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Highlights

- *We developed a participatory approach combining co-design workshops, on-farm experimentation and co-evaluation workshops.*
- *We involved different types of stakeholders in the participatory approach: winegrowers, researchers and advisors.*
- *This participatory approach involved winegrowers in the 3-step-process of reducing the use of pesticides.*
- *Two management strategies (one for organic systems, and one for conventional) were co-designed.*
- *The two co-designed strategies significantly reduced the use of pesticides in viticulture.*

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Abstract

Viticulture involves high pesticide use. While methods to reduce this use have been proposed by researchers, they have not yet been widely implemented by winegrowers. Involving winegrowers in the participatory design of new management strategies could encourage the adoption of these methods to reduce pesticide use. In this study, we designed and tested a participatory approach to reducing pesticide use that would be acceptable to winegrowers from a South-Western cooperative (*i.e.*, not 'pioneering' winegrowers). The approach was composed of three main steps: A) co-design of the management strategies, B) implementation of the management strategies, and C) co-evaluation of the performances of the implemented management strategies. Winegrowers, researchers, advisors and engineers were involved in the study. The application of this participatory approach enabled the co-design and testing of two management strategies: IPM for Integrated Pest Management [50% reduction of pesticide treatment frequency index (TFI) as compared to the French High Environmental Value reference (HEV)], and ORG2kgCo for organic farming system with a maximum of 2 kg of copper/ha/year. These two management strategies were implemented by 11 winegrowers in three vineyards in South-Western France. In both management strategies, two main technical levers were selected to reduce pesticide use: a Decision Support System to optimise the use and substitution of pesticides by biocontrol products. The implementation of the IPM management strategy resulted in a significant reduction of TFI (from -14% to -57%, with an average of -25%, for all pesticides combined) compared to HEV, and the winegrowers who tested ORG2kgCo managed to not exceed the limit of 2 kg of copper per year. This original participatory approach, combining co-design workshops, on-farm experimentation and co-evaluation workshops, highlighted the benefits of involving winegrowers in the reduction of pesticide use.

Introduction

Reducing the use of pesticides is a major issue in agriculture, for environmental [*e.g.,* pollinator decline (Brittain *et al.*, 2010)] and health reasons (Inserm, 2021). In France, viticulture is one of the agricultural sectors with the most intensive pesticide use (Urruty *et al.*, 2016), with fungicides representing 80% of treatments, followed by insecticides (15%) and herbicides (5%) (Mailly *et al.*, 2017). This intensive use is due to several diseases (downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), botrytis (*Botrytis cinerea*), black rot (*Guignardia bidwellii*)) and insects such as grape berry moths (*Eupoecilia ambiguella* and *Lobesia botrana*) that harm quality and quantity of grape yield at harvest (Fermaud *et al.*, 2016). In French viticulture, as in other agricultural sectors, the application of pesticides is not decreasing (Urruty *et al.*, 2016), despite significant efforts in research and development since the Ecophyto plan was launched in 2008 by the French government (Barzman and Dachbrodt-Saaydeh, 2011; Guichard *et al.*, 2017). Research and Development highlighted a large diversity of technical levers, which may be categorized by the ESR (Efficiency-Substitution-Redesign) framework (Hill and MacRae, 1996). Efficiency levers correspond to the optimization of the timing, dose, frequency of application (Mailly *et al.*, 2017), and the quality of spraying (Pertot *et al.*, 2017). Substitution levers correspond to the substitution of synthetic products by biocontrol products (Pertot *et al.*, 2017). Finally, Redesign levers for grape-growing systems mainly involve planting grape varieties resistant to downy mildew and powdery mildew (Pertot *et al.*, 2017), and increasing biodiversity in the case of agroforestry viticulture (Romero *et al.*, 2022). However, these technical levers remain under-utilised in most wine-growing regions (Mailly *et al.*, 2017).

This current persistent consumption of pesticides in France (Hossard *et al.*, 2017) is the result of a socio-technical lock-in involving a large number of actors in the agricultural world, of which pesticides have become the *keystone* (Guichard *et al.*, 2017). Several obstacles limiting the adoption of innovative strategies to reduce pesticide use have been identified: a lack of knowledge (Giampietri and Trestini, 2023), farmers' risk aversion (Pereira *et al.*, 2017; Aka *et al.*, 2018), a need for organisational flexibility, and the influence of traditional methods of working (Pereira *et al.*, 2017). However, pesticide reduction has been proven to be effective when winegrowers are directly involved in the design of innovative systems, such as in the *Dephy Ferme' farmers* groups (Fouillet *et al.*, 2022). The main objective of these groups, funded by the Ecophyto plan, was to demonstrate the capacity of farms to reduce their pesticide use. In these groups, winegrowers have been able to achieve an overall pesticide reduction rate of about 33%, with a 27% reduction in fungicides over 10 years (Fouillet *et al.*, 2022). This urges us to promote the involvement of farmers from the beginning to the end in the process of reducing pesticide use.

