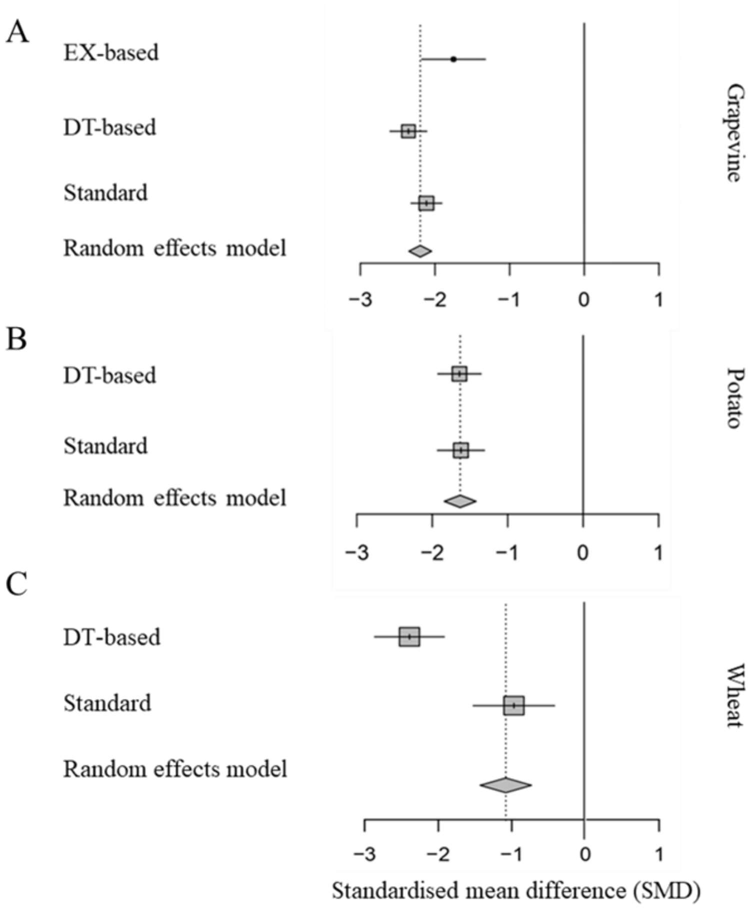

Figure 2. Effect of the disease management strategies (Standard, Ex-based or DT-based) on the effect size SMD (Standardised Mean Difference) on the disease severity on grapevine (n= 202) (A), potato (n= 155) (B) and wheat (n= 76) (C). SMD (grey squares) is the difference in Standard deviation units between each strategy and its corresponding UTC (UnTreated Control, black vertical line). Error bars indicate the 95% confidence interval, while the dotted line represents the overall weighted mean of the random effect model (grey diamond).

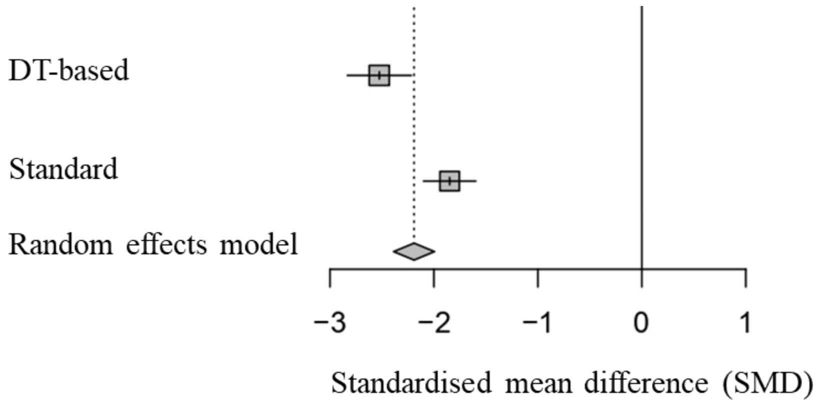

Figure 3. Effect of the disease management strategies (Standard or DT-based) on the effect-size SMD (Standardised Mean Difference) on the disease severity using all eligible studies (n=433). SMD (grey squares) is the difference in Standard deviation units between each strategy and its corresponding UTC (UnTreated Control, black vertical line). Error bars indicate the 95% confidence interval, while the dotted line represents the overall weighted mean of the random effect model (grey diamond). The diamond represents the overall effect estimate of the meta-analysis.

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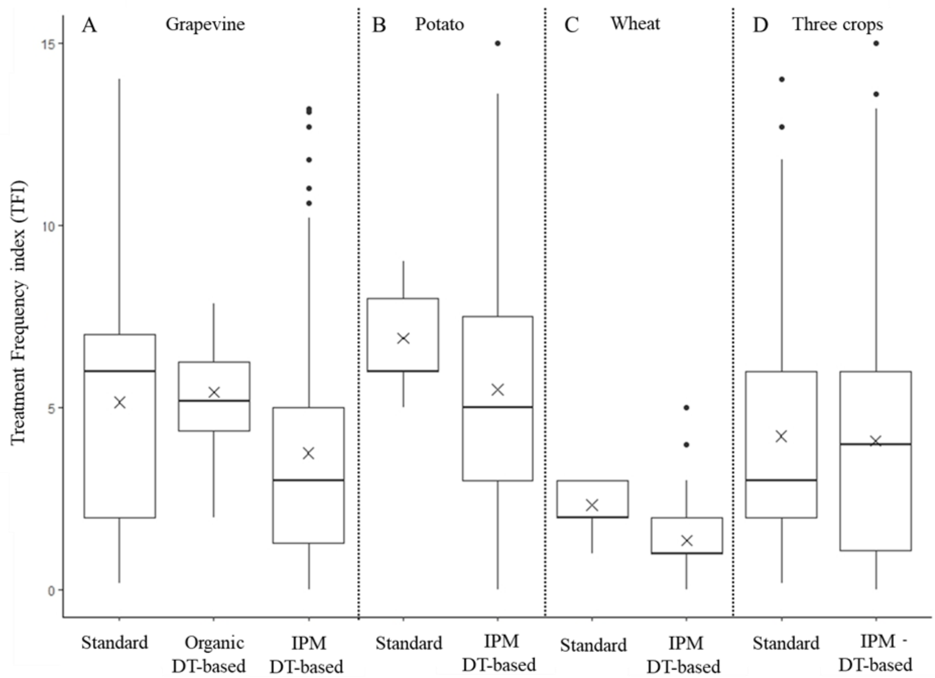

Figure 4. Treatment Frequency Index (TFI) calculated according to Gravesen (2003) for the Standard, IPM DT-based, and Organic DT-based (when available), crop protection strategies for grapevine (A), potato (B) and wheat (C) crops and the three crops together (D). Whiskers represent maximum and minimum values; the horizontal black line is the median, "x" represents the mean, while dots the outliers.

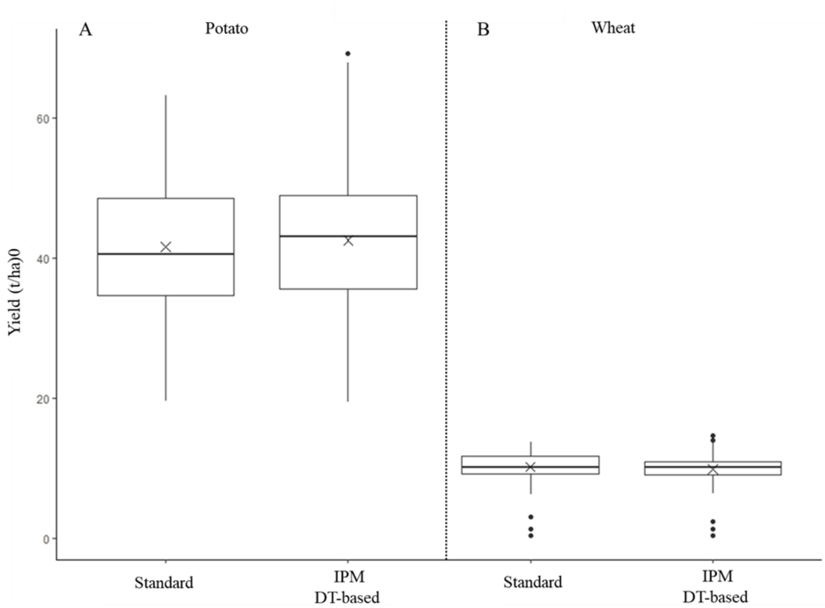

Figure 5. Yield (tons/ha) for the Standard and DT-based crop protection strategies for potato (A) and wheat (B) crops. Whiskers represent maximum and minimum values, the horizontal black line is the median, "x" represents the mean while dots represent the outliers.

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Table 1. Meta-analysis results for grape, potato and wheat, and the three crops together, expressed as effect size (SMD). Standardized mean difference was used to express the effect size, compared to UTC, and Confidential Interval (95%) of SMD. The heterogeneity between studies was estimated using I^2 test to quantify heterogeneity. τ^2 is estimated Standard deviation of underlying effects across studies. χ^2 represents results of test for subgroup differences

Data set	Crop protection strategy	N. of comparison	SMD	CI 95%		Heterogeneity		χ^2 test
				inf	Sup	I^2	τ^2	
Grape	Standard	202	-2.11	-2.32	-1.91	36%	0.1952 (p<0.0001)	6,92 (p=0.03)
	EX-based	44	-1.75	-2.18	-1.32			
	DT-based	158	-2.36	-2.6	-2.11			
	Random effect model		-2.2	-2.35	-2.05			
Potato	Standard	154	-1.62	-1.93	-1.31	55%	0.1849 (p<0.0001)	0,01 (p=0.93)
	DT-based	154	-1.64	-1.93	-1.35			
	Random effect model		-1.63	-1.84	-1.42			
Wheat	Standard	76	-0.97	-1.52	-0.42	84.9%	1.7376 (p=0)	14,85 (p=0.0006)
	DT-based	76	-2.39	-2.86	-1.92			
	Random effect model		-1.43	-1.08	0.73			
All crops	Standard	433	-1.85	-2.1	-1.6	76%	1.0238 (p=0)	18.43 (p<0.01)
	DT-based	433	-2.53	-2.83	-2.22			
	Random effect model		-2.19	-2.39	-1.99			

2.7 References

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3 Short survey on DSS

3.1. Summary

During the final year of the project (2024-25), a simple and short survey was created to examine the factors influencing the adoption or not of Decision Support Systems (DSS) by farmers and advisors, with the goal of understanding stakeholders' perspectives, potential barriers, and incentives for their use in crop protection. This survey represented the second step of the multi-step approach adopted to meet the objectives of the project within WP4. The survey was designed using Google Forms, ensuring anonymity. It was translated into multiple languages to reach a broad audience. The survey was disseminated with the help of Hub Coaches among the IPMWORKS farmer hubs and promoted also via social media channels.

The survey was divided into five sections. Firstly, gathered general information about respondents, their involvement in the IPMWORKS project and their experience with DSS. Based on responses, participants followed different paths of the survey: "user" or "not-users" paths.

70% of respondents were using DSS, and the vast majority were farmers or advisors. DSS "users" reported positive experiences, finding that DSS or models are tools useful for their cropping systems and may contribute to a significantly reduction in plant protection product (PPP) application. Among "not-users", 65% regularly consulted local phytosanitary bulletins. They highlighted lack of knowledge or trust as a principal barrier to their adoption.

The survey provided valuable insights into DSS adoption patterns, providing information about the barriers and potential improvements to enhance DSS or models use, increasing the accessibility and reliability perception of these tools, to achieve a more sustainable crop protection.

3.2. Introduction

A simple and short survey was designed to explore the factors and reasons influencing the adoption or not of DSS or models by farmers and advisors, aiming to understand stakeholders' perspectives, potential barriers or incentives to their use in crop protection. This survey represents the second step in the multi-step approach adopted to achieve the goals of this work package. In particular, the objective addressed in this section is the analysis of the current IPM DSS consultation within IPMWORKS and associated networks.

Thus, data collected from several respondents across Europe could provide valuable insights about factors influencing DSS and/or models adoption by final users, as farmers and advisors. The results could help in understanding and improving usability, reliability, and effectiveness of DT to achieve a sustainable crop protection strategy.

3.3. Survey structure

The short survey on DSS was developed on "Google forms". The survey was anonymous and did not collect any personal information. In order to reach as much stakeholders as possible, the survey was translated into the several languages, as follows: English, Italian, French, Spanish, German, Portuguese, Slovenian, Finnish, Dutch, Serbian, Danish, Greek and Polish. The survey was disseminated through the help of Hub Coaches among the IPMWORKS farmer hubs and the other IPMWORKS partners. Then, it was also sponsored through social media channels like

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LinkedIn. The survey was conducted during the last year of the project, establishing the deadline for the end of January 2025.

The survey was structured as with five main sections:

- Section 1 was about general information, in particular: the country, the main job, if respondents are part of IPMWORKS or IPM Decision networks, and if they have tried to use DSS. Based on the answer given to the two last questions, the respondents followed different Section paths.
- Section 2 asked about the "IPM Decision" platform;
- Section 3 asked about which DSS they use.
- Section 4 asked if farmers advisors are using DSS and if farmers are normally consulting the local phytosanitary bulletin.
- Section 5 was divided into two paths: the users and not users paths, respectively.

Thus, more in detail, if they answered being part of one of the two projects network in Section 1, they moved to Section 2, where we asked if they have tried the "IPM Decision" platform (IPM Decisions Platform), that provides several decision support systems and models for several crops for free (Marinko et al., 2024). Depending on the answer to "have you ever tried to use DSS" in Section 1, different questions were posed.

If the answer was "I never tried DSS", they will follow the "not user" question path of the survey; thus, in Section 4 the survey asked three questions as follows: "Do you know if your advisor is using a DSS?"; "Do you normally consult the local phytosanitary bulletin?"; and "Why have you never tried DSS or models?"

The "not users" survey then concluded with Section 5 about their opinion on DSS, trying to understand the reasons for not using DT. A set of sentences were reported, and the respondent was asked to give a score to each sentence, from 1 to 5, where 1 was "I totally disagree with the statement" and 5 was "I totally agree with the statement". The sentences were: "There are not models/DSSs for my cropping system"; "Model outputs are not reliable and useful"; "DSS/models dashboard is complicated"; "DSS/models are not user-friendly".

On the other hand, if in Section 1 the answer was "I'm using DSS/models", they will follow the "user" question path of the survey; thus, in Section 2 if they have tried "IPM Decision" platform, and then in Section 3 the survey asked "which DSS/model are you using?".

The "users" survey then concluded with the Section 5 about their opinion on DSS/models, in order to understand which are the positive or negative aspects of their adoption. A set of sentences were reported, and the respondent was asked to give a score to each sentence, from 1 to 5, where 1 was "I totally disagree with the statement" and 5 was "I totally agree with the statement". The sentences were: "Models are useful for my cropping system"; "Models output are reliable and useful"; "The user-dashboard is clear and intuitive"; "DSS/models are very easy to use"; "Would you estimate that using the DSS reduced the use of PPPs?".

3.4. Survey results

We received a total of 89 answers, from 14 different countries (Fig. 6), with about 70% of the respondents being farmers or advisors (Fig. 7). Only 43% of the answers were from IPMWORKS network members, but 70% of the respondents were users of DSS.

Among non-users, 65% indicated that they normally consult the local phytosanitary bulletin to schedule treatments application. Only 27% of them were aware of the use of DSS/models by their advisors, while the majority (42%) did not know. Then the survey asked the main reasons of not using DSS, with an open question, the most frequent answers were "I don't know the

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tools or lack of knowledge about these tools"; followed by "I don't feel the need" or "models are not reliable" or "there are no models for my cropping system".

On the other hand, among the users, 41% have tried "IPM decision" platform, while others indicated different private DSS as Horta®, Doseviña etc. as the one that they normally use.

The final section of the survey was about users (Fig. 8) and non-users (Fig. 9) opinions about Decision Tools where they had to give a score from 1 to 5 to a series of sentences (1 = I totally disagree; 5 = I totally agree).

Among users, 63% found models useful for their cropping systems (value >4); 57% found models output reliable and useful, 51% the dashboard clear and intuitive and models easy to use; while 48% indicated that the models use allowed a reduction in PPP use (Fig. 7); on the other hand only few users provide negative answers (value <2), about 8.5% do not find models/DSS useful and their output reliable; only 6% indicated that the dashboard is not clear and intuitive, while 14% indicates that models are not easy to use, and 20% did not reduce PPP thanks to the use of these tools (Fig. 8).

Among non-users, about 16% agree that there are no models for their cropping system (value >4); 21% found models output not reliable and useful; 5% found models dashboard complicated and 26% indicated that models are not user-friendly (Fig. 9).