Designing innovative agricultural systems can be achieved by different approaches, classified by Meynard *et al.* (2012) into three categories. First, the *step-by-step* approach is a progressive *in situ* change (over several years) of practices, supported by learning loops and producing an innovative system whose characteristics were not predictable at the beginning. This approach leads to a cautious evolution of practices, which requires time (Meynard *et al.* 2012). Second, the model-based approach offers a very broad exploration of combinations of techniques and environments, using agronomic models to determine which ones meet the desired objectives. However, this approach is difficult to implement because many research models are still ill-adapted to use by stakeholders in the field (Jeuffroy *et al.*, 2008).Third, the participatory design of prototypes in design workshops involves stakeholders with diverse skills and knowledge to develop proposals towards a shared objective for all stakeholders (Jeuffroy *et al.*, 2022). The prototypes consider options that are technically, economically and organisationally compatible with farmers' expectations and available resources (Lacombe *et al.*, 2018). The experimentation of these prototypes is increasingly performed directly on farms in collaboration with farmers (Lacoste *et al.*, 2021). This method, called on-farm experimentation, seems to lead to better adoption of new practices because, as winegrowers learn how to manage those practices, they comprehend the associated risks and become convinced of the value of these practices (Kummer *et al.*, 2012; Catalogna *et al.*, 2018; Toffolini and Jeuffroy, 2022). In exploring farmers' learning processes, Chantre *et al.* (2014) highlighted the importance of sharing feedback from experiences with others stakeholders (*e.g.*, farmer, advisor, researcher) to gain new knowledge, especially through experimentation. Indeed, these farmers can be the catalysts for the change required for widespread adoption in the community (Pant and Hambly Odame, 2009). The involvement of farmers in the evaluation of these prototypes, is interesting because they participate in the definition of the evaluation method, and they select indicators that are relevant and meaningful to themselves (King *et al.*, 2000) such as yield, labor time, nitrogen rate, and irrigation amount (Nolot and Debaeke, 2003). A few recent studies have combined participatory co-design, on-farm experimentation, and co-evaluation on other cropping systems or topics such as the introduction of camelina as a second crop (Leclère *et al.*, 2018) or reduction of herbicide use in citrus orchards (Le Bellec *et al.*, 2012). Recently, Masson *et al.* (2021) analysed from an epistemological perspective the interdisciplinarity process of associating the human and social sciences with agronomic and biological sciences to reduce herbicide use in viticulture on a transnational scale. Until now, we have found no study describing technically a participatory approach mobilising winegrowers and other stakeholders at a regional scale, to simultaneously co-design, co-implement (on-farm experimentation), and co-evaluate management strategies to reduce pesticide use (fungicides, insecticides and herbicides). In this study, management strategies correspond to a combination of technical levers that can be used by winegrowers. This paper aims to answer the following research question "How to promote pesticide use reduction in real winegrowing conditions? What strategies does this participatory method produce for reducing pesticide use?". To answer these questions, we created and applied an original participatory approach combining co-design workshops, on-farm experimentation and co-evaluation workshops in viticulture involving different stakeholders that included winegrowers. We assume that this combination is relevant to facilitate the reduction of all pesticides used. Our case study took place in the South-Western region of France. Participants were winegrowers, researchers from INRAE (National Research Institute for Agriculture, Food and the Environment), engineers from IFV (French Institute on Vine and Wine), wine advisors and engineers of the Research & Development team from a wine cooperative. After presenting the participatory approach and the results it produced, we discuss the relevance of our participatory approach regarding three aspects: involvement of winegrowers, effective reduction in pesticide use, and perspectives towards a large adoption of these management strategies.

Materials and Methods

Study area

This study was realised through the VITI OBS project in partnership with a regional wine cooperative (VINOVALIE) willing to push for a reduction in pesticide use. This cooperative is the biggest wine producer in the South-Western part of France, representing about 300 winegrowers and 4000 hectares of vineyards, out of the 53,863 ha in the South-Western region in 2019 (IVSO, 2022). Our case study was located in this area, covering three Protected Designation of Origin (PDO) regions: Cahors, Fronton and Gaillac (Figure 1). This study is focused on PDO fields with targeted yields of 50-55 hl/ha depending on the PDO. Winegrowers often achieve these yields. This region is influenced by an oceanic climate, characterised by an average annual rainfall of about 800 mm. The rainfall intensity is low in winter and high in summer due to thunderstorms. These thunderstorms cause significant pressure from cryptogamic diseases: downy mildew and black rot, which may require high use of fungicides for their control. Even if the quantity of pesticides fluctuates depending on the

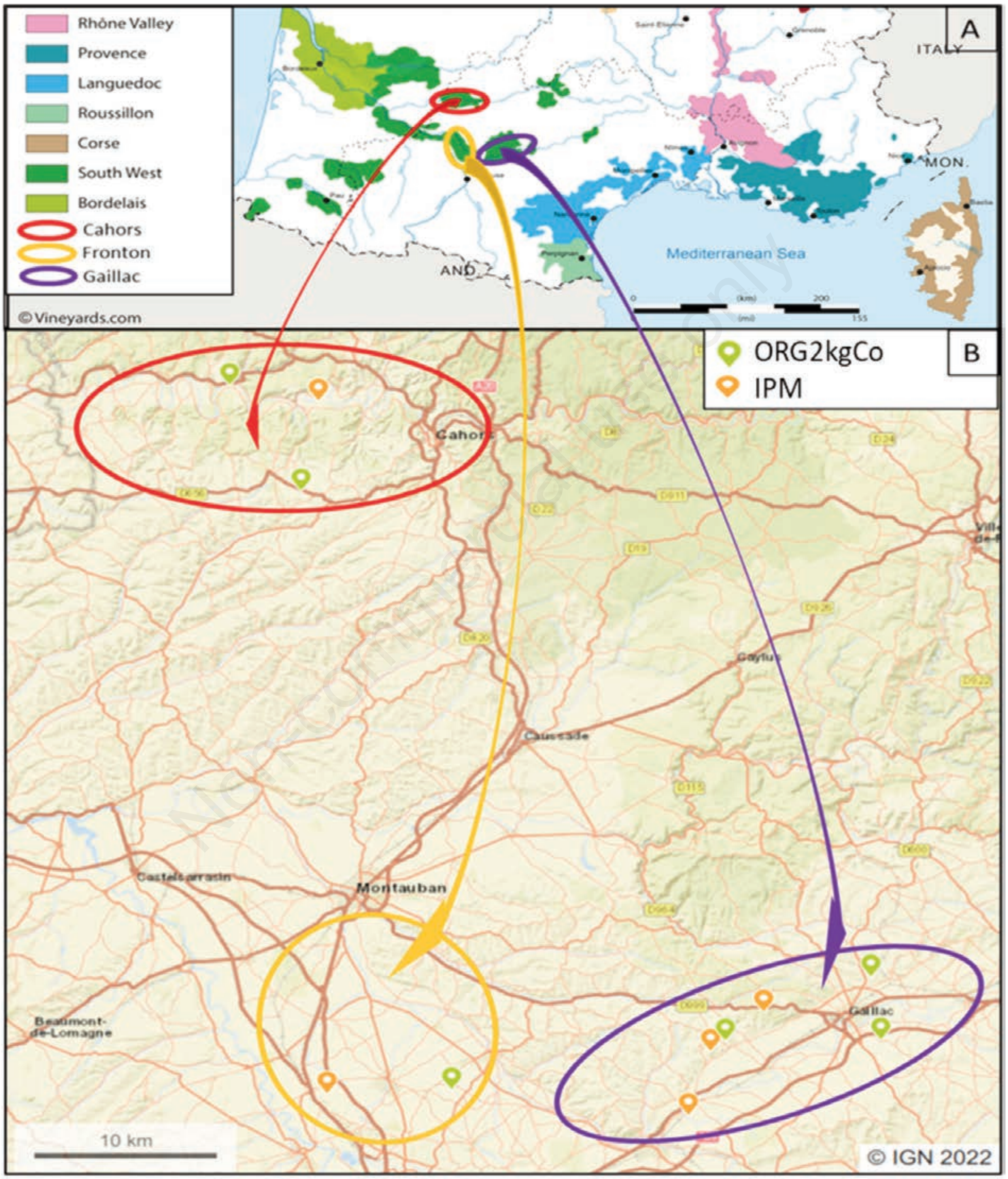

Figure 1. Location of (**A**) the winegrowing areas in South-Western France included in the study and (**B**) the fields where management strategies were implemented in 2021. The three ellipses represent the boundaries of each winegrowing region (Cahors in red, Fronton in yellow, and Gaillac in purple). The orange symbols represent the fields dedicated to the IPM management strategy and the green symbols represent the fields with the ORG2kgCo management strategy.