3.5 Discussion and conclusions

The survey was able to cover most of the European countries, being characterised by very different agricultural conditions (Rega et al., 2020), and farmers and advisors were the most reached by the survey, while the others were partially involved as technician or DSS expert/researcher/student.

Even though "not-users" are not adopting DSS or models, 65% of them are consulting the local phytosanitary services, that in many cases are using models to support farmers in scheduling PPPs applications (Bregaglio et al., 2022). Moreover, even if the majority (42%) don't know if their advisor is using a model or a DSS, the 27% are aware of their use, thus we cannot exclude that many advisor are probably using DSS to support farmers, even though they do not know.

Furthermore, among the reasons why they are not using DSS, non-users indicated a lack of knowledge about these tools, thus this can indicate a further need of communication about these technologies and their potentiality. Other reasons were lack of trust and reliability of their output, that can be related to the use of empirical models in areas far from where they were developed, hence increasing their possibility to fail (Rossi et al., 2019). This indicates the potential need of teaching more about the different DT available and explain better which one is the best choice for a specific context. One more interesting answer was a lack of models for the cropping system, and this clearly can be a barrier to their adoption (Marinko et al., 2023). Up to now, most of the models are about the most cultivated crops (Fedele et al., 2022), and only few are for minor crops. However, with the increased interest for DT, in a next future more models and DSS will be developed also for other essential crops (Fedele et al., 2022). In the last section of the survey, among the most interesting results found is that only a small proportion indicates a lack of models for their cropping system. We should consider that among not users we had many technicians or DSS expert/researcher/student, thus not directly involved in the practical use of DSS, but probably knowing well the potentiality of these tools.

However, one reasons of not using DSS is confirmed in Section 5, where a 21% indicates a lack of reliability, and 26% indicates that DSS or models are not user-friendly, similarly to the results of Marinko et al. (2023). These two results can clearly indicate a need for implementing final-

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users knowledge about these tools, but also the need for improving the final user interaction with DT dashboard, making them simpler and more intuitive (Rossi et al., 2014).

On the other hand, most of the "users" agreed on the utility of these tools and reliability. However, only half indicated that DSS dashboards are clear and that DSS are user-friendly, again indicating how these tools can be improved for the final user. These can be a great barrier to their adoption (Rossi et al., 2014). One interesting result is that half of them agreed about the achievable PPPs reduction through DSS adoption, by optimizing the treatments scheduling, in agreement with several studies (Caffi et al., 2010; 2012; Rossi et al., 2012).

3.6 Figures

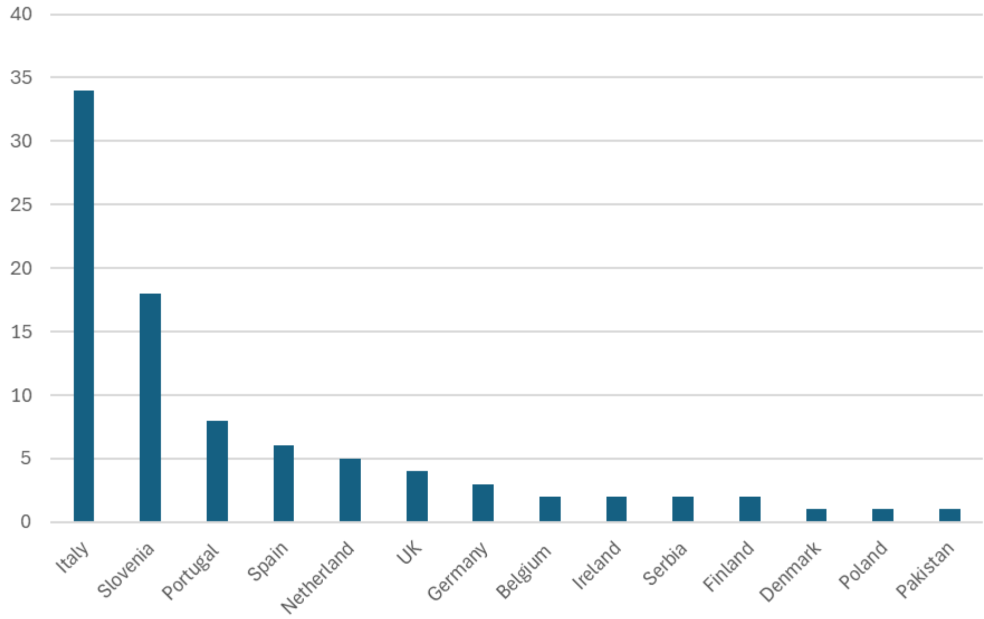

Figure 6. Number of survey respondents by country.

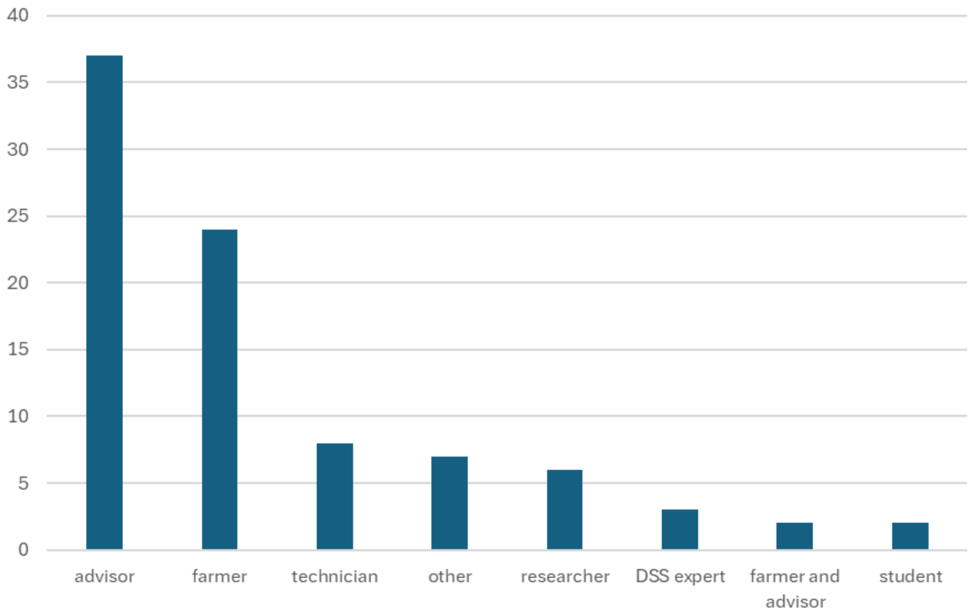

Figure 7. Number of survey respondents by job.

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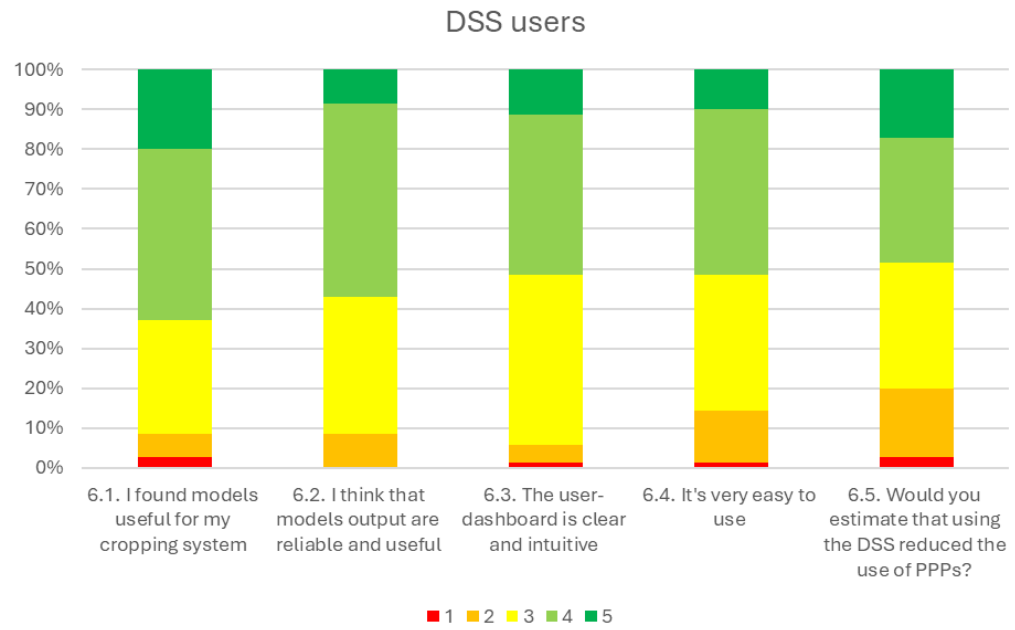

Figure 8. DSS users scores (1= I totally disagree; 5= I totally agree) to each sentence.

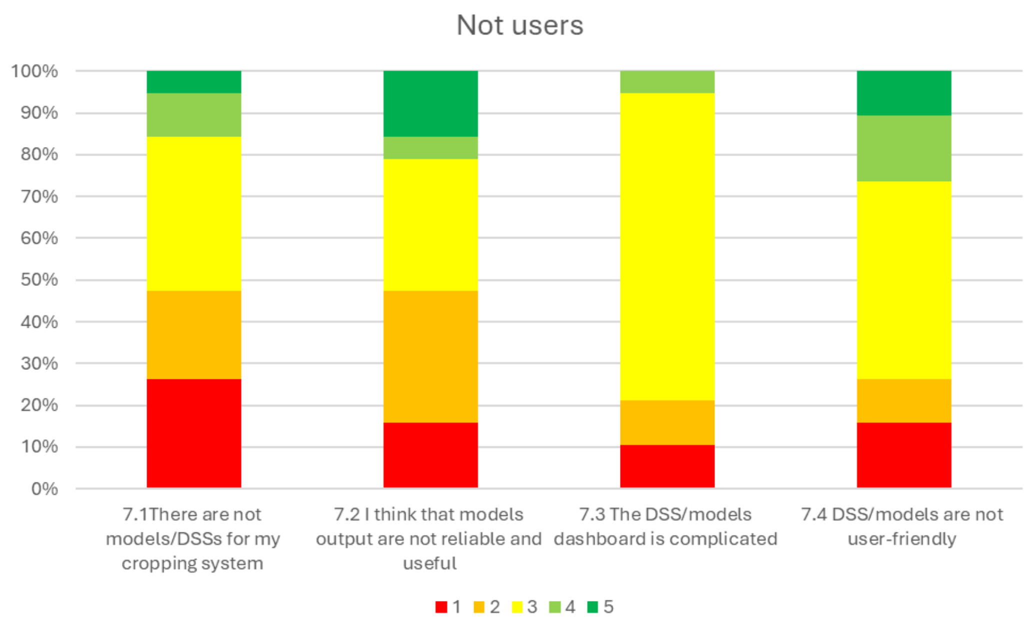

Figure 9. DSS not users scores to each sentence (1= I totally disagree; 5= I totally agree)

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4 IPM DSS case studies

4.1. Summary

The objective of this Work Package (WP4) was to compare traditional management practices, normally used by farmers, with Decision Support System (DSS)-based approaches for disease or pests control, based on trials that could be also used for demonstration events. Indeed, practical field demonstrations can be a powerful tool to promote and demonstrate the utility of innovative IPM-based strategies.

During the IPMWORKS project, we were able to set nine in-field comparisons based on DSS assessment: three of them in Italy on grapevine, chickpea and winter wheat, respectively; one in Scotland on potato; one in Sweden on wheat; two on winter wheat in England; one in The Netherland on winter wheat. The last comparison was done as an ex-post evaluation considering several grapevine growers across Italy, comparing their standard farm practice and the output of vite.net® DSS.

IPM DSS case study on grapevine in Italy

In the case study conducted in Tuscany (Italy) on grapevine downy mildew, the DSS vite.net® was used for two seasons (2022 and 2023) in an organic vineyard. DSS-based management reduced the number of treatments, between 64% and 58%, and the total copper amount, between 34 and 62%, compared to the conventional practice. The economic analysis highlighted the potential reduction in the total crop protection strategy cost by 45-56%, demonstrating both financial and environmental benefits of DSS adoption.

IPM DSS case study on chickpea in Italy

In the case study on chickpea, the DSS legumi.net® helped farmer in optimizing the sowing density and date, determining an increase in the final yield compared to the standard practice, in terms of total fresh biomass (+17.3%), dry grain weight (+29%) and chickpea number per square meter (+36%) (see also Deliverable 3.7).

IPM DSS case study on wheat in Italy

The last comparison conducted in Italy was on wheat. The DSS grano.net® was adopted for two seasons, considering multiple diseases potentially affecting crop, as rusts, septoria tritici blotch and fusarium head blight. In both seasons, the two disease management strategies achieve a similar diseases control, with the same number of treatments, even in the second season that was characterized by a higher diseases pressure.

IPM DSS case study on potato in the UK

In the case study conducted on potato in Scotland, historical data were analysed comparing fungicide applications based on calendar application (standard) and based on the risk alert provided by Hutton criteria model, for seven seasons. On average, model adoption allowed a reduction of 1.7 treatment applications per season, without increasing the disease level. The yield was considered only during 2019, founding a slight increase (+2.7%) in model-based strategies.

IPM DSS case study on wheat in Sweden

Seven plots were set in Sweden on winter wheat to compare model-based strategies and the standard farmer practices for the diseases control. However, the season was characterized by a

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low diseases pressure, and in four out of seven plots, models never suggested a fungicide application, while in remaining three plots *Septoria triticii* blotch or tan spot diseases symptoms appeared. For both diseases, the model-based strategy was able to achieve the same control of farmer practice and a comparable yield, in most cases reducing the number of fungicide application, thus, potentially unnecessary (see also Deliverable 3.7).

IPM DSS case study on wheat in the UK

Three more comparisons were conducted on winter wheat for the control of Barley yellow dwarf virus (BYDV) and its vector, two in England and one in The Netherland. The first trial in England tested the T-sum model, available on the "IPM Decisions" platform, in both an IPM approach (only model-based) and in a holistic approach where T-sum model was used together with field observations. These two strategies were compared to the risk-averse approach (conventional). The IPM approach sprayed only twice in the season, conventional sprayed 4 times, while in holistic IPM approach no treatments were applied. Overall, the holistic IPM did not show a higher aphids density or BYDV symptoms in field compared to the conventional, but yield was reduced. On the other hand, the highest yield (t/ha) was achieved in innovative IPM approach. The second trial in England was comparing two DSS, T-sum and ACroBAT, for BYDV disease and vectors control, considering two wheat varieties with different susceptibility to the disease. The season was not favourable to aphids and disease, and both DSSs did not suggest any insecticide applications. Yield was variable within the same field and among different plots, due to a poor crop establishment and different varieties potential. The impact of DSS in disease management was not particularly evident due to the low aphid presence and low risk of BYDV disease.

The last case study on BYDV disease was conducted in the Netherland, where two fields were managed according to the T-sum model suggestions. In one additional field, model and delayed sowing date were tested as practices to reduce the risk of aphids and then BYDV disease. The T-sum model suggested to treat due to the high risk, however, due to the wet soil conditions, insecticide treatment was not applied. Even though, in spring no symptoms were present, probably indicating that aphids were not transmitting the virus. In the third field, the model did not reach the threshold triggering treatment, thus thanks to the delayed sowing date the risk was reduced compared to the other two fields.

IPM DSS case study on grapevine in Italy

The last comparison was an ex-post analysis of 180 vineyards, in four different regions across Italy, characterized by different environmental and growing conditions, for three seasons. The comparison between DSS-based strategy (vite.net®) and farmers practices was conducted in terms of treatment frequency index (TFI) and using several environmental indicators to compare the two practices as: Carbon footprint, human toxicity score, eco-toxicity scores. The DSS-based strategy was generally characterized by a reduced number of fungicide applications and improved indicators values, indicating an improvement in the total sustainability of the crop protection strategy.

These comparisons, conducted in both perennial and annual crops, have demonstrated the potentiality of DT (models or DSS) compared to the standard practice used by farmer. In most of the comparisons, the number of applications or TFI was reduced following the suggestion of models/DSS. In some crops, as chickpea and potato, the yield was even improved, while in grapevine the DSS adoption determined a reduction in crop protection costs and an improvement in the overall sustainability as measured through environmental indicators. In none of the comparisons the disease level in DT-based plots was higher than conventional practice. These findings provide evidence of DSS efficacy and reliability as tools to support farmers in optimizing crop protection strategies. DSS can contribute to lower treatments and to achieve more targeted interventions, with potential reduction in input costs and environmental

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impacts. Ultimately, DSS can support a transition to more sustainable agricultural systems across European countries and in different crops.

4.2. Introduction

Decision Support Systems (DSS) are essential tools to optimize fungicide applications for managing diseases. DSS use allows farmers to make informed decisions, potentially reducing fungicides input without compromising disease management or yield, as already demonstrated through the meta-analysis results reported in Chapter 2.

The objective of this Work Package (WP) was to compare traditional management practices, normally used by farmers, with Decision Support System (DSS)-based approaches for disease control; in particular, the objective of this section was to develop a short series of IPM DSS case studies, evaluating the on-farm impacts and benefits.

During IPMWORKS project, as part of IPM field demonstrations, nine field comparisons were set up, on different crops and in various areas across Europe, assessing the impact of DSS-based strategies under real farming conditions. Farmers involvement in in-field trials was on a voluntary basis and detailed in **IPMWORKS Deliverable 3.7** (Francis, C., Dearlove, E., Jones, I., and Ramsden, M., 2025). **Four cases, specifically investigated the use of DSSs in IPM and for this reason they were selected also for further analysis, as part of WP4 activities**. In addition, three more case studies were conducted in Italy on grapevine, chickpea and wheat, respectively; one in Scotland on potato and a further case study was performed as an ex-post evaluation considering several grapevine growers across Italy, comparing their standard farm practice and the output of vite.net®, a DSS provided by Horta srl (Italian company linked with IPM Decisions platform). Results of these comparisons provided valuable evidence on the benefits of DSS in IPM supporting wider adoption and encouraging farmers and advisors to integrate these tools into their crop protection strategies.

4.3. IPM DSS case studies

4.3.1 IPMWORKS DSS Case Study #1 – Using DSS to target copper-based fungicides on organic grapevine in Italy, 2022-2023.

Introduction:

Grapevine plants are affected by several diseases as downy (caused by *Plasmopara viticola*) and powdery mildews (caused by *Erysiphe necator*) or black rot (caused by *Guignardia bidwellii*) that can determine severe yield losses and quality reduction (Gessler et al., 2011; Gadoury et al., 2012; Molitor & Beyer, 2014). In organic grapevine production, only phytosanitary products reported in Annex II of Reg. 2018/848/EU can be applied to control diseases.

In this case study, the aim was to compare the use of a decision support system and the standard conventional practice normally used by farmers to manage the main disease affecting vineyards, in a commercial organic farm. The comparison was conducted under both technical and economical perspectives.

Material and Methods:

"Il Borro" farm, located in Tuscany (Italy), has 90 ha of organic vineyards, growing varieties as Chardonnay, Cabernet Sauvignon, Sangiovese, Merlot and Syrah, all susceptible to the main grapevine diseases.

Disease control is based on calendar intervention according to the conventional farm practice. The conventional practice was compared to the suggestion provided by a Decision Support

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Systems (DSS), vite.net®, for grapevine downy mildew control, where fungicides application was scheduled according to the risk and weather conditions. Being an organic farm, copper-based fungicides represent the main chemical products available to control downy mildew (Reg. 2018/848/EU; La Torre et al., 2008). The comparison was performed during two growing seasons: 2022 and 2023.

The two management strategies (conventional and DSS-based) were compared in terms of number of treatments and kg/ha of copper applied. An economic analysis was carried out on the costs of the two crop protection strategies, considering the cost of each fungicide treatment, the cost of fuel per hectare, and the cost of the DSS and weather station purchases.

Results:

During season 2022 a total of 14 interventions were carried out according to the conventional farm practice, while DSS suggested only 5 interventions to control downy mildew infections. Season 2023 was characterized by a higher number of rainfall events, especially during May, increasing the risk of downy mildew infections (Bove et al., 2020) compared to the previous season. In 2023, the conventional practice applied 19 fungicide interventions, while the DSS suggested only 8 (Fig. 10). The DSS allowed a reduction of 64% and 58% in fungicide intervention in 2022 and 2023, respectively.

The conventional practice applied about 4.2 and 3.9 kg/ha of copper in 2022 and 2023, respectively, while the DSS suggested applying 1.6 and 2.5 kg/ha of copper in the two seasons, allowing a reduction of 62 and 34% of copper, respectively (Fig. 11).

The cost of one treatment with a copper-based fungicide was estimated at 25 €/ha, the cost of fuel at 10 €/ha per intervention, the DSS purchase at 2.500 €/year and the weather station at 6.000€. During season 2022, the estimated cost of conventional practice for the 90 ha, based on the number of interventions and products applied, was about 44.100 €, while the cost of the management based on DSS was about 24.250 €. During 2023, the estimated cost of conventional practice was 59.850 €, while the DSS practice cost was 27.000 €, not considering the weather station purchase already done in 2022 (or 33.700 € including the weather station cost). Thus, the DSS practice allowed a reduction in the total management cost between 45 and 56%.

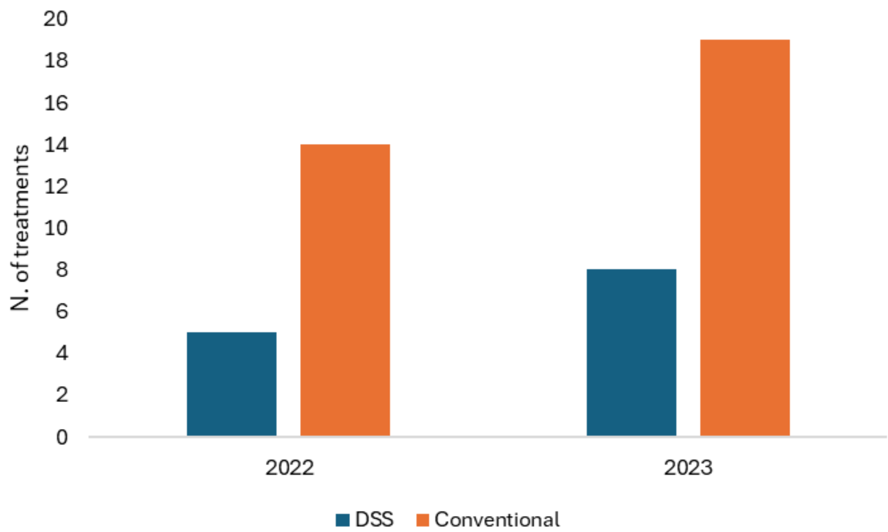

Figure 10. Number of treatments applied according to DSS and Conventional practice during season 2022 and 2023.

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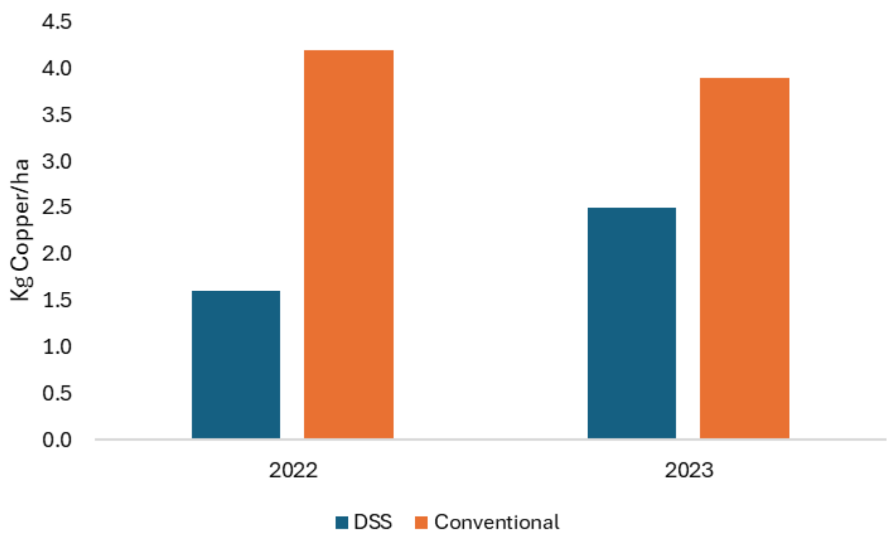

Figure 11. Copper (kg/ha) applied according to DSS and Conventional practice during season 2022 and 2023.

Discussion and conclusions:

The efficacy of the use of DSS vite.net® in controlling diseases on grapevine was already demonstrated (Rossi et al., 2014). Nevertheless, this trial showed the utility of DSS in vineyard protection strategies to significantly reduce both the total number of treatments and the total amount of copper (kg/ha) applied each year, compared to the conventional practice. The reduction was achieved in both seasons, with the highest copper reduction in the first season, that was less favourable to the downy mildew development, compared to the second. The decrease in the number of treatments and copper (kg/ha) did not negatively affect the crop protection efficacy, in agreement with results of Rossi et al. (2014), Delière et al. (2015) and Kuflik et al. (2009). Moreover, the economic analysis carried out in this case study has also estimated a potential decrease in the cost of crop protection strategy between 45 and 56%, thanks to the DSS adoptions, as found by Rossi et al. (2014).

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4.3.2 IPMWORKS DSS Case Study #2 – Using DSS to optimize chickpea production.

Introduction:

Some Decision Support Systems integrate several models, such as diseases, insects models, or crop model describing phenology and growth, or weather models etc., by adopting the multi-modelling approach (Fedele et al., 2024). Multi-modelling takes into consideration the huge number of variables affecting crop growth and production, integrated into one single system, in order to support farmers in the decision-making process and in the management of the agro-system complexity (Fedele et al., 2024).

In this case study, chickpea production was considered. The objective was to compare the conventional farmer practice and the suggestions provided by the DSS for the entire chickpea production cycle, supporting farmers since the sowing time. The entire crop cycle was considered, and the DSS was used for decision making to maximize yield and minimize interventions and inputs.

Material and methods:

The chickpea case study was conducted at "Azienda Agricola Musu Francesco", located in Tuscany (Italy), where the grower normally rotates wheat and chickpea (var. Lambada), over a total of 80 ha. The trial was conducted during season 2023, comparing the conventional farm practice to suggestions the DSS legumi.net®. The DSS was used to determine the optimal sowing density based on a model developed for wheat (Rossi et al., 2010) and lately calibrated on pulses during the LIFE project AGRESTIC (Grant Agreement Number: LIFE17 CCM/IT/000062 www.agrestic.eu).

Weed control was achieved by combining both chemical and mechanical control, while the population of *Helicoverpa armigera,* one of the most important pests affecting chickpeas (Mahmood et al., 2021) was monitored with traps, applying insecticide only when the threshold was overcome. Main diseases affecting chickpeas, caused by *Fusarium oxysporum* (Pande et al., 2005) and by *Uromyces cicer-arietini* (Vandana et al., 2020) were monitored during the whole season.

At harvest, sampling was conducted to evaluate the difference between the two management techniques in terms of total fresh biomass (g/m^2), chickpea grain dry matter (g/m^2), and number of chickpea (n/m^2).

Results:

Chickpea sowing date was March 28th, delayed from the usual time (end of February) due to the wet conditions during spring. The farmer usually uses a sowing rate of 43 seeds/m^2, while the DSS suggested 45 seeds/m^2, keeping 50 cm interrow and reducing the row space from 4.7 cm to 4.4 cm. Weed control was necessary due to the wet conditions that favoured their development, in both managements by applying pre-emergence herbicides on March 29th, and post-emergence on May 5th, followed by mechanical weeding on May 9th. *Helicoverpa armigera* is an extremely widespread and polyphagous Lepidoptera (Noctuidae). It overwinters in the soil as a pupa (or chrysalis) and performs up to a maximum of 3 generations in our climate. The overwintering adults usually flicker between late April and mid-May and oviposit many eggs from which the larvae hatch. Upon reaching maturity, larvae incrisalidate in the soil forming pupae from which the first generation adults will emerge and oviposit, giving rise to the second generation, and so on. *H. armigera* population dynamic was estimated by the farmer by means of the specific model within the DSS legumi.net® (Fig. 12) and monitored with traps, placed in fields on July 1st. An insecticide treatment (active ingredient: deltamethrin) was applied during

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the second week of July, when the risk threshold (4 adults/day captured by trap) was reached, confirming the model simulation. No fungicide treatments were applied.

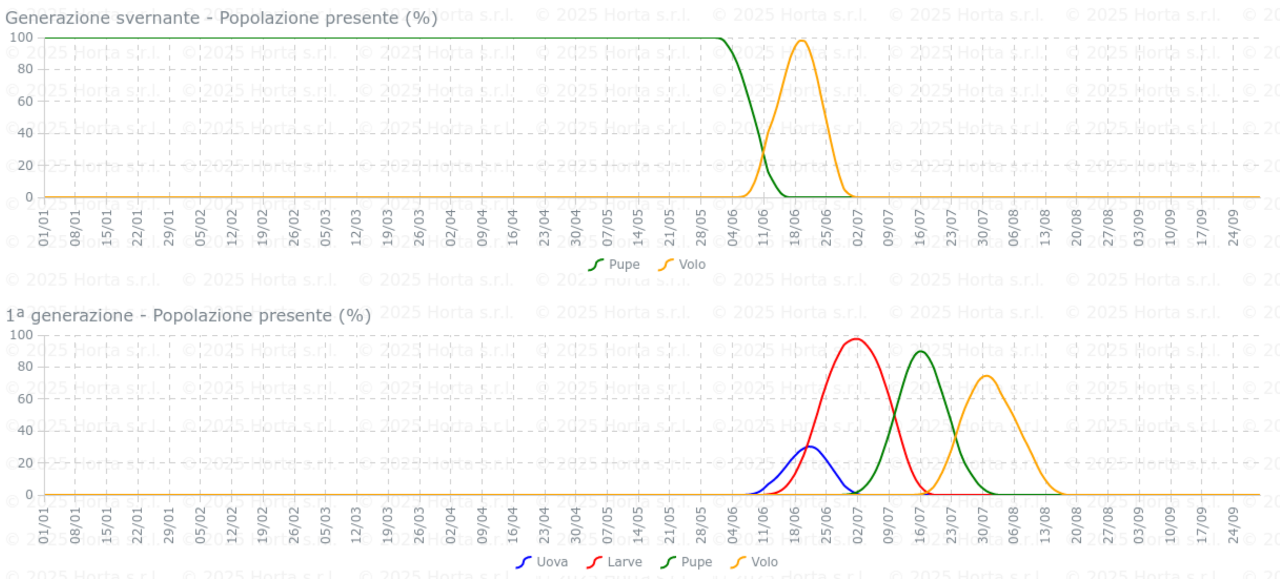

Figure 12. Output of Legumi.net® DSS: estimated dynamic of overwintering population of *H. armigera* (upper graph) as pupae (green line) and adult flight (yellow line); estimated development of the first generation (lower graph), as eggs (blue line), larvae (red line), pupae (green line) and adult flight (yellow line).

Harvest occurred on July 28th and chickpeas were sampled from the two management systems to evaluate yield parameters. The total fresh biomass was about 594 g/m^2 in plot managed according to DSS suggestions, and about 506 g/m^2 in conventional plot (Fig. 13). Thus, DSS resulted in an increase in fresh biomass of about 17,3%. The dry grain weight in DSS plots was about 133 g/m^2, while it was about 103 g/m^2 in conventional plots. Thus, the DSS increased dry grain per m^2 by about 29% (Fig. 14). The number of chickpeas per m^2 was about 281 and 206 in DSS and conventional plots, respectively, corresponding to an increase in chickpeas density of about 36% by following DSS suggestions (Fig. 15).

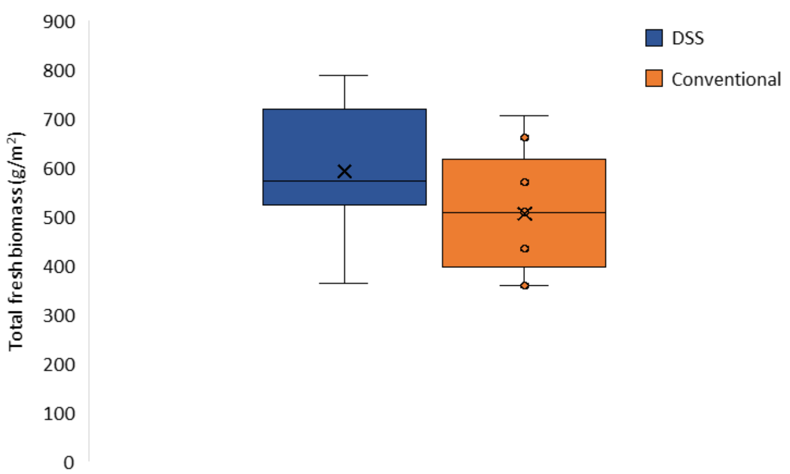

Figure 13. Total fresh chickpea biomass (g/m^2) at harvest in plots managed according to DSS (blue) and Conventional (orange) practice during 2023.