vintage, disease, insect and weed pressure, the three considered PDO had overall total TFI higher than the national average. In 2019, the average total TFI of VINOVALIE members was close to this TFI (Table 1). In general, the VINOVALIE winegrowers apply 7-9 rounds of fungicides, often combining two molecules. They mechanically weed alternate inter-rows, the intervening rows being left with natural vegetation cover. The soil under the vine is managed by chemical weeding (2-3 herbicide applications on average per season). In the wine-growing region, two treatments against the leafhopper vector of Flavescence Dorée are mandatory. On average, winegrowers apply one more insecticide to manage green leafhoppers and grape berry moths.

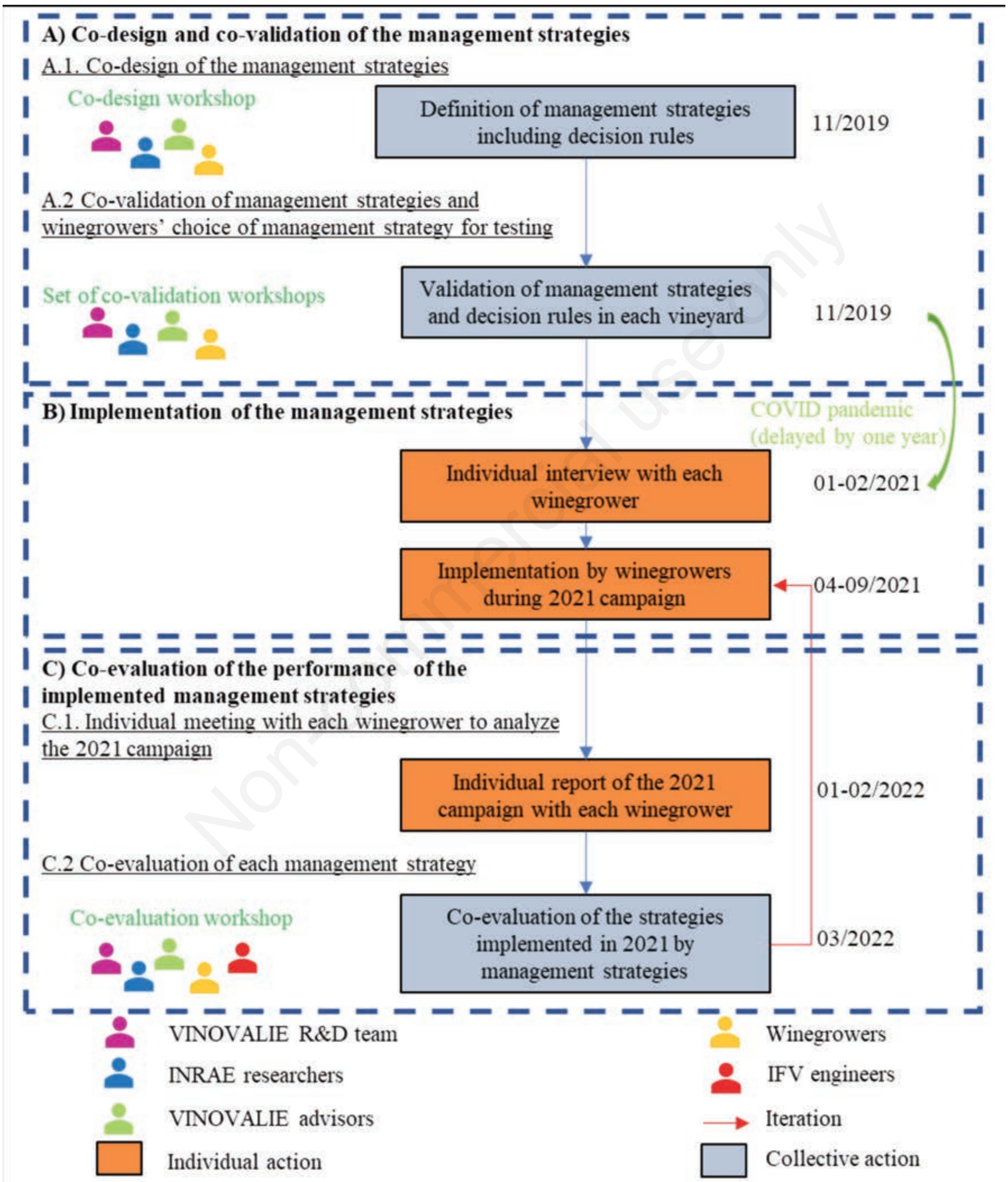

Figure 2. General framework of the participatory approach with its three main steps: **A**) Co-design and co-validation of the management strategies, **B**) Implementation of the management strategies and **C**) Co-evaluation of the performance of the implemented management strategies. The date of each step is written in month/year format. R&D, Research & Development; INRAE, French National Research Institute for Agriculture and Environment, Food and the Environment; IFV, French Institute of Vine and Wine.

Methodological approach

General framework

The original participatory approach we created, combines experimentation and workshops based on three main steps: Step A) Co-design and co-validation of the management strategies, Step B) Implementation of the management strategies, and Step C) Co-evaluation of the performance of the implemented management strategies (Figure 2). This participatory approach combined individual interviews carried out with one winegrower at a time, and collective actions carried out in groups during workshops. Note that the people involved in the different workshops differed according to the different steps. This participatory approach allowed the co-design of four management strategies, but this paper focuses only on two management strategies.

Characteristics of the participants

Five types of participants were mobilised with different roles throughout the process (Table 2). Two types of participants were involved in all steps: the winegrowers and VINOVALIE Research & Development (R&D) team (Table 3). The participation of the winegrowers was essential, as they are the ones who test and (eventually) adopt the new practices. We worked with a diverse group of winegrowers, all VINOVALIE members. The VINOVALIE R&D team included the R&D manager and the study coordinator. Two other types of participants were present at all steps except step B: VINOVALIE advisors and INRAE researchers (Table 3). The VINOVALIE advisors included the vineyard technicians and the environmental coordinator. The last type of participants was IFV engineers, who only participated in the last step (Table 3). Their absence in the previous steps is due to the fact that the co-design step was performed before the official start of the VITI OBS project in which the IFV engineer was involved.

Table 1. Treatment frequency index data per vineyard. Fronton was not concerned by the study in 2019.

	Mean total TFI of the vineyard in 2019 (Simonovici and Caray, 2021)	Mean total TFI of VINOVALIE members in 2019
Gaillac	13.1	12.4
Fronton	-	12
Cahors	14.4	11.5
France	12.4	-

Table 2. Type and role of participants in the three steps of the collaborative study.

Participant's type	Role
Winegrowers	Bring their experience of the problems encountered in their vineyard to the design process and implementation of the management strategies.
VINOVALIE advisors	Bring their experience of the problems encountered in the vineyard to the design process. Their knowledge on technical issues for each management strategy was important as they are the first interlocutors of the winegrowers during the crop protection campaign. The participation of the coordinator is important because he will be in charge of promoting the new strategies to the winegrowers, after their co-design, co-testing, and co-evaluation.
INRAE researchers	Bring specialist knowledge into the co-designing and the co-evaluating processes, using results of the latest studies on pesticide reduction to help identify the most relevant and effective solutions.
IFV engineers	Bring results of the latest local studies on pesticide reduction to help identify the most relevant and effective solutions.
VINOVALIE R&D	Supervision and coordination of the study.

Table 3. Type and number of participants in the three steps of the collaborative study.

Type of the stakeholders	Step A.1: co-design of the management strategies	Step A.2*: co-validation of management strategies and winegrowers' choice of management strategy for testing			Step B: implementation of the management strategies		Step C.1: individual meeting with each winegrower to analyse the 2021 campaign	Step C.2: co-evaluation of each management strategy	
		Gaillac	Fronton	Cahors	IPM	ORG 2 kg Co		IPM	ORG 2 kg Co
Winegrowers	5	5	7	7	5	6	11	4	4
VINOVALIE advisors	5	2	1	1	0	0	0	5	5
INRAE researchers	2	2	2	1	0	0	0	0	2
IFV engineers	0	0	0	0	0	0	0	1	0
VINOVALIE R&D team	2	2	2	2	1	1	1	1	1
Total	14	11	12	11	6	7	12	11	12

*The number of winegrowers corresponds to the total number of participants, involved in the co-design of the four management strategies.

Step A: co-design and co-validation of the management strategies

Step A.1: Co-design of the management strategies

Shortly before the co-design workshop, VINOVALIE defined the main objectives for the two strategies to be co-designed. First, the objective of the Integrated Pest Management (IPM) management strategy aimed at respecting the current non-constraining pesticide reduction objective of the Ecophyto II+ plan (Ministère de l'Agriculture et de la Souveraineté Alimentaire Français, 2022). Second, the ORG2kgCo management strategy was designed to anticipate the future re-registration of copper in 2025, the specifications of which might limit use to 2 kg/ha/year (currently 4 kg/ha/year). The objectives of management strategies were:

- IPM: Reduction by half of TFI as compared to the HEV (High Environmental Value) reference. As according to HEV standard TFI is 14.98 (with biocontrol products not included in TFI calculation), the objective of IPM is to maintain TFI below 7.49. All carcinogenic, mutagenic and reprotoxic (CMR) pesticides are prohibited.
- ORG2kgCo: organic farming system with a maximum of 2 kg/ha/year of copper.

The co-design workshop was organised over one day, including sessions aimed at listing the potential levers to decrease pesticides, and their organization within each strategy (Table 4). Five winegrowers were selected because they had already hosted previous experiments for VINOVALIE concerning the reduction of pesticide use: two from Gaillac and Fronton, and one from Cahors. Among the five winegrowers, two were organic farmers: one in Fronton and one in Gaillac.

Step A.2: Co-validation of management strategies and winegrowers' choice of management strategy for testing

The objective of the cooperative was to implement the two management strategies in three different fields in each of the three PDO production zones (which represent a total of 18 fields, managed by 18 different winegrowers). To be representative of the different production conditions, VINOVALIE advisors and the study coordinator divided each of the three PDO production zone into three sub-zones representative of the different soil types and climatic contexts. They then compiled a list of winegrowers potentially interested in the project who owned fields in the 9 sub-zones. No selection criteria on their cropping practices were applied. Afterwards, the study coordinator called on each of the winegrowers individually to present the project and to invite them to the co-validation workshops. All contacted winegrowers (seven in Gaillac and Cahors, and five in Fronton) participated in the co-validation workshops. One co-validation workshop (4 hours, step A.2) took place in each of the three wine-growing areas. The VINOVALIE advisors were represented by the local vineyard technician (Table 3). The objective was to define specificities and local adaptations of management strategies for each of the three wine-growing areas. First, the two previously co-designed management strategies were presented to each group of volunteer winegrowers. Second, the winegrowers were asked to discuss the strategies to adapt them to the specificities of their vineyards. Note that no changes were made by local winegrowers at this step. Thirdly, the winegrowers chose one management strategy and committed to implementing it.

Step B: Implementation of the management strategies

The implementation of the management strategies was supposed to start in 2020 but due to the COVID pandemic, it was delayed by one year.

The individual interview with each winegrower

During the winter (January to February 2021) preceding the 2021 campaign, an individual interview with each winegrower was organised on his/her farm. These interviews aimed to discuss the winegrower's vision of about plant protection and his/her current protection practices to create a stimulating and supportive work environment. During the interview, the choice of management

Table 4. Detailed content of the six sessions of Step A.1: Co-design of the management strategies.

Session number	Detailed content of each session	Duration (in min)	Form
1	Introduction of the study and the workshop participants.	15	Round table
2	Definition of the constraints on reaching the objectives of the two management strategies.	30	Open discussion
3	Listing of technical levers concerning disease management (downy mildew, powdery mildew, black rot and *botrytis cinerea*), insect management (phytoplasma, grape berry moths and green leafhopper), and weed management. that could be used for the two management strategies.	30	This brainstorming session took place around a whiteboard presenting the vine phenological cycle on which the participants were invited to position the technical levers
4	Definition of the IPM management strategy in three parts: (1) building the decision rules from scratch; (2) presentation of the systems tested in the DEPHY EXPE ECOVITI South-Western project (Serrano *et al*., 2019); (3) modification of the decisions rules according to new knowledge from part (2)	90	All the participants discussed and chose technical levers from the inventory compiled in session 3, For each lever, the participants collectively defined the decision rules expressed in the form of "If-Then" sentences (*e.g*., "If mass contamination of downy mildew is modelled by the Decision Support System (DSS), then a treatment must be performed" in the IPM management strategy). Each diease and insect pest were considered independently.
5	Definition of the ORG2kgCo management strategy.		
6	Definition of the agronomic, ecological and economic i ndicators to be used to assess the management strategies.	15	Open discussion

strategy and the field for its application was confirmed by each winegrower, and time was dedicated to a detailed re-explanation of the management strategy, using a document which was then left with the winegrower. To formalise the commitment to the study, the winegrowers signed a contract composed of five parts stating: i) the winegrower's confidentiality commitment about the tests carried out on his farm, ii) the purpose of the experiment, the experimental field and the surface area of the trial, and the start and end dates of the experiment, iii) VINOVALIE R&D's responsibility in case of damage to the experimental field, iv) the VINOVALIE R&D's confidentiality commitment concerning the data collected, and v) the framework for the triggering of crop loss compensation. This indemnity was planned in case of yield loss (compared to the winegrower's control) due to the implementation of the management strategy.