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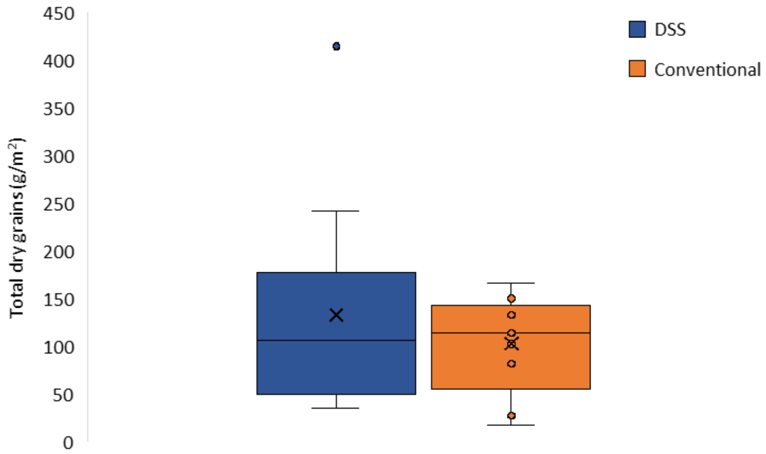

Figure 14. Total dry weight of chickpea grains (g/m^2) at harvest in plots managed according to DSS (blue) and Conventional (orange) practice during 2023.

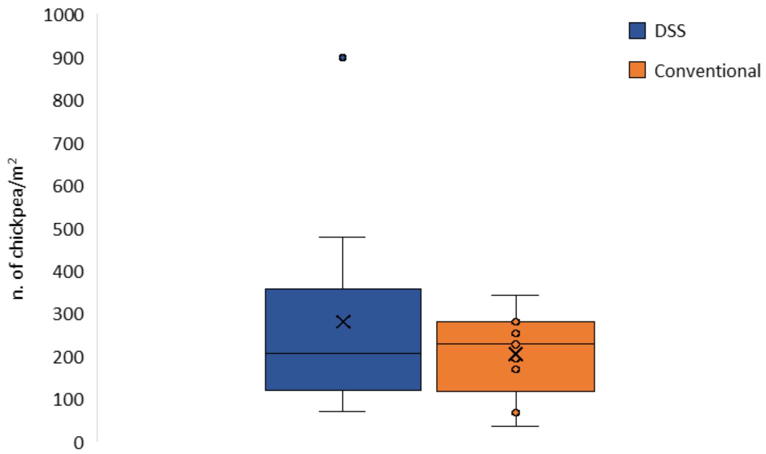

Figure 15. Total number of chickpeas per m^2 at harvest in plots managed according to DSS (blue) and Conventional (orange) practice during 2023.

Discussion and conclusions:

Legumi.net® DSS was tested for optimizing the entire chickpea production cycle. Thanks to the DSS suggestion, the chickpea sowing density was increased and the within row space was reduced. These changes have determined an increase in the final yield, in terms of total fresh biomass (+17.3%), dry grains weight (+29%) and number of chickpeas per square meter (+36%), compared to the conventional farmer practice. On the other hand, diseases did not develop during the seasons, thus in both systems no fungicide application was carried out. These case studies wanted to show how DSS can be integrated and use to optimize the entire crop cycle, with a holistic approach that consider all the crop production and protection aspects.

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4.3.3 IPMWORKS DSS Case Study #3 – Evaluation of winter wheat diseases control with grano.net® DSS for two seasons.

Introduction:

Wheat (*Triticum aestivum* L.) is the most cultivated crop in Europe (Eurostat, 2025) ranging from the Northern to the Southern European countries. Depending on the environmental conditions, wheat can be affected by several diseases, that can cause severe damages and yield reductions in both quantity and quality (Figueroa et al., 2018). In Italy, wheat is the most cultivated cereal (Istat, 2025), and according to the regional disciplinary of production (Regione Emilia-Romagna, 2024), two treatments maximum can be applied to control wheat diseases. Fusarium head blight, caused by *Fusarium sp.,* septoria tritici blotch, caused by *Septoria tritici*, and yellow and brown rusts (*Puccinia sp.*), are the most common diseases affecting wheat in Italy (Serfling et al., 2016, Birr et al., 2020, Thomas et al., 1989). Due to the limited number of fungicide applications allowed, DSS may represent a valuable tool to more precisely define the most appropriate moment for their application (Rossi et al., 2010).

In this case study, two management practices were compared, namely the conventional farmer practice (with calendar-based application of fungicides) and a DSS-based strategy, and diseases were monitored during the growing period to assess possible differences between the two systems.

Material and methods:

The Italian wheat case study was conducted in two farms located in the Emilia-Romagna region (Italy) during two growing seasons, 2022 and 2023. Plots were sown with winter wheat on October 29th during the first season (var. Rebelde) and on October 28th in the second season (var. Rebelde and var. Altamira). The DSS adopted was grano.net®. The active ingredients used were triazole against septoria blotch rust and QoI against fusarium head blight. Disease assessments were conducted during both seasons in the two farms to evaluate the incidence and severity of the main diseases affecting winter wheat in the area, as septoria tritici blotch, rusts and fusarium head blight, at critical phenological stages (Zadoks et al., 1974) for diseases: flag leaf (BBCH 37-39), ear completely emerged above flag leaf ligule-start of flowering (BBCH 59-61), full-flowering (BBCH 65), and late milk stage (BBCH 77-80). Disease incidence was evaluated with a scale from 0 to 3 (where 0 indicates no symptoms, 1: few plants with symptoms, 2: several plants with symptoms, 3: most of the field with symptoms). Disease severity was evaluated with a scale from 0 to 4 (where 0 indicates healthy plant, 1: symptoms only in the basal part of the plant, 2: mild symptoms in the upper part of the plant (last three upper leaves and ear), 3: severe symptoms in the upper part of the plant (last three upper leaves and ear), 4: whole plant is compromised).

Results:

In season 2022, septoria blotch was the most prominent disease, already detected during the first assessment in both farms and both plots. However, symptoms were only present on leaves until the end of the season. During the last assessment some sporadic rust symptoms were found. Both management systems (conventional and DSS-based) included two treatments, and showed the same diseases incidence and severity at harvest (Fig. 16 a).

During season 2023, both management systems included only one treatment. At the first assessment, sporadic septoria tritici blotch symptoms were found only in one farm. During the second assessment, septoria symptoms were more diffused and present in both farms, while yellow rust symptoms were sporadically present in both farms, but only on leaves. Furthermore, brown rust had a higher incidence than yellow rust in one farm, but only on leaves. At full-

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flowering, septoria, yellow and brown rusts maintained the same incidence and severity as at the previous assessment, while at BBCH 77-80 septoria symptoms increased only in one farm, yellow and brown rusts were quite diffused in both farms. Very few symptoms of fusarium head blight were found during the last assessment, but with high severity (Fig. 16 b). On average, conventional and DSS-based disease management reached the same control in both farms in both seasons (Fig. 16).

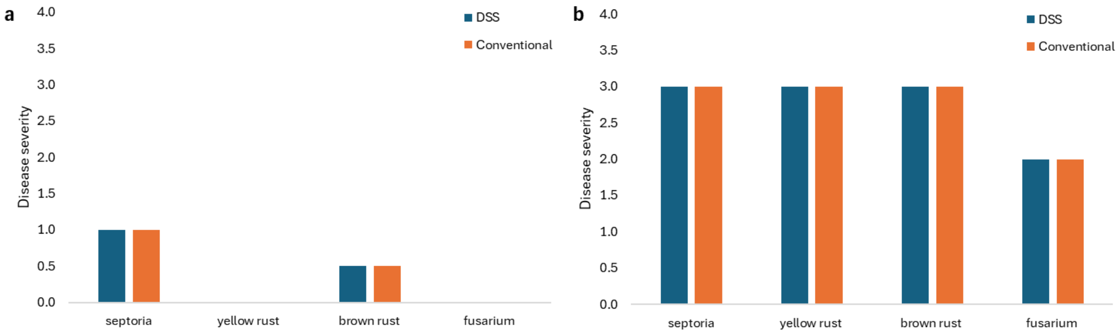

Figure 16. Average diseases severity of the two farms according to the DSS (blue) and Conventional (orange) management in seasons 2022 (a) and 2023 (b) at stage BBCH 77-80. The disease assessed were: septoria, yellow and brown rust and fusarium head blight. disease severity was evaluated with a scale from 0 to 4: 0 healthy plant; 1 symptom only in the lower part of the plant; 2 mild symptoms in the upper part of the plant (3 last upper leaves and ear); 3 severe symptoms in the upper part of the plant (3 last upper leaves and ear); 4 whole plant is compromised.

Discussion and conclusions:

In this case study, conducted in two wheat farms for two years, the calendar-based fungicide application and the DSS-based management produced the same results, both in term of number of treatments and of disease severity. Four main diseases were considered, fusarium head blight, septoria leaf spot, yellow and brown rusts, and no one presented a higher severity in the DSS-based strategy. Thus, also facing regulatory limitations in terms of products availability and timing of fungicide applications, the use of a Decision Support System allows the farmer to obtain, at least, the same results of a calendar-based approach. This aspect can be extremely relevant with regard to the spread of DSSs use among growers: maybe not everyone is skilled enough or expert to decide the proper timing of application. In such cases, the information retrieved from a DSS can help rooky farmers (see also chapters 2 and 3 for more discussion on this aspect).

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4.3.4 IPMWORKS DSS case study #4 – Hutton Criteria Model for Potato late blight control optimization.

Introduction:

Potato is very important crop in North Europe, that can be severely affected by diseases, as potato late blight, caused by blight (*Phytophtora infestans*), causing important yield reduction (Tsedaley, 2014, Dowley et al., 2008). Fungicides still represent the main method for controlling the disease (Koppel et al., 2025). However, their application can be optimized through the adoption of models and/or decision support systems (Schepers, 2004), as already seen in the results of D4.4 Chapter 2 “Meta-analysis”.

This case study was based on historical data about treatments application to control late blight in plots managed according to the conventional practice adopted by farmers, and according to model risk alert, respectively. The Hutton criteria model, available on the “IPM DECISION” platform, was specifically assessed. The Hutton criteria model was developed to forecast potato late blight occurrence, based on weather conditions, and suggests or not a fungicide application based on the estimated risk. The high-risk alert occurs when two consecutive days have a minimum temperature of 10°C and at least 6 hours of relative humidity of 90% or higher (Dancey et al., 2017).

Material and methods:

The Potato case study was conducted at Balruddery Farm, Angus (Scotland), where Maris Piper variety was grown, a moderately resistant variety to potato late blight (Koppel et al., 2025). Historical data, from 2017 to 2023, were reporting the number of treatments. Yield data could be considered for season 2019 only.

The conventional practice was based on repeated sprays every 7 days, while the innovative management (integrated) used Hutton criteria model to estimate the disease risk and schedule the spray application accordingly.

Results:

The model adoption reduced by 1-3 applications over the season (Fig. 17), without increased risk for the crop. On average over 2017-2023, the conventional calendar-based practice applied 11.8 treatments per season, while the innovative (integrated) practice applied 10.1 treatments, therefore saving 1.7 treatments per season on average. Estimating a spray cost of 30 £/ha, this adds up to a substantial saving over a larger area.

Moreover, the yield in season 2019 was 39.5 t/ha in the conventional practice, and 40.6 t/ha in the DSS-based practice, that therefore allowed a slight increase in yield (+2.7%).

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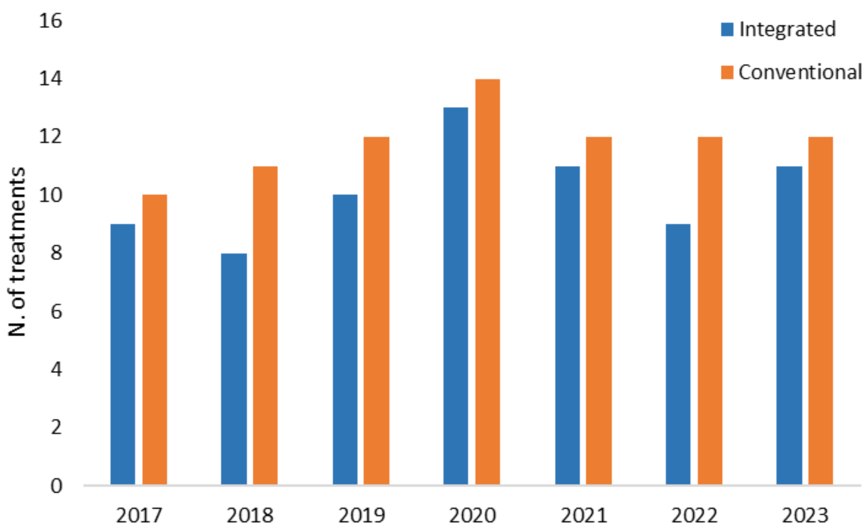

Figure 17. Number of treatments applied per season according to conventional (orange) and integrated (blue) practices between seasons 2017 and 2023.

Discussion and conclusions:

The main strength of this case study is the 7-year period of comparison of the two crop protection strategies. It demonstrated that model-based strategies can really reduce the number of treatments, avoiding the unnecessary ones (Schepers et al., 2004). Indeed, even if yield data is reported for one year only, the final yield (t/ha) was not reduced, but even slightly increased in the integrated plot.

This is a further example of the utility of models in scheduling crop protection intervention, ensuring effective disease control with reduced number of fungicide applications, while yield is maintained or even increased.

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4.3.5 IPMWORKS DSS Case Study #5 – Exploiting available models on the "IPM DECISION" platform in winter wheat in Sweden.

Introduction:

In Sweden, winter wheat is one of the major cultivated crops, that can be severely affected by diseases, as septoria triticii blotch (*Zymoseptoria tritici*), with variable infection level according to weather conditions and variety susceptibility (Jalli et al., 2020). Diseases are mainly controlled with preventative applications of fungicides during the most critical phenological stage of plant susceptibility. However, the adoption of models or DSS can optimize fungicide applications (Jørgensen & Hagelskjær, 2003; Burke & Dunne, 2008; Jørgensen et al., 2020; Andersson et al., 2022), avoiding the unnecessary ones. This comparison aims to assess the performance of available models on "IPM DECISION", suggesting the best timing for fungicide applications based on the estimated risk for winter wheat. In this study, two models were used: Septoria Humidity model and infection risk of tan spot model.

Material and methods:

In mid-south Sweden, 7 trials were conducted during 2023 by the Sweden Agricultural University with winter wheat, to compare conventional farmer practices and the innovative decision-making for treatments application, based on models output. The comparison is based on the same fields as those described in IPMWORKS Deliverable 3.7 (Francis, C., Dearlove, E., Jones, I., and Ramsden, M., 2025). Two diseases were considered: septoria tritici blotch (*Septoria tritici*) and tan spot (*Pyrenophora tritici repentis*) (Serfling et al., 2016, Thomas et al., 1989).

Four different conventional practices were evaluated: i) application of only one fungicide treatment at stage 39; ii) application of only one fungicide treatment at stage 47; iii) application of two fungicides sprays at stages 39 and 55; iv) application of three fungicide sprays at stages 32, 39, 55. Wheat phenological stages were assessed according to Zadoks et al. (1974). The innovative practice applied none or one fungicide treatment according to the risk provided by model for septoria (Septoria Humidity model) (Fig. 18) and tan spot (Infection risk of tan spot in winter wheat model). Both models are available on the "IPM Decision" platform.

Septoria Humidity model aims to estimate the risk of septoria triticii blotch development. The model considers weather data from wheat growth stage 31 (GS 31). It estimates the risk of disease based on humidity. The risk is high when 20 consecutive hours of wetness occur, where an hour of wetness is defined as 0.2 mm of precipitation in one hour or a minimum relative humidity of 85%. To provide a more accurate and precise prediction, the date of GS31, GS32, GS33, GS37/39 and GS75 should be inserted into the model. Even the date of an eventual fungicide application can be inserted into the system, and the model then considers that the crop is protected for the 10 following days. Based on this information, the model provides an alert to farmers about the risk of disease development (Jørgensen et al., 2017).

Infection risk of tan spot in winter wheat model aims to calculate the daily risk of infection of tan spot. The model is a weather-driven simulation model, that calculates the probability of infection of tan spot, to provide alert to farmers about the period of high risk. Since the model do not consider agronomical factors, such as sowing data or variety susceptibility, the primary purpose of the model is to serve as indicator for field monitoring (IPM Decisions Platform).