Implementation of management strategies by winegrowers during the 2021 campaign

A total of 11 winegrowers out of a target of 18 committed to implementing co-designed management strategies for three years (2021 to 2023): five selected the IPM management strategy and six chose the ORG2kgCo strategy (Figure 2). The other winegrowers who participated in the co-validation workshops worked on the two other management strategies not described in the paper. The characteristics of these 11 winegrowers were *a posteriori* compared to the average population of VINOVALIE winegrowers (internal source VINOVALIE for 2019): age (46 *versus* 52), vine area (51.3 *versus* 15.3) and TFI (12.58 *versus* 13.1). Moreover, an *a posteriori* qualitative analysis of their practices (pruning, tillage, fertilization, grapevine protection) showed that they were "classical" for the VINOVALIE cooperative; this allows us to consider these 11 winegrowers as "mainstream winegrowers". As we chose to work only with volunteer winegrowers in the fields network, some situations were missing: in Fronton, two fields for both management strategies and in Cahors, one field for the ORG2kgCo management strategy and two fields for the IPM management strategy were missing. In each vineyard, the main PDO grape variety was selected: Négrette N for Fronton, Syrah N for Gaillac and Malbec N for Cahors. For each winegrower, the management strategy was implemented on a field of at least 0.5 hectares. The choice of the field was a trade-off between the distance between the field and the shed, the representativity of the vineyard field in the PDO production zone, and the field homogeneity. The field was divided in two parts: one was managed according to the co-designed management strategy (minimum 0.25 hectares) and the other was managed according to the usual practices of the winegrower. Even if the two plots were close one from each other, we excluded the side-by-side rows to make the observations. The implementation of the management strategies was monitored during the 2021 season through numerous phone calls and in-field meetings for disease observations. The purpose of the frequent phone calls was to understand how the winegrowers were adapting to the decision rules of the management strategies, and the associated difficulties. In parallel, various data were collected to calculate the agronomic, ecological and economic indicators defined during the co-design workshop.

Step C: Co-evaluation of the performance of the implemented management strategies

Step C.1: Individual meetings with each winegrower to analyse the 2021 campaign

During winter 2022 (January to February), individual interviews (1-2 hours) were organised with winegrowers. The objective was to present a summary of the strategy and its field implementation to each winegrower, and check if the performance of the strategy agreed with their observations and perceptions. The individual summary was composed of four parts: Objective of the management strategy, Experimental conditions, Results (TFI, disease and insect notation, yield, fungicide costs), and Conclusion.

Step C.2: Co-evaluation of each management strategy.

This third series of workshops (4 hours) was organised separately for each management strategy, with most winegrowers having implemented each strategy (Table 3). Both workshops were organised in two main sessions. First, the study coordinator reminded the group of the decision rules for the management strategy and presented a summary of the results. Second, four topics were discussed: disease control, insect control, weed control, and finally, general questions. Each topic discussion was organised in two steps. First, participants had to answer specific questions defined by the study coordinator (Table 5), with a binary answer (yes/no or positive/negative) and a justification of their answer. Then, a round table discussion was conducted for each topic. After one year of implementation, we chose to focus the questionnaire on the commitment of winegrowers, the feasibility and the technical relevance of the co-designed prototypes and not on the practices-changing process itself contrary to another recent study (Delecourt *et al.*, 2019). The questionnaire differed between the two workshops, since synthetic herbicides and insecticides were not relevant to the organic management strategy. The questions also differed between winegrowers and other types of participants: for example, questions concerning the implementation of management strategies (*e.g.* "Would you have made this reduction in fungicide use by yourself?") were only asked to winegrowers (Table 5). The purpose of this questionnaire was to collect feedback from the winegrowers. Workshops were also recorded to extract verbatims, which were compiled to choose the ones expressing the best the reactions of winegrowers.

Results

The results are divided into two parts. First, we describe the two co-designed management strategies. Second, we present the results in terms of pesticide use reduction, and the evaluation of the strategies by the winegrowers.

Co-design and co-validation of the management strategies (steps A.1 and A.2)

Disease control

In both management strategies, two technical levers were selected to reduce the use of fungicides by the stakeholders and validated by winegrowers. The first solution to reduce the use of fungicides was the optimisation of disease treatments using a Decision Support System (DSS). Through their partnership with IFV, the winegrowers have free access to the DeciTrait® DSS developed by IFV. This DSS combines various types of information to optimise the protection strategies for downy mildew, powdery mildew, black rot and botrytis. This optimisation is realised by carrying out the required treatments and reducing the doses of products at these treatments as recommended by Davy *et al.* (2020) and by encouraging their substitution with biocontrol products (*e.g.* sulfur, potassium bicarbonate, *Bacillus pumilus*). During the co-design workshop, management strategies included specific active molecules to be used at each vineyard stage. Here, we mention only the type of active molecules (synthetic or biocontrol), as the availability of specific actives may change according to French or European regulations. According to the ESR (Efficiency-Substitution-Redesign) framework (Hill and MacRae, 1996), the use of a DSS corresponded to Efficiency and the use of biocontrol products to Substitution.

The IPM management strategy to disease control has been shown in Figure 3.

In the ORG2kgCo management strategy, the DSS was used only to schedule the treatments according to the periods of heightened risk of contamination for downy mildew and powdery mildew. The development of the vine has been divided into 4 periods corresponding to the period of sensitivity of the vine to diseases: Budburst to Flower buds; Flower buds to Fruit Set; Fruit Set to Bunch closure; Bunch closure to Veraison. Copper levels varied across the four time periods. If symptoms of downy mildew were observed, a biocontrol product could be used during the treatments. Sulfur (biocontrol molecule) was used against powdery mildew and black rot, and sulfur was added for each copper treatment. Against botrytis, the same strategy as the IPM management strategy was utilised.

Insect control

The insect control strategy did not differ between the IPM and ORG2kgCo strategies (Figure 4). The general aim was to limit the use of insecticides in mandatory treatments against phytoplasma (*Candidatus phytoplasma vitis*). To control grape berry moths, sexual confusion was favoured and treatments with biocontrol products were allowed if needed depending on the pressure. The use of a biocontrol product was selected to control the green leafhoppers. To decide the date of application, the Plant Health Newsletter (Bulletin de Santé du Végétal in French) was used. This newsletter (published by the local Chambers of Agriculture for each vineyard and by sector) assesses insect and disease risks (Guichard *et al.*, 2017).

Weed control

Weed management was not integrated into the ORG2kgCo strategy because in organic agriculture the use of herbicide is forbidden. Each winegrower decided on his soil management. To reduce herbicide use in the IPM management strategy, mechanical weeding was encouraged among winegrowers who were equipped with suitable tools.

For weed management, no decision rules were considered in the development of either of the two management strategies. This choice was motivated by the fact that the winegrowers did not have the same tools to control weeds, and that the pedoclimatic situations, and thus the weed pressure, differed between the fields.

Implementation and co-evaluation of the strategies (steps B and C.2)

The set of agronomic, ecological and economic indicators defined and validated by winegrowers for the field assessment is presented in Table 6.

The co-evaluation of the strategies implemented in 2021 was conducted through individual meetings with each winegrower to analyse the 2021 campaign and a specific workshop for each management strategy.

Implementation and field assessment results

In 2021, the rainy weather conditions favoured fungal diseases. Black rot exerted strong pressure and downy mildew took over at the end of the season. Despite this high-pressure context for the first year of experimentation, the winegrowers testing the ORG2kgCo management strategy managed to not exceed 2 kg of copper with 9 to 15 applications of different copper doses depending on the winegrowers. In all situations, the IPM management strategy reduced the use of pesticides compared to the reference field in each farm. This led to TFI that was lower than the HEV reference in all but one field. The reduction of TFI compared to the HEV reference varied from -14% to -57% (average of -25%). The winegrower who did not achieve the 50% TFI reduction, presented

Table 5. Questions addressed to all participants (plain text) or winegrowers (italicised text) to co-evaluate the management strategies during the co-evaluation workshop (step C.2).

Management strategy	IPM	ORG2kgCo
Disease control	How do you judge the disease control of the management strategy? Do you want to go back to the same disease management strategy? *Would you have made this reduction in fungicide use by yourself?* *Do you take into account the information coming from the Decitrait® DSS?* *Will you be willing to implement this strategy on your farm without financial support?* What dose of copper should be used for each treatment?	How do you judge the disease control of the management strategy? Do you want to go back to the same disease management strategy? *Would you have made this reduction in fungicide use by yourself?* *Do you take into account the information coming from the Decitrait® DSS?* *Will you be willing to implement this strategy on your farm without financial support?* What dose of copper should be used for each treatment?
Insect control	Do you agree with the objective of reducing the use of insecticides only to mandatory insecticides against phytoplasma (Candidatus phytoplasma vitis)? Would you [prefer to] use clay for additional treatment against grape worms? Would you [prefer to] use *Bacillus thuringiensis* for additional treatment against grape worms? Can you imagine any other solutions?	*Do you use sexual confusion?* *How do you manage the application of the clay?*
Weed control	*Have you already done your winter herbicide treatment?* *Have you used a CMR herbicide?* *Do you want to limit the use of herbicides or completely stop?* What solutions do you prefer to limit the use of herbicides? How do you want to monitor weed control?	
General question	*Would you have been available in the study if the harvest loss indemnity had not been present?*	*Would you have been available in the study if the harvest loss indemnity had not been present?*

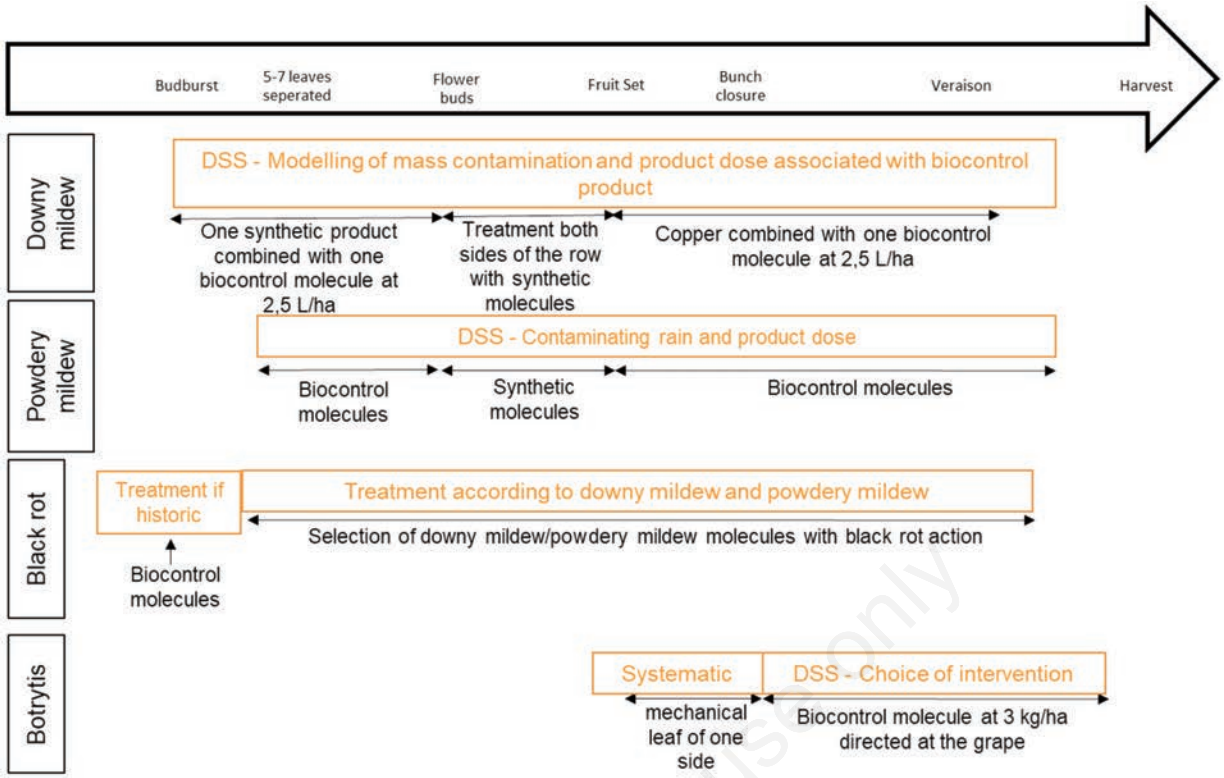

Figure 3. Disease control against downy, powdery mildews, black rot and botrytis of IPM management strategy as designed during the co-design workshop step A.1 of the method. The decision rules for applying a treatment are shown in orange and the product to apply in black. The black lines delimited the period to apply this product. DSS, Decision Support System.