Results:

In four experimental plots, diseases never developed during the season, and models did not suggest any treatment application. Only three plots showed diseases symptoms, two fields for septoria, located at Emtunga gård and Forsby (Fig. 18), and one field for tan spot, located at Staby säteri (Fig. 20).

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In Emtunga gård, the septoria humidity model did not suggest any fungicide application, and the disease severity was about 12%, significantly higher than in conventional plots (Fig. 18 a). However, the yield (t/ha) of the DSS plot was 10.2 t/ha, only slightly lower than the conventional plots (Fig. 19a). In Forsby trial, septoria severity was very low. In untreated plots the severity was about 4.4%. The model suggested one application during the season for controlling disease. Both model-based and conventional plots showed a very low severity, lower than 1% (Fig. 18 b). The yield (t/ha) in Forsby was generally higher than Emtunga gård plots, and plots managed according to model output had a yield of 11.47 t/ha, not significantly different from the conventional plots (Fig. 19 b).

In Staby säteri, tan spot model suggested only one application, and tan spot severity was about 2.5%, not significantly different from conventional plots, where severity ranged between 1.8 and 2.6%. All treatments were significantly different from the untreated control (6.5%) (Fig. 20). The yield (t/ha) of conventional and DSS plots ranged between 6.68 and 7.03 t/ha, without any significant differences (Fig. 21).

A deep economic analysis of the two systems is reported in Deliverable D3.7 (Francis, C., Dearlove, E., Jones, I., and Ramsden, M., 2025).

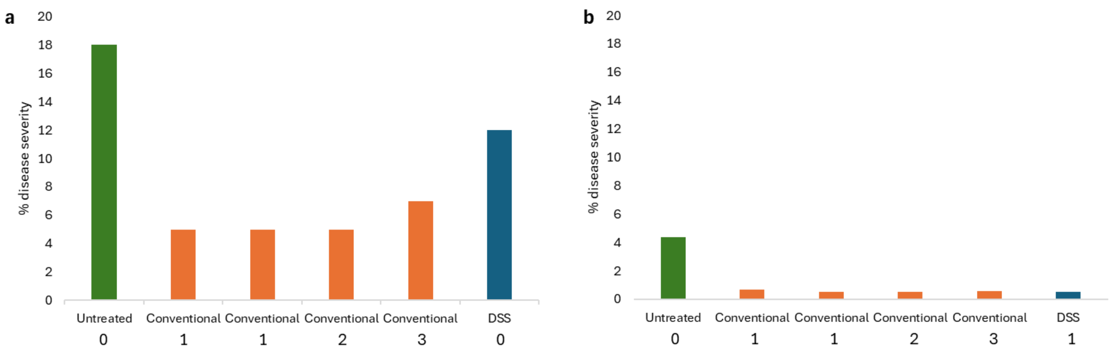

Figure 18. Septoria severity (%) in Emtunga gård (a) and Forsby (b) plots, according to the different management systems: untreated control, conventional practices, and model output (DSS) during 2023. The number below each treatment indicates the number of fungicides application during the season.

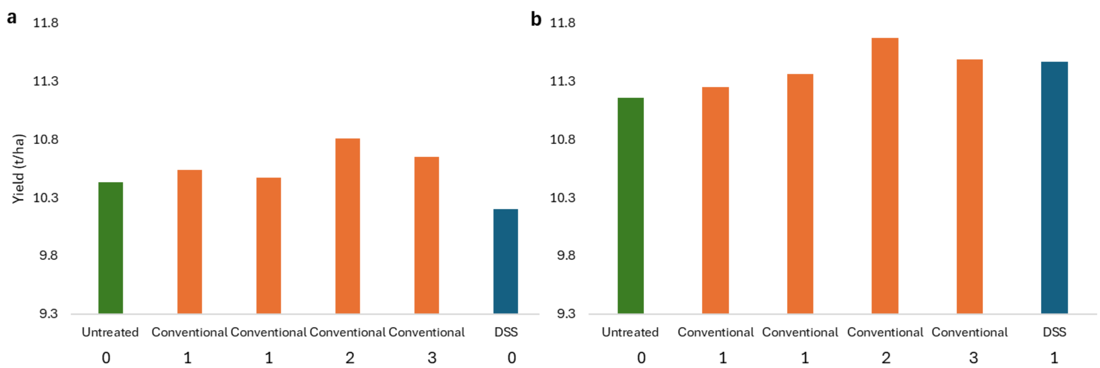

Figure 19. Yield (t/ha) in Emtunga gård (a) and Forsby (b) plots, according to the different management systems: untreated control (green), conventional practices (orange), and model output (DSS) (blue) during 2023. The number below each treatment indicates the number of fungicides application during the season.

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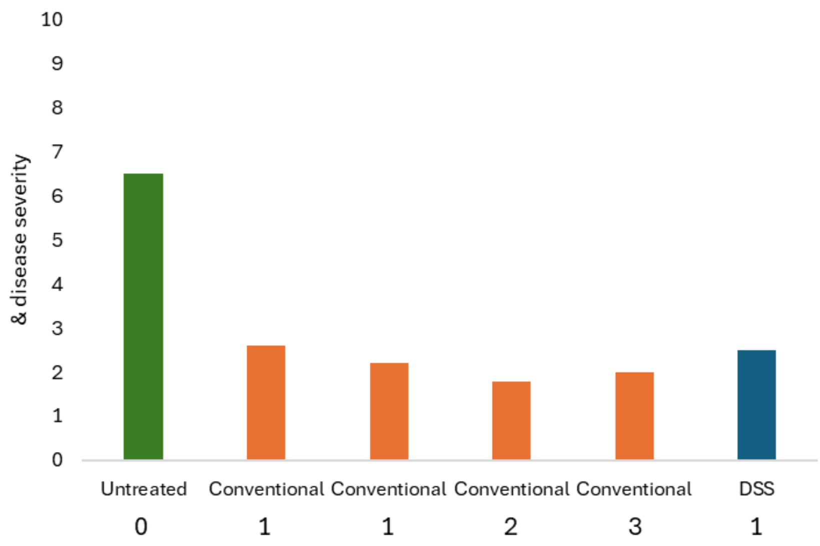

Figure 20. Tan spot severity (%) in Staby säteri plots, according to the different management systems: untreated control (green), conventional practices (orange), and model output (DSS) (blue) during 2023. The number below each treatment indicates the number of fungicides application during the season.

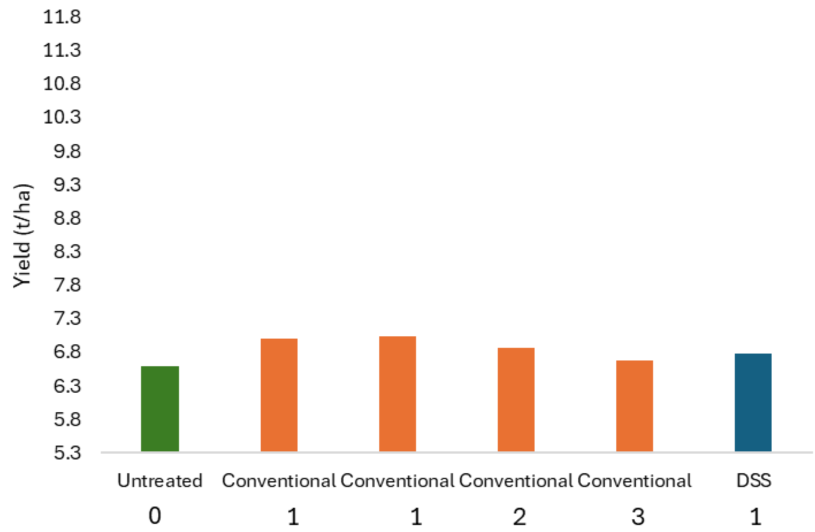

Figure 21. Yield (t/ha) in Staby säteri plots, according to the different management systems: untreated control (green), conventional practices (orange), and model output (DSS) (blue) during 2023. The number below each treatment indicates the number of fungicides application during the season.

Discussion and conclusions:

These trials demonstrated the good performance of the models in supporting farmers in winter wheat diseases management. Indeed, two different diseases were considered in different Swedish areas, and in both cases, the results were promising. In DSS-based plots the final yield was not statistically different from the conventional managed plot. The only yield reduction registered was in Emtunga gård plot, where the DSS did not suggest any treatment against septoria leaf blotch, and a slight yield decrease occurred. However, in Forsby and Staby säteri plots, the DSS suggested only one fungicide application, reaching the same diseases control of the conventional, where between 1 and 3 treatments were applied, and this without compromising the final yield.

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4.3.6 IPMWORKS DSS Case Study #6 – Exploiting T-sum model to optimize BYDV disease control in winter wheat in England.

Introduction:

Barley yellow dwarf virus (BYDV) significantly impacts cereals in UK, and severe infestations can cause yield losses in winter wheat and barley (Nancarrow et al., 2021). The virus is transmitted by bird cherry-oat aphids (*Rhopalosiphum padi*) and grain aphids (*Sitobion avenae*) and the control of virus is often mainly related to vectors control through insecticide application (Walls et al., 2019). Due to the increasing number of resistant insect vectors to the main insecticides (Foster et al., 2014), their application should be avoided or limited, and applied only when necessary, to avoid insecticide molecules losses. In this context, in addition to the anti-resistance strategy adoption, models or DSS may represent a further tool to optimize vectors control. A T-sum Decision support system is available on “IPM DECISION” platform, predicting the appearance of the second winged generation of aphids in the crop, which are associated with the start of secondary spread (HGCA, 2003).

The aim of this trial was to test the use of the DSS, T-sum model, developed to optimize BYDV disease and vector control in winter wheat, in terms of reduction in insecticides use, without negatively affecting the control efficacy and the final yield.

Materials and methods:

The experiments were set up in the east of England in autumn 2022 where winter wheat (var. Skyscraper) was grown over 27 ha. The case study was conducted comparing different strategies for controlling BYDV in winter wheat as follows: i) risk-averse approach, where the maximum amount of insecticide permitted is used (conventional); ii) an innovative IPM approach, based on the consultation of T-sum model to aid with risk decision and spray timing (IPM approach), and iii) an innovative holistic approach, which combine the use of T-sum model and farm-wide monitoring of aphid vectors to assess the overall level of infestation and therefore the risk. Hallmark Zeon (active ingredient: lambda-cyhalothrin) was the only insecticide used to control aphids.

The T-sum model considers the start of secondary generation appearance after 170-degree days (DDs) accumulated, above a baseline temperature of 3°C. the DSS aim is to suggest the best time for crop monitoring. In case of high infestation, and when no non-chemical alternatives are available to prevent the emergence of a second generation, a treatment should be considered to limit the spread of the virus. The model takes into consideration the last insecticide applied, and restarts calculations.

In the conventional strategy, insecticides were applied at the first spray window after crop establishment, then repeated almost every three weeks. In the innovative IPM approach, insecticides applications were scheduled based on T-sum accumulation model. When T-sum is 170 DD between crop emergence and GS31, the model suggests checking the crop for aphids’ presence. In the innovative holistic approach, insecticides were applied when the second generation of aphids appeared in significant numbers in clusters, observed across the farm.

The assessment was conducted on aphids’ population, BYDV symptoms and yield during the growing season. Aphid populations were assessed at the beginning and at the end of November, counting the number of aphids on ten plants at ten points equidistantly located along each tramline, counting separately grain aphids and bird cherry-oat aphids. BYDV symptoms (leaf yellowing and stunting) were assessed estimating the percentage of leaf area on a 2-m wide section of the tramline, repeated at 10 intervals along each tramline, between GS39 and GS59. Yield (t/ha) was assessed at harvest time.

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Results:

Winter wheat was sown on October 10th, 2022. The emergence occurred on October 24th.

The risk averse strategy applied four treatments during the season, the first spray occurred on October 29th, followed by treatments application on November 23rd, December 18th, January 14th. In the innovative IPM approach, two treatments were applied, on November 23rd and February 11th, while in the innovative holistic approach, no insecticide applications were made.

During the first week of November, four aphids were present in the innovative holistic approach, eight on conventional plots, and twenty-four in innovative IPM approach (Fig. 22a). During the second assessment at the end of November, no aphids were recorded. The BYDV symptoms were assessed on June 8th, no significant differences were found between strategies, with the highest symptoms in innovative IPM approach (3.5%), followed by the holistic (1.3%) and the risk averse (1%) strategy (Fig. 22b). Yield was significantly different among strategies, the lowest was recorded in innovative holistic approach (8.1 t/ha), followed by conventional risk averse (8.2 t/ha) (Fig. 22c).

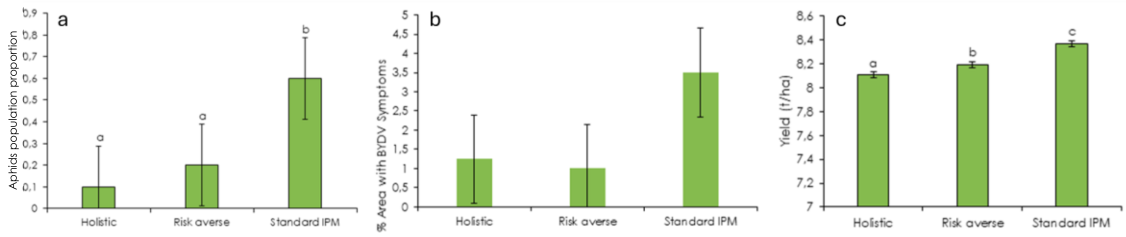

Figure 22. a) Mean number of BYDV vectors per plant recorded in the three different treatments (Innovative holistic IPM, Conventional Risk averse; innovative IPM) on November 3rd (1° assessment). Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P<0.05). b) Mean area (%) of tramline with observed BYDV symptoms across different management approaches. Error bars represent the standard error of the mean. c) Mean harvested yield (t/ha) across different management approaches. Bars represent the standard error of the mean. Bars followed by different letters are significantly different (P<0.05).

Discussion and conclusions:

This case study showed the performance of three different strategies, two innovative ones based on the use of a model, compared to the conventional risk averse practice. The growing season was characterized by a low BYDV pressure. Although the conventional practice applied the highest number of insecticides, this strategy did not cause a significant reduction in aphids' density or symptoms. In the innovative IPM approach based on DSS suggestion for monitoring time, the highest number of aphids and symptoms were present, but the highest yield was also recorded. In the innovative holistic approach, no clusters of aphids were detected, thus no insecticide was applied. A deep economic analysis was conducted and reported in Deliverable 3.7 (Francis, C., Dearlove, E., Jones, I., and Ramsden, M., 2025).

Even if the T-sum model is still a simple and conservative system, this study demonstrates the utility of the tool in avoiding unnecessary treatments, reducing the total pesticide inputs, and therefore reducing the environmental impact. The tool can assist farmers in scheduling the proper timing for field monitoring.

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4.3.7 IPMWORKS DSS Case Study #7 – BYDV disease control in winter wheat, testing T-sum and ACroBAT DSSs in two varieties.

Introduction:

Barley yellow dwarf virus (BYDV) can significantly reduce yield in cereals (Nancarrow et al., 2021) and its spread is associated with two main vectors: bird cherry-oat aphid (*Rhopalosiphum padi*) and grain aphid (*Sitobion avenae*). Their control is often primarily based on the use of insecticide as pyrethroid, however, in recent years some resistance in *S. avenae* was found (Foster et al., 2014, Holland et al., 2019). According to the current management guidance, a foliar insecticide should only be considered if aphids are seen within the crop (Ramsden et al., 2017), but monitoring can be difficult. A T-sum Decision support system is available on the “IPM DECISION” platform, predicting the appearance of the second winged generation of aphids in the crop, which are associated with the start of a secondary spread (HGCA, 2003). Based on this information, the DSS is suggesting the best time for crop monitoring. However, the T-sum model assumes all aphids are carrying BYDV, and that aphid populations are unaffected by rainfall, abundance of natural enemies, and other factors known to influence the risk of BYDV. A new DSS under development by ADAS and AHDB, known as ADAS-Crop BYDV Assessment Tool (ACroBAT) was evaluated during this case study.

Field trials conducted during this study aim to compare an untreated plot with two different strategies based on models or DSS use for the control of aphid vectors transmitting barley yellow dwarf virus in winter wheat. The study aimed to evaluate if models/DSS support can lead to insecticides reduction without compromising the final yield.