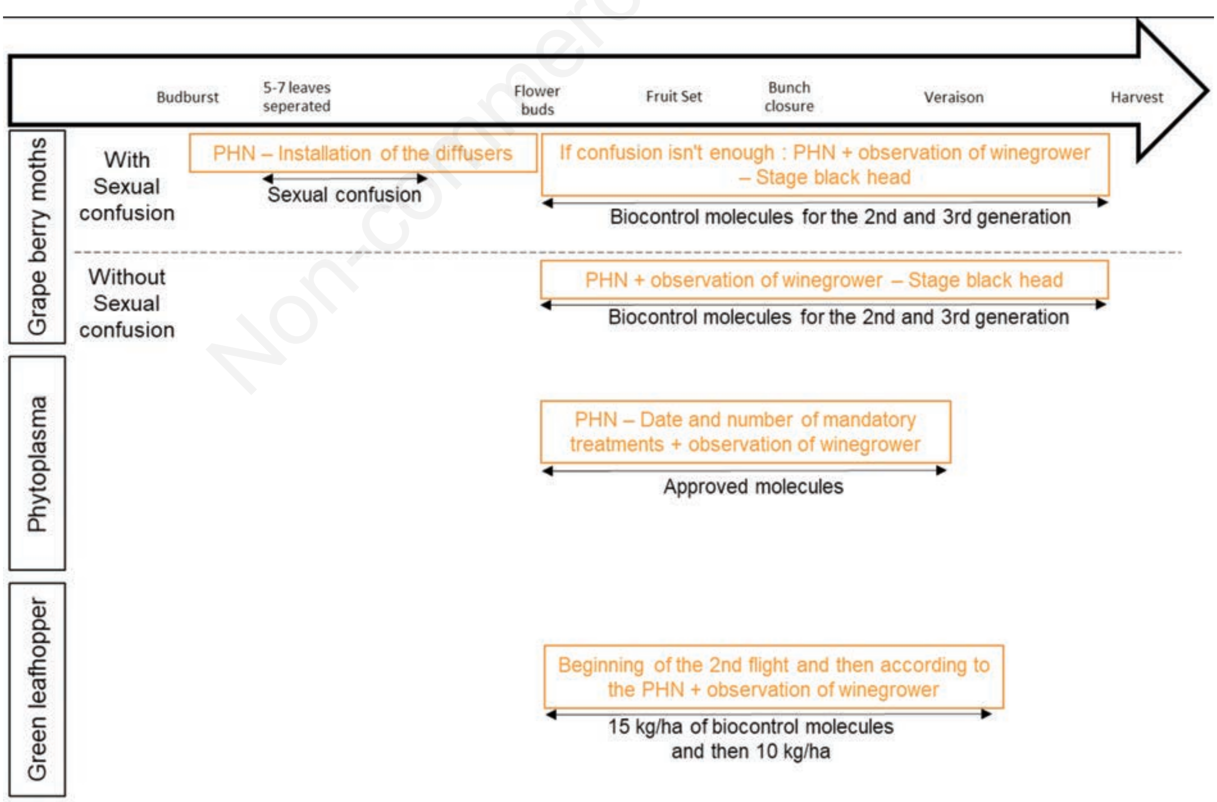

Figure 4. Insect control (grape berry moths, phytoplasma, green leafhopper) of the two management strategies as designed during the co-design workshop step A.1 of the method. The decision rules for applying a treatment are shown in orange and the product to apply in black. The black lines delimited the period to apply this product.

a TFI higher than the HEV reference (+7%), even though the winegrower reduced TFI by 19% compared to his farm standard. Note that TFI reduction was only due to a reduced use of fungicide, as we observed no change in the use of herbicides and insecticides, *i.e.* winegrowers involved in the IPM management strategy did not implement co-designed weed and insect control. Therefore, the decrease in fungicide TFI was the most significant, and varied from -14% to -70% with an average of - 38.6%.

Co-evaluation of disease control for the two management strategies and further adaptations

We focus here on the results of disease control only, as the co-evaluation workshops mainly concerned this topic and the winegrowers implemented only the disease control part of the management strategies.

All participants gave a positive assessment of disease control for both strategies. For example, participant 4 of the co-evaluation workshop on the IPM management strategy mentioned “the management strategy was positive as there was very little difference in yield loss between the winegrower’s control and the part of the field treated with the management strategy. Given the year and the strong disease pressure we had this year, this is very positive.” Regarding the ORG2kgCo management strategy, Participant 8 mentioned “Given the context of the year, I think this is positive. The two subfields achieved similar yields. It’s difficult to conclude because the mildew arrived late. It would be interesting to see if we manage to stay below 2kilos if the mildew arrives earlier. I would stay with the same strategy [in case it works even in this case].” However, all winegrowers were not ready yet to expand the implementation of management strategies to their whole farm, as they prefer to wait for longer-term assessment results.

During the two co-evaluation workshops, the group decided to keep the same strategy in 2022. Participant 2 of the co-evaluation workshop on the IPM management strategy mentioned that “If the year was under normal pressure, the reduction in pesticide use could be greater”. The same remark was made at the co-evaluation workshop of the ORG2kgCo management strategy. Even if the choice was made to maintain the same strategy, a few changes were made for each management strategy.