Materials and methods

The trial was conducted in two fields during the autumn 2023 in the east of England at Norfolk, comparing different crop management: i) based on T-sum model consultation; ii) based on ACroBAT DSS consultation; and iii) untreated, independently from the DSS risk and field observations. The trial was conducted comparing the three management systems on two wheat varieties, one susceptible to BYDV (Field 1 cv. Dawsum) and one resistant to BYDV (Field 2 cv. Grouse). Both T-sum model and ACroBAT DSS-based strategies were combined with field observations, and insecticides were applied only when monitoring indicated aphid activity. Fields were drilled on October 27th and 28th. Aphid presence was monitored through 12 yellow water traps installed in each field, and the number of aphids and natural enemies in each trap was counted every 3 days, from crop emergence until mid-December, resetting the traps at each visit. Each trap acted as the central point for tissue sampling. Fifteen leaves were collected within a 2 m radius around each water trap on December 20th, 2023, and on April 9th, 2024. Due to adverse conditions, and poor establishment of the crop, tissue samples were not collected from field 2 during the first tissue sampling. Plants were selected randomly as representative sample of the area and tested for BYDV by NIAB using ELYSA protocols. On April 16th, 2024, at each sampling point, the percentage of crop stunted and the percentage of crop showing clear BYDV symptoms were estimated.

ACroBAT DSS incorporates detail on the agronomy of the farm/ field (seed rate, drilling data, treatment costs, predicted yield and grain price), aphid numbers and proportion of aphids carrying BYDV. All aphid data is collated from the Rothamsted Insect Survey. The proportion of aphids carrying BYDV was obtained from additional work carried out by Dr. Martin Williamson (Rothamsted Research), based on aphid samples collected between the 23rd and the 29th of October 2023 (Aphid bulletin No. 30) from the Brome’s Barn suction trap, being the closest trap to the field sites. 16 aphids were tested out of which 3 were positive for BYDV and 0 positive for

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CYDV (Cereal Yellow Dwarf Virus). No other viruses were screened for. This produced a starting percentage infection of 19% of aphids carrying BYDV. ACroBAT requires daily data about regional aphid abundance, and this information was taken from the Rothamsted Insect Survey's aphid bulletin 3. The weather data was extracted from the IPM Decisions Weather Service (data sourced from Open Meteo) to run both T-sum model and ACroBAT DSS.

Results

The wheat emergence occurred on November 17th. October was rainy leading to high soil moisture in both fields. The number of aphids observed regionally were relatively low compared with previous years during the early stages of crop development. The T-sum model indicated a high risk of winged aphids, but the field count was low, while the ACroBAT model forecasts a low risk throughout the period from crop emergence until late November. As both models reported low risk of BYDV (Fig. 23-24), and travel on the wet soil risked damaging the crop, no insecticides were applied to any of the strategies in either field. Field monitoring of aphids and natural enemies through yellow traps revealed a low number of aphids in both fields. Furthermore, a low number of tested samples resulted being positive to BYDV in December in Field 1, while no positive samples were found in Field 1 and 2 during April. On April 16th, 2024, due to the poor crop establishment and waterlogging in some areas, the disease symptoms assessment was difficult due to similar symptoms of BYDV and other stresses (Fig. 25). The discrepancy between tissue samples and visual assessments could also be influenced by the possibility of other similar viruses present in the region. The Wheat Dwarf Virus (WDF), for example, is known to be present in the UK and transmitted by leaf hoppers (*Psammotettix sp*). Although the species was not identified, several leaf hoppers were caught in the yellow water traps. Furthermore, any varietal resistance or tolerance to BYDV does not necessarily provide resistance or tolerance to other cereal viruses. The T-sum model (Fig. 23) reported a low risk between crop emergence and December 6th, which was the last date of aphids observations. T-sum model was reset at this date, and no risk was reported until the end of January, when after consulting host farmers, no insecticide application was carried out. The T-sum model consultation was then interrupted. The ACroBAT model was run for the entire growing season, and the risk level never went above "very low" (Fig. 24), so no insecticide was applied during the season. Weather conditions impacted the quality of crop establishment, especially in Field 2, where the average yield (cv. Grouse) was about 6.39 t/ha, while in Field 1 the average yield (cv. Dawsum) was about 7.94 t/ha. However, it is not appropriate to directly compare crop performance of the different varieties between fields.

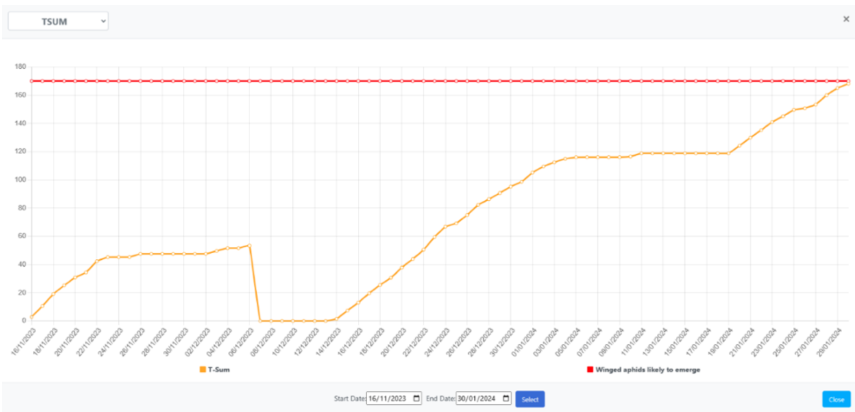

Figure 23. Timeline Output generated from T-Sum giving the 170 threshold (red) and the model output for aphid flight (orange).

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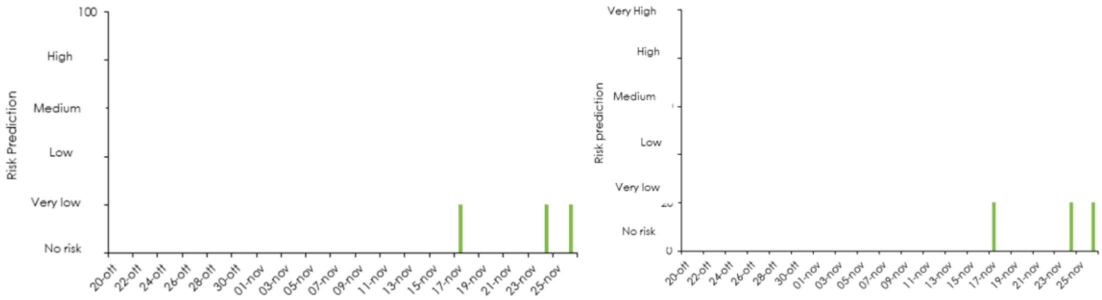

Figure 24. Risk level predicted from the ACroBAT model in field 1 (left) and field 2 (right).

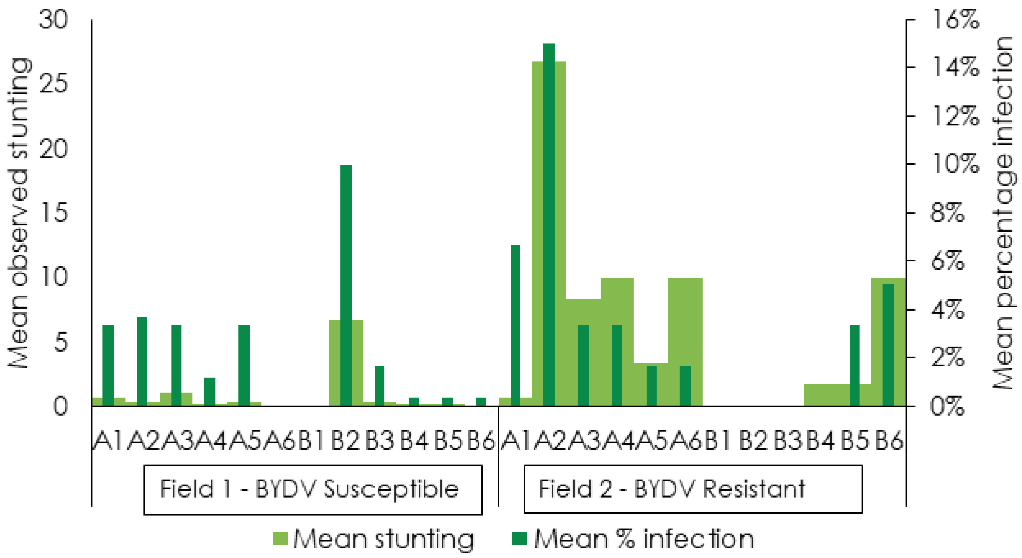

Figure 25. Levels of observed stunting (light green) and the percentage area exhibiting infection (dark green). Labelled with each sampling location and field separately. Assessment carried out on 16th April 2024.

Discussion and conclusion

During autumn and winter 2023, the aphid population was low in both fields. Both DSS together with field monitoring indicated a low risk of BYDV. DSS suggestion supported not to treat with insecticides. The results achieved (tissue analysis and yield) demonstrated the relevance of this strategy, as there was a low BYDV spread and a low potential impact on yield. The yield variability within the same field and between Field 1 and 2 was mainly due to poor crop establishment and variable conditions among fields. Furthermore, yield differences can be related to the different varieties grown, with different yield potential, or to different soil conditions. Overall, this study demonstrated the benefit of DSS in avoiding unnecessary treatments.

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4.3.8 IPMWORKS DSS Case Study #8 – Decision Support System and alternative strategies to improve Barley Yellow Dwarf Virus (BYDV) management in the Netherlands

Introduction:

Barley yellow dwarf virus (BYDV) affects a wide range of cereal crops worldwide, spread by aphid vectors such as *Rhopalosiphum padi*, *Sitobion avenae* and *Myzus persicae*. The disease causes discoloration due to chlorosis of the leaves and stunting of the crop, which can result in significant reductions in yields (Walls et al. 2019). Control of aphid vectors typically relied on the application of pyrethroid insecticides, but this led to resistance and tolerance development in aphid populations (McNamara et al. 2024). Pyrethroids can also have negative effects on not target organisms (Ranatunga et al. 2023). Thus, to avoid negative effects on the environment and to reduce the risk of resistance development, an integrated approach should be adopted for aphid vectors control. For instance, delaying sowing time can help to reduce the impact of BYDV, since crop emergence will occur later, when the environmental conditions are less favorable to aphid flight (Kennedy and Connery, 2001). Furthermore, the adoption of DSS or models can improve the timing of insecticide application. For instance, the T-sum model, available on the "IPM Decision" platform, predicts when the second wingless generation of aphids, responsible for secondary BYDV spread, will appear in the crop, highlighting when the risk is high and an insecticide application can be needed, after checking the real presence of aphids in field. The use of models or DSS can provide more confidence to farmers when not treating when the risk is low, thus ensuring insecticides are applied only when required, optimizing their use in the control of aphids.

This case study aimed to demonstrate the impact of sowing date and the benefits of decision support systems (DSS) for the control of BYDV vectors in winter wheat. The two strategies can be integrated into an IPM holistic approach.

Material and methods:

Two fields of winter wheat in The Netherland were monitored during the autumn 2023 for aphids presence. Insecticides were applied only based on the suggestions provided by T-sum model on "IPM Decision" platform, after field monitoring to verify aphids' presence. In a third field, sowing date was delayed, and aphid management was compared to the previous two fields.

An accurate risk prediction with the T-sum model requires to input the crop emergence date, and eventual insecticide application dates, because the T-sum count restarts after an insecticide application.

Aphids were monitored in each field, randomly selecting 10 places across the field and 10 plants for each place (i.e. 100 plants per field), checking the plant base and just under the soil surface. Assessments were conducted one week after crop emergence and about 3-4 weeks after emergence.

Results:

In Field 1, winter wheat emerged on October 18th, 2023. Monitoring was conducted on October 27th and November 9th, and in both assessments, aphids were present in the field. The T-sum model reached the threshold (170 Day Degrees) on November 6th, indicating the emergence of winged aphids, that can act as vector of BYDV (Fig. 26). Taking together the high risk indicated by T-sum and the demonstrated aphid presence during monitoring, an insecticide application was suggested, however due to the wet soil conditions, the spray could not be applied. Since no insecticide had been applied and the estimated risk was high, BYDV symptoms should have been

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seen in spring, but actually no infection symptoms were found. Thus, probably aphids were not carrying the disease.

In Field 2, wheat emerged on October 16th, 2023. Monitoring was conducted on October 31st and November 27th, and in both assessments, aphids were present in the field. The T-sum model reached the threshold (170 DD) on November 3rd, associated with the emergence of winged aphids potentially transmitting BYDV (Fig. 27). Thus, since aphids were present and the risk of BYDV was high, an insecticide application was suggested, but due to the wet soil conditions, the spray could not be applied. However, as in Field 1, even though the aphids were present in crop and the risk of BYDV was high, no symptoms were found during spring, indicating that aphids were probably not carrying the disease.

In Field 3, crop emergence occurred on October 27th. The T-sum count did not reach the threshold until mid-November, due to the lower temperatures (Fig. 28). Thus, the overall risk of BYDV in Field 3 was generally lower than Field 1 and 2.

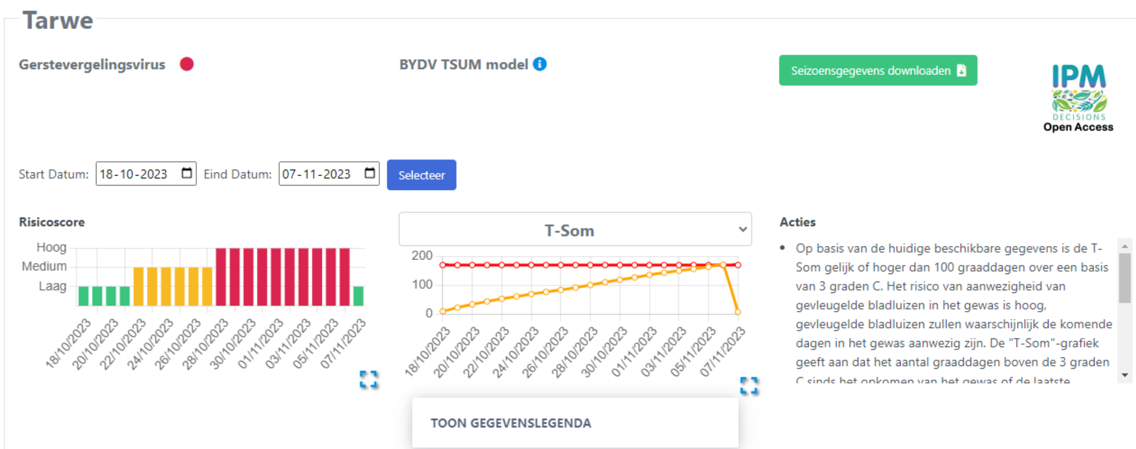

Figure 26. T-sum output on "IPM Decision" platform for the crop that emerged on October 18th (Field 1). Green, yellow and red colors represent low, medium and high risk, respectively.

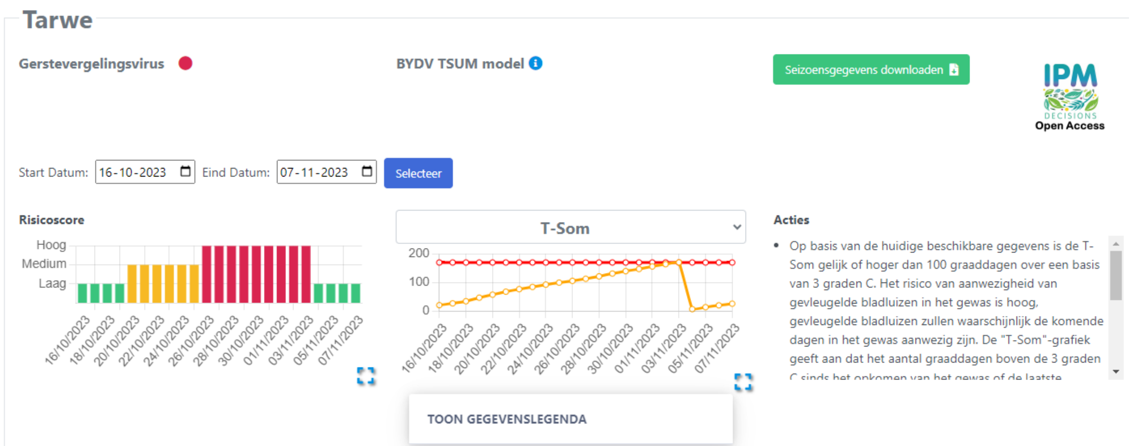

Figure 27. T-sum output on "IPM Decision" platform for the crop that emerged on October 16th (Field 2). Green, yellow and red colors represent low, medium and high risk, respectively.

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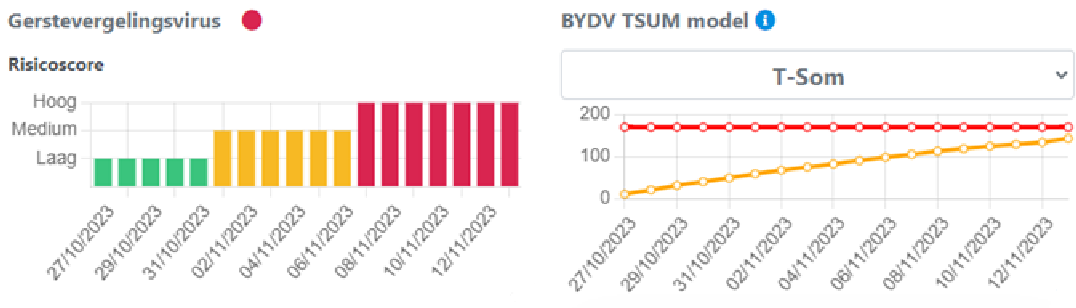

Figure 28. T-sum output on IPM Decision platform for the crop that emerged on October 27th (field 3). Green, yellow and red colors represent low, medium and high risk, respectively.

Discussion and conclusions:

BYDV is a challenging disease to control, since it is spread by aphid vectors, and symptoms normally appear later in the season, when it is too late for the control. DSS helping farmers in scheduling insecticide applications can be crucial, to choose the best application timing and to avoid unnecessary treatments. During this comparison, aphids were present in fields and T-sum model reached the threshold for suggesting a treatment, but due to the wet soil conditions for tractor pass, no insecticide was applied. Despite this, BYDV symptoms in spring were not detected, suggesting that aphids were not carrying BYDV. The wet conditions may also impact aphid populations from growing and thus limit their spread. DSS can improve BYDV control by avoiding unnecessary insecticide applications, but if insecticides are needed and the environment / weather conditions do not allow spray applications, the risk of yield loss can be high. Therefore, the integration of multiple strategies in a holistic approach for plant protection is fundamental. This case study demonstrated how delayed sowing time can be a relevant option, along with the use of more tolerant or resistant varieties.

4.3.9 IPMWORKS DSS Case Study #9 – Ex-post analysis on DSS use in Italian vineyards: a tool to reduce environmental impact and human health risk.

Introduction:

Some Decision Support Systems integrate several tools to support farmers, not just about if and when to treat, but they can even provide support in adopting the best practice or technique to limit PPPs applications to the ones really needed (Rossi et al., 2014). In vite.net® DSS, additional tools calculating the overall sustainability of the farm practice were integrated into the system, in order to calculate the farming activities impacts on both the environment and human health.

In this case study, the conventional farmer's practice and an innovative one based on DSS suggestions were considered, not just in terms of PPPs reduction, but also through the evaluation of potential benefits of these tools to reach a more sustainable agriculture, decreasing the risk for both the environment and human health.

Material and methods:

An ex-post analysis was conducted in collaboration with Horta s.r.l. comparing the treatment frequency index (TFI) of conventional practice, thus the TFI applied by farmers based on the suggestion provided by the local phytosanitary bulletins (Conventional), and the TFI following suggestions by the DSS vite.net® (innovative) in Italy between seasons 2018 and 2020.

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Several vineyards (180) from four different regions across Italy were considered, to cover different climatic conditions (Alba et al., 2024): 68 in Tuscany (central Italy), 56 in Veneto (north-east Italy), 35 in Apulia (south Italy) and 21 in Piedmont (north-west Italy). For each area, impact indicators were calculated, in particular: Carbon Footprint, Human Tox Score, Eco Tox Score, and Dose Area Index

Carbon Footprint

Carbon footprint index can quantify the greenhouse gasses emission produced directly or indirectly by human activities. The index is normally expressed as t of CO_2 equivalent (eq.)/t of products or t of CO_2 equivalent/ha.

The Carbon Footprint index is used to calculate the environmental impact of each activity reported in the Cultivation Operation Register (ROC) that can release molecules in the atmosphere involved in the greenhouse effect.

Human Tox Score (HTS)

Human tox Score evaluates the risk (“hazard”) for the human health due to chemical substances applied in fields. Each fungicide, insecticide, herbicide, acaricides etc. reported in ROC is evaluated from a toxicological point of view. Each plant protection product, for law, is assigned in a toxicological class and risk phrases (hazard phrases). The toxicological information (intrinsic risk) and applied dose (hazard exposure) are both considered to evaluate the toxicological risk of the product applied in field. The final evaluation considers every plant protection product reported in ROC. Higher the final value will be, higher the toxicological risk will be for humans close to the treated area (operators, residents, etc.).

Eco Tox Score (ETS)

Eco tox score evaluates the eco-toxicological risk (“hazard”) on both aquatic and terrestrial ecosystems, due to chemical substances applied in fields. Each fungicide, insecticide, herbicide, acaricides etc. reported in ROC is evaluated from a toxicological point of view. Each plant protection product, for law, is assigned in an eco-toxicological class and risk phrases (hazard phrases). The toxicological information (intrinsic risk) and applied dose (hazard exposure) are both considered to evaluate the eco-toxicological risk of the phytosanitary product applied in field. The final evaluation considers every plant protection product reported in ROC. Higher the final value will be, higher the eco-toxicological risk will be for the agricultural ecosystem.

Dose Area Index (DAI)

The dose area index evaluates the chemical exposure due to each phytosanitary treatment applied in field. The exposure is quantified by comparing the applied dose to the maximum dose reported on label, and/or comparing the treated agricultural surface to the total surface. Applying a phytosanitary product at a dose lower than the maximum allowed dose (reported on the label), or reducing the treated surface, can reduce the negative impacts of chemical molecules on not target organisms (both plants and animals). For instance, treatment done with 50% of the maximum applicable dose and on 50% of the agricultural surface, will determine a reduced exposure to toxic substances of the area, 75% lower compared to treatment done at full dose and on the entire agricultural surface.

The dose area index considers: the dose applied in field; the maximum dose allowed and reported on label; the treated surface; and the total productive surface. A reduced dose and applications on a portion of the agricultural surface will permit a reduced chemical exposure of the agroecosystem.

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Treatment Frequency Index (TFI)

TFI considers the number of treatments application done with a plant protection product. The index takes into consideration the treated surface and the total productive surface (Gravesen, 2003). Furthermore, also the number of tractor passes; litre of fuel (L/ha) and kg of phytosanitary products per hectare (kg/ha) were considered.

While the Treatment Frequency Index (TFI) quantifies the relative intensity of pesticide use based on the number of applications and the proportion of authorized doses applied (Gravesen, 2003), the Dose Area Index (DAI) provides a more direct measure of the chemical load per hectare by accounting for the actual amount of active substance applied per unit area (Bergkvist, 2004), thus offering a complementary perspective on environmental impact

Results:

The percentage (%) of reduction of each index in the innovative plots compared to the conventional plots were calculated (Tab. 2) and the distributions for the four Italian regions are displayed in Fig. 29-33.

On average, the reduction of impact indicators in the innovative practice, compared to conventional ones, was 21% for Carbon Footprint index (about -0.31 t CO_2/ha, see Tab. 3), 35% for the Dose Area Index, 21% for Treatment frequency index, 39% for the Human Tox Score and 36% for the Eco Tox Score (Tab. 2). At regional level, Veneto had lower average values, while Piedmont and Apulia had higher average values. Apulia showed the highest reduction in indexes when using the DSS (Fig. 33), followed by Tuscany (Fig. 30), and then Piedmont (Fig. 31) and Veneto (Fig. 32) regions.

The innovative practice allowed a reduction in the total number of tractor passes (-2.4), a reduction in fuel consumption (-32.4 L/ha), and a reduction in the amount of plant protection product (-19.7 kg/ha) (Tab. 3).

Table 2. Reduction (%) of Carbon Footprint (CO_2 eq. t/ha); Dose Area Index; TFI; Human Tox Score; and Eco Tox Score in innovative plots compared to conventional, in the four Italian regions (total) and in each Italian region: Tuscany; Piedmont; Veneto and Apulia.

		Carbon Footprint (CO2 eq. t/ha)	Dose Area Index	TFI	Human Tox Score	Eco Tox Score
Total	min	-25	-22	-21	-27	-21
	25 perc	8	20	4	19	15
	mean	21	35	21	39	36
	75 perc	34	50	36	54	55
	max	68	90	77	96	92
Tuscany	min	-25	-22	-18	2	-21
	25 perc	10	22	4	24	15
	mean	20	36	21	42	35
	75 perc	28	48	34	54	56
	max	68	90	77	96	92
Piedmont	min	-23	-16	-21	-27	5
	25 perc	-5	6	-2	18	15
	mean	22	32	21	39	45
	75 perc	45	50	45	66	69
	max	62	83	59	84	89
Veneto	min	-18	-15	-13	-16	-19
	25 perc	1	16	3	15	13
	mean	14	29	18	36	34
	75 perc	27	46	29	54	50
	max	46	71	51	91	82
Apulia	min	-3	4	-15	-6	2
	25 perc	18	25	7	15	21
	mean	32	43	27	35	39
	75 perc	47	60	50	49	55
	max	63	87	75	88	89

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Table 3. Average reduction of Carbon Footprint (t CO_2 eq. /ha); Number of tractor passes; Fuel (l/ha); Plant protection product (kg/ha) in innovative plots compared to conventional, in the four Italian regions (total) and in each Italian region: Tuscany, Piedmont, Veneto and Apulia.

	t CO_2 eq /ha	N. of tractor passes	Fuel (l/ha)	Plant protection product (kg/ha)
Total	0,31	2,4	32,4	19,7
Tuscany	0,24	1,5	27,0	15,1
Piedmont	0,25	2,4	28,0	10,1
Veneto	0,22	2,7	31,1	12,0
Apulia	0,61	3,9	47,6	46,1

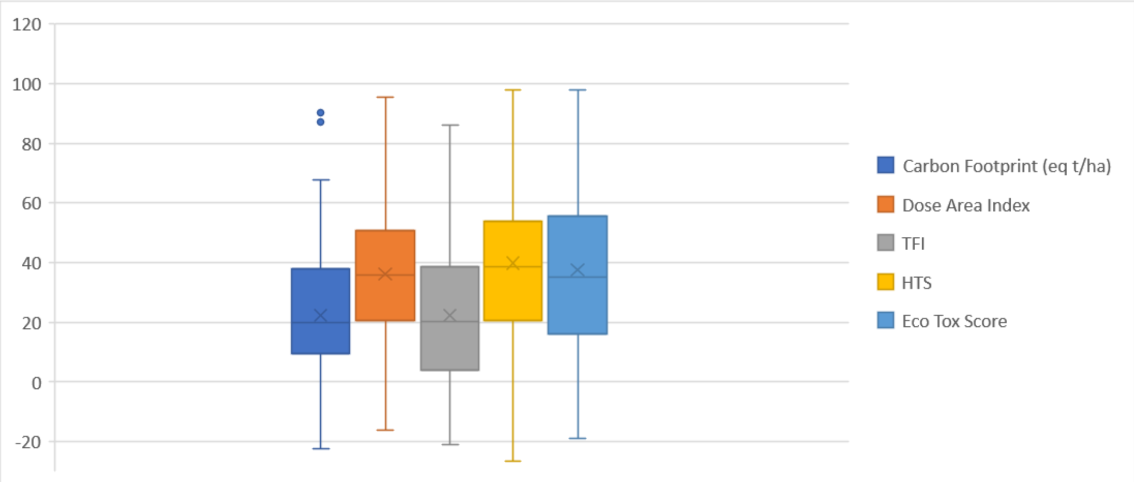

Figure 29. Distribution of the percentage reduction (%) of: Carbon Footprint (CO_2 eq. t/ha); Dose Area Index; TFI; Human Tox Score (HTS) and Eco Tox Score, in innovative plots compared to conventional in the four regions (Total) (n=180 farms). The horizontal line represents the median; "x" is the mean; the box goes from the 25° and 75° percentiles; whiskers are the minimum and maximum values. Dots are outliers.

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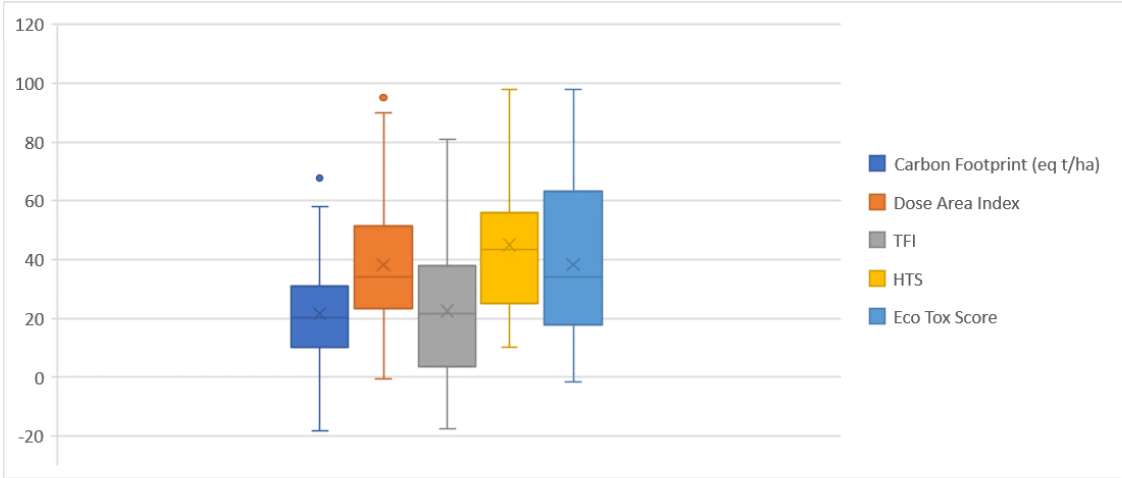

Figure 30. Distribution of the percentage reduction (%) of: Carbon Footprint (CO_2 eq. t/ha); Dose Area Index; TFI; Human Tox Score (HTS) and Eco Tox Score, in innovative plots compared to conventional in Tuscany (n=68 farms). The horizontal line represents the median; "x" is the mean; the box goes from the 25° and 75° percentiles; whiskers are the minimum and maximum values. Dots are outliers.

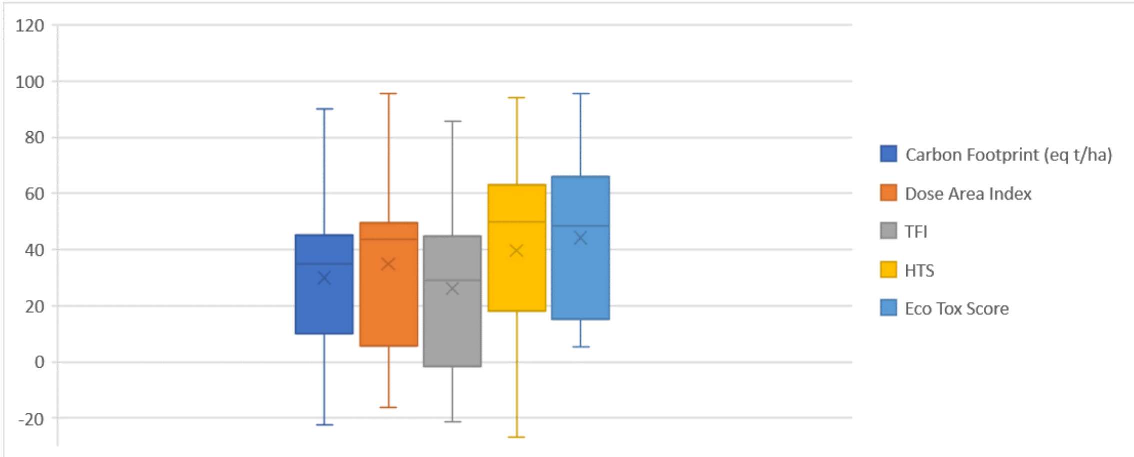

Figure 31. Distribution of the percentage reduction (%) of: Carbon Footprint (CO_2 eq. t/ha); Dose Area Index; TFI; Human Tox Score (HTS) and Eco Tox Score, in innovative plots compared to conventional in Piedmont (n= 21 farms). The horizontal line represents the median; "x" is the mean; the box goes from the 25° and 75° percentiles; whiskers are the minimum and maximum values. Dots are outliers.

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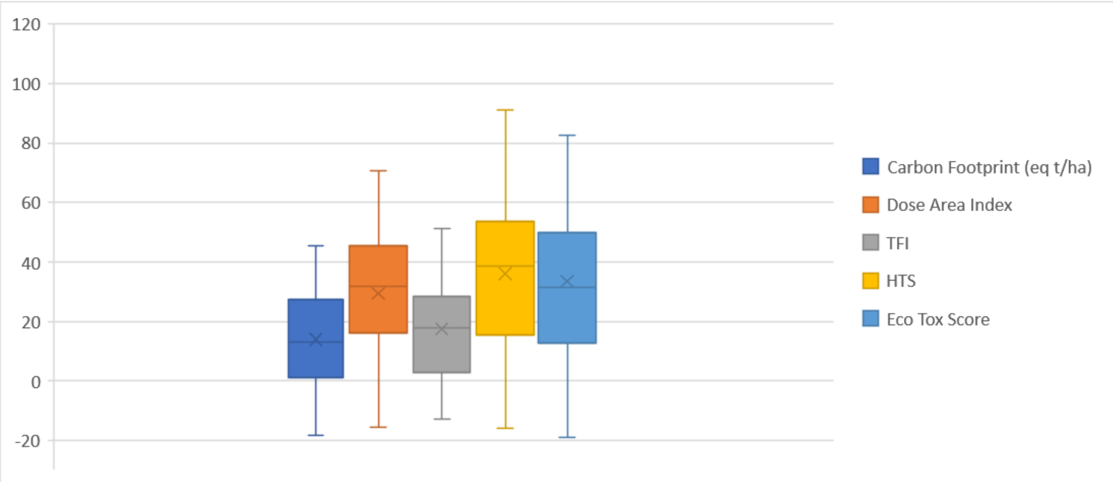

Figure 32. Distribution of the percentage reduction (%) of: Carbon Footprint (CO_2 eq. t/ha); Dose Area Index; TFI; Human Tox Score (HTS) and Eco Tox Score, in innovative plots compared to conventional in Veneto (n= 56 farms). The horizontal line represents the median; "x" is the mean; the box goes from the 25° and 75° percentiles; whiskers are the minimum and maximum values. Dots are outliers.

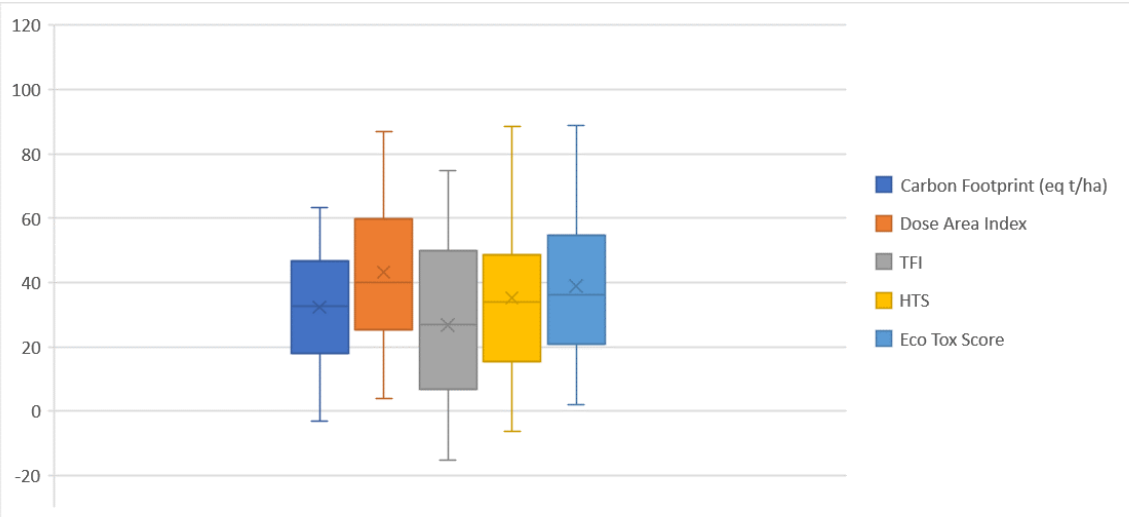

Figure 33. Distribution of the percentage reduction (%) of: Carbon Footprint (CO_2 eq. t/ha); Dose Area Index; TFI; Human Tox Score (HTS) and Eco Tox Score, in innovative plots compared to conventional in Apulia (n=35 farms). The horizontal line represents the median; "x" is the mean; the box goes from the 25° and 75° percentiles; whiskers are the minimum and maximum values. Dots are outliers.

Discussion and conclusions:

In all the wine-growing regions analysed, the use of the DSS vite.net® led to considerable reductions of indicators of impact on the environment and human health. By having access to the information provided by the DSS, winegrowers were able to optimise their crop protection strategies in each of the three monitored years. The support provided by the DSS is much more detailed and site-specific than the guidelines proposed in the territorial bulletins and winegrowers can therefore better calibrate when and how to treat. Through its various functionalities, the DSS not only makes it possible to understand whether and when there are

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predisposing conditions for the occurrence of infectious events for different diseases (Lázaro et al., 2021), but also to what extent a given treatment with a specific product can guarantee protection (Rossi et al., 2014). The DSS can also be used for the purpose of simulating different scenarios and understanding a priori which product is the most promising in each situation. The presence of a very detailed product database in the DSS makes it possible to reason and identify the product that has the least impact on the environment and human health, with the same effectiveness.

4.4. Discussion and conclusions of Case Studies

The nine reported case studies demonstrate the utility of DSS and models in the optimization of crop protection strategies. The case studies were conducted on very different crops, either annual crops, as wheat and potato, or perennial crops, as grapevine, in very different environments across EU, from North Europe (Sweden) to South Europe (Italy).

Overall, results have demonstrated the potential benefits of these tools adoptions. Indeed DT-tools (DSS or models) often allowed a reduction in the plant protection products applications, as reported in the organic grapevine case study, where the number of treatments was lowered by 58 – 64%, and the total amount of copper was reduced by 34 – 62%, depending on the seasons, without negatively affecting the crop protection efficacy, in agreement with previous results of Rossi et al. (2014), Delière et al. (2015) and Kuflik et al. (2009). The economic analysis carried out in this case study also highlighted a potential decrease in the cost of crop protection strategy between 45 and 56%, thanks to the DSS adoptions, as found by Rossi et al. (2014).

Furthermore, the ex-post case study on grapevine reported an average reduction of 22% in the TFI in DSS-based systems compared to farmer practices, and a global reduction in impact indicators (on average by 22% for the Carbon footprint, by 40% and 38% for the human and eco tox score, respectively, and by 36% for the dose area index). The achieved reductions were variable depending on the regions: the highest decreases were reached in Apulia region in terms of tons of CO_2 eq./ha (-0.61), number of tractor passes (-3.9), fuel (-47.6 L/ha) and plant protection products (-46.1 kg/ha). These results demonstrated the benefits of DSSs for increasing the overall sustainability and for reducing risks for both the environment and human health (Kasimati et al., 2024). Similarly, the potato case study reached an average reduction of 1.7 treatments per seasons using models, without negatively affecting the disease control, in agreement with Liu et al. (2017), Eremeev et al. (2006) and Abuley (2019), and without negatively affecting the final production (Liu et al., 2017, Abuley, 2019).

Then, two case studies were conducted for fungal diseases in winter wheat, one in Italy and one in Sweden. The first trial was considering multiple diseases potentially affecting the crop, and an equal disease control was reported in conventional and DSS-based plots for two seasons (but without reducing fungicide inputs). In the second set of trials in Sweden, several conventional practices were compared to model-based decision making. The model suggested between 0 and 1 treatment application in the two fields affected by septoria leaf blotch, resulting in a slightly higher or equal disease severity, but the final yield of the two systems was not different in both fields.

Similarly in the last field affected by tan spot, no differences were found between the two systems in terms of yield. These results are in line with the results of El Jarroudi et al. (2014, 2015).

Three more case studies were conducted on winter wheat, considering BYDV disease and the control of its vectors. The T-sum DSS was tested in the three cases, and in one case also ACroBAT model was used. DSSs effectively predict aphid occurrence in fields, and when the risk was low, no insecticides were applied, without compromising the yield. In the second case study in UK,

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the risk of aphid presence was high, however, due to the wet soil conditions, it was not possible to apply insecticide, expecting to find symptoms during spring, but symptoms were not detected, probably indicating that aphids were not transmitting the virus. The last case study showed how delayed sowing time can reduce BYDV risk, by avoiding the period of high aphid activity, as reported by McGrath & Bale (1990). These results highlighted that DSS recommendations, when combined with field monitoring and agronomical practice, can help avoid unnecessary treatments.

The chickpea case study showed a different way of using a DSS. The DSS legumi.net® was exploited to optimize the production, by increasing the sowing density and reducing the interrow distance. Thanks to these changes, the crop production was increased, in terms of total fresh biomass (+17.3%), dry grains weight (+29%) and number of chickpea plants per square meter (+36%), compared to the standard farmer practice.

Overall, these comparisons conducted in different countries and on different crops have demonstrated the utility of DT in suggesting how to improve farming practices, with the possibility of optimizing crop protection strategies, of reducing PPP applications to only the needed ones, without negatively affecting both crop health and yield. Their integration in farming practices, along with other measures combined in a holistic approach to Integrated Pest Management, can increase the overall sustainability (including profitability) of the agricultural systems.

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5 General Discussion and Conclusions

The main aim of this task in Work Package 4 (WP4- D4.4) was to evaluate Decision Support Systems (DSS) as relevant tools to be included in Integrated Pest Management (IPM) strategies. To achieve the objective, three sub-objectives were identified and addressed, through a multi-step approach, combining (i) a literature analysis, (ii) engaging stakeholders through a short survey, and (iii) validations of DSS or models under in-field conditions. The first objective was addressed through a meta-analysis of existing scientific literature, confirming that DSS-based crop protection strategies can significantly reduce PPPs applications without compromising the disease or pest control and yield. The second objective was achieved by conducting a short survey about current use and perception of DSS among farmers and advisors in IPMWORKS network and outside. The survey revealed that DSS users positively evaluate these tools, especially in the support in the decision-making process. Among non-users, the survey identified the main barrier to adoption, as a limited awareness, lack of trust and perceived complexity of the tools. These findings are in line with the results of the survey performed in the framework of the sister project IPM Decisions, underlining the importance of improving usability, reliability, and communication about DSS to support a wider uptake. The third objective was addressed though in-field case studies, comparing conventional and DSS-based management in different crops and countries. The case studies provided additional evidence of different way in which DSS can be integrated into IPM strategies. Results showed reduction in the number of treatments or TFI, without negative impact on disease or pest control. In some cases, DSS adoption also led to yield improvements (e.g. chickpea, potato), economic savings (e.g. grapevine), and increased environmental sustainability as reported by sustainability indicators in a grapevine case study.

Deliverable 4.4 offers a comprehensive cost-benefit analysis of Decision Support Systems (DSS) adoption for Integrated Pest Management (IPM) across Europe, based on these three pillars: meta-analysis, case studies, and farmer surveys.

- The meta-analysis, synthesizing data from 65 studies, confirmed that DSS adoption consistently reduces pesticide inputs without compromising crop protection. Treatment Frequency Index (TFI) decreased by 25% in vineyards, 20% in potatoes, and 39% in wheat. Environmental indicators such as the Dose Area Index (DAI), carbon footprint, and eco-toxicity also improved significantly (up to -40%), emphasizing the positive externalities of DSS-supported decision-making.
- The case studies provided field-level validation of the benefits of DSS consultation. In organic vineyards using vite.net®, fungicide applications dropped from 16.5 to 6.5 treatments per hectare, generating a 61% reduction in protection costs (from 580 to 230 €/ha), while maintaining disease control. In chickpea fields managed with legumi.net®, optimized sowing and reduced pesticide use led to a 29% increase in dry grain yield and a 36% increase in seed count, with operational costs stable or reduced. In wheat, grano.net® enabled a reduction of 1–1.5 fungicide treatments per season, lowering TFI by 39%, with a slight yield penalty (~6%) that was offset by lower input costs.
- The farmer surveys revealed nuanced adoption dynamics. Trust in the DSS output, perceived complexity, and system usability emerged as key factors influencing uptake. Farmers reported that DSS tools were most readily adopted when they demonstrated clear economic

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benefits, simple interfaces, and when supported by peer-to-peer knowledge sharing within networks like IPMWORKS.

The analysis indicates that the adoption of DSS enhances economic profitability, reduces environmental impacts, and bolsters the resilience of IPM strategies. For these benefits to be maximized across Europe's varied agricultural systems, it is crucial to strategically invest in user training, model validation, and technology transfer. The findings in this D4.4 underscore the importance and efficiency of DSSs as vital tools for advancing the sustainability of crop protection. DSS helps in effectively lessening the use of PPPs, without hindering pest or disease control, and in some instances, also heightening economic and environmental performance. However, to fully harness their potential, efforts are still needed to boost their widespread adoption, such as by enhancing trust, usability, and accessibility. Field trials and hands-on experiences, like those in IPMWORKS comparisons, remain imperative for overcoming adoption hurdles. Rather than being viewed as isolated solutions, DSS should be considered an integral part of a comprehensive IPM approach. Their incorporation into farming practices is crucial for achieving more resilient and sustainable agriculture in Europe.

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Annex 1.

Table 1. Table of abbreviations used in D4.4

Abbreviation	Description	Reference
DSS	Decision Support Systems	Caffi T, Rossi V. (2017). Fungicide models are key components of multiple modelling approaches for decision-making in crop protection. Phytopathologia Mediterranea (2018), 57, 1, 153–169. DOI: 10.14601/Phytopathol_Mediterr-22471
Vite.net®	Horta srl (link with IPM Decisions)	Rossi, V., Salinari, F., Poni, S., Caffi, T., & Bettati, T. (2014). Addressing the implementation problem in agricultural decision support systems: the example of vite. net®. Computers and Electronics in Agriculture, 100, 88-99.
Grano.net®	Horta srl (link with IPM Decisions)	González-Domínguez, E., Meriggi, P., Ruggeri, M., & Rossi, V. (2021). Efficacy of fungicides against Fusarium Head Blight depends on the timing relative to infection rather than on wheat growth stage. Agronomy, 11(8), 1549
Legumi.net®	Horta srl (link with IPM Decisions)	Agrios, G.N. (2005). Plant pathology (5° Ed), Academic Press, ISBN 0120445654, New York
Hutton Criteria model	IPM Decisions	Dancey, S. R., Skelsey, P., & Cooke, D. E. (2017). The Hutton Criteria: a classification tool for identifying high risk periods fo potato late blight disease development in Great Britain
Septoria Humidity model	IPM Decisions	Jørgensen, L. N., Justesen, A. F., Heick, T., Matzen, N., & Olsen, B. B. (2017). Testing different Septoria models (MS project). In *Applied Crop Protection 2016* (pp. 85-96). DCA-Nationalt Center for Fødevarer og Jordbrug.
Infection risk of tan spot	IPM Decisions	https://www.platform.ipmdecisions.net/
T-sum model	IPM Decisions	HGCA (2003). Pest management in cereals and oilseed rape – a guide. Home - Grown Cereals Authority
ACroBAT	IPM Decisions	White, S., Telling, S., Griffiths, H.G., Skirvin, D.J., Williamson, M., Ellis, S., Schaare, T. & Potte, O. (2023). Management of aphid and BYDV risk in winter cereals. AHDB Project Report No. 646. Agriculture and Horticulture Development Board.
DT	Decision Tools	Rossi, V., Sperandio, G., Caffi, T., Simonetto, A., and Giolioli, G. 2019. Critical Success Factors for the Adoption of Decision Tools in IPM. Agronomy. 9:1–19.

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TFI	Treatment Frequency Index	Gravesen, L. (2003). The Treatment Frequency Index: an indicator for pesticide use and dependency as well as overall load on the environment. In Reducing pesticide dependency in Europe to protect health, environment and biodiversity, Copenhagen, Pesticides Action Network Europe (PAN), Pure Conference
SMD	Standardized mean difference	Ojiambo, P. S., & Scherm, H. (2006). Biological and application-oriented factors influencing plant disease suppression by biological control: a meta-analytical review. Phytopathology, 96(11), 1168-1174
EX-based	Expert-based	Jermini et al., 2003; Kast and Bleyer, 2011
HTS	Human Tox Score	Bergkvist, P. (2004). *Pesticide Risk Indicator at National Level and Farm Level. A Swedish approach.* Swedish Chemicals Inspectorate, Jonkoping, Sweden
ETS	Environment Tox Score	Bergkvist, P. (2004). *Pesticide Risk Indicator at National Level and Farm Level. A Swedish approach.* Swedish Chemicals Inspectorate, Jonkoping, Sweden
BYDV	Barley Yellow Dwarf Virus	
DD	Degree Day	
GS	Growth Stage	
ROC	Cultivation operation register	
FH	Farmer hub	
HC	Hub Coach	
IPM	Integrated Pest Management	
PPP	Plant Protection Product	
UTC	Untreated control	

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