The first change to the IPM management strategy mentioned by the group was to ban molecules that will be withdrawn from the market within the next two years. This change was suggested first by participant 6 “Concerning the modifications, at the beginning of the campaign a molecule is used and it is a molecule that will disappear quite quickly so it would be interesting to envisage a plan B from now on”. The second change was the dose of copper to be applied during the treatments. Indeed, winegrowers used high doses of copper, thereby increasing the TFI of their experiment. To manage the dose of copper to be applied, all the participants decided to follow the output of the DeciTrait® DSS. The question remains on who would use the DSS, as not all winegrowers are current users. For the ORG2kgCo management strategy, the only modification mentioned by the group concerned the addition of the use of plant extract products. This modification was mentioned by two winegrowers already using such preparations. One of them said, “To continue to reduce my copper dose, I plan to use more and more horsetail and nettle preparations. I plan to add them to each treatment”. During the co-evaluation workshop, there were many discussions about the management of black rot, especially in fields with a strong history of this disease: “I have a question about fields with a strong history. Does the management of 2 kilos of copper make it possible to control black rot with a strong history over three years?” (Participant 10, ORG2kgCo co-evaluation workshop). The second issue concerning black rot was the timing of the first treatment. All winegrowers planned to schedule their first black rot treatment earlier for future years, as mentioned by participant 6 “The objective for next year is to start treatments earlier to try to manage the black rot as well as possible”. This was reinforced by one winegrower already using this treatment and was satisfied with the results. The last topic on the management of black rot was about the quantity and formulation of sulfur to be applied. One of the winegrowers mentioned difficulties “Each time I use powdered sulfur, I add liquid sulfur to give a better hold on the leaves. It has a sticky effect” (Participant 8, ORG2kgCo co-evaluation workshop). Overall, black rot was the main topic of the workshop, due to the high-pressure in 2021 across the three vineyards. For all winegrowers, except one, it was the first year using the tool. Only two winegrowers did not follow the information given by the DSS. For instance, one ORG2kgCo winegrower believed that spraying according to rainfall alone was sufficient: “No I didn’t use it. I don’t need it. I have my treatment routine which is set up according to the forecasted rainfall.”. For the others, the DSS was used by the study coordinator, and results were discussed with each winegrower, except for one winegrower who used it by himself. One of these winegrowers said “I had never used it before. Often, I used it with the study coordinator by phone to adjust the doses on the trial part.” The reasons why winegrowers found it difficult to use the tool independently were the lack of time and the fact that it was not familiar to them.

Discussion

The participatory approach presented in this paper succeeded in launching a dynamic towards the reduction of pesticides in viticulture in the South-Western region of France. This participatory approach allowed the co-design of two innovative management

Table 6. Agronomic, ecological and economic indicators used for the field assessment.

Categories of indicators	Indicators
Agronomic	Average frequency and intensity of attack of downy mildew, powdery mildew, black rot and botrytis on leaves and grapes Average frequency and intensity of attack of green leafhopper on leaves
Ecological	TFIs Copper quantity
Economic	Yield Cost of plant protection (product + tractor use)

strategies that were implemented by 11 winegrowers and then co-evaluated during participatory workshops. In the following section, we discuss the relevance of our participatory approach regarding three aspects: involvement of winegrowers, effective reduction in pesticide use, and perspectives towards a wider adoption of these management strategies.

A participatory approach that allows the involvement of diverse stakeholders and a strong commitment from winegrowers

In this study, we chose to involve a diverse group of stakeholders for the co-design and co-evaluation steps. While participant choice is a crucial step in co-design workshops (Jeuffroy *et al.*, 2022), several studies have shown the benefits of actively involving a range of stakeholders from various sectors or organisations to explore possible strategies and favour knowledge sharing, each with their own skills and knowledge (Chantre *et al.*, 2016; Puech *et al.*, 2021). We involved different types of participants: winegrowers, the VINOVALIE R&D team, VINOVALIE advisors, INRAE researchers, and IFV engineers. In particular, the participation of the winegrowers at all steps of the process showed their commitment to this participatory approach, with all winegrowers willing to continue experimenting in the following year. This strong involvement of winegrowers legitimises the management strategies and ensures that the proposed management strategies and criteria used to assess them are relevant (Salembier *et al.*, 2016; Lairez *et al.*, 2020).

Three factors in this participatory approach helped to promote the involvement of winegrowers. First, this participatory approach is based on pre-existing farmer networks. Indeed, all of the winegrowers who participated in the study already knew each other because they are members of the same cooperative, VINOVALIE. As a consequence, the winegrowers were already used to sharing their experiences and working together. They were engaged in a relationship of trust, which is a key element for innovation (Skardon, 2011). In addition, an integrated pest management group already existed in one of the PDO concerned by the study (Gaillac), with weekly telephone meetings led by the viticultural technician. During these meetings, the viticultural technician reports on observations and pest pressure, and a discussion on the protection strategy takes place among the winegrowers and the viticultural technician, enabling winegrowers to better adjust treatments to the pest pressure. Leclère *et al.* (2023) have also shown the importance of pre-existing farmer networks such as a local group of development. Second, the goal of our participatory approach matched the priorities of the stakeholders, *i.e.*, pesticide use reduction [this match being considered key by Hossard *et al.* (2013)]. Indeed, the participatory approach aims to anticipate potential regulations on pesticides that could come into effect in the next few years, such as the limitation or elimination of an active molecule. Thirdly, the implementation by winegrowers of the co-designed management strategies on a small field (0.25 hectare) in the first phase is essential. Indeed, the winegrowers agreed to experiment with these strategies because the area is small and thus the risk is limited. For example, participant 4 highlighted, on the IPM management strategy, that "On the reduction, I had started to do a little bit, but to reduce the doses so much I would say no. I would not have done this reduction on the whole farm this year, I admit I would not have done it. Thanks to the study and the fact that it is on a small surface area, the risk taken is limited, which allows us to go further in the reduction". This highlights the value of experimenting with management strategies in a small area in the process of adopting new practices.

A participatory approach that allows a significant reduction in the use of pesticides based on limited innovation levers

The participatory approach allowed us to co-design management strategies with a significant reduction of TFI (between -14% and -57%, with an average of -25% for all pesticides and between -14% to -70%, (average -38.6%) for fungicides) for IPM management strategy and a significant reduction of copper sprays for the ORG2kgCo management strategy after one year of experimentation. This reduction is encouraging in comparison to the results obtained in the Dephy Farm farmers' group, where the reduction was about 33% for all pesticides, and 27% for fungicides, after 10 years of involvement in the group (Fouillet *et al.*, 2022). These co-designed management strategies mobilise technical levers that have shown to be effective in reducing the use of pesticides in the vineyard (Mailly *et al.*, 2017).

The participatory approach was key to effectively reduce pesticide use. Indeed, the diversity of the stakeholders involved in the co-design workshops allowed us to co-design management strategies combining technical levers that can be implemented by the winegrowers, are accessible to them and effective in reducing the use of pesticides. Moreover, the co-evaluation performed with stakeholders highlighted that these two management strategies were considered feasible.

In both management strategies, the two measures used were: optimisation of the timing, dose, frequency of pesticide application (Efficiency (E)) and substitution of synthetic products by biocontrol products (Substitution (S)). Redesign (R), *e.g.* resistant varieties or new type of pruning, was not explored during the co-design workshops. Even if the co-designed management strategies could be seen as innovative by the considered cooperative members, as the combinations of technical levers had previously never been implemented by any of the participants or cooperative's winegrowers, the level of innovation was rather low, mainly based on E and S levels. This low level of innovation could be explained by the fact that the aim was to co-design management strategies that could be adopted immediately by the greatest number of winegrowers and adapted to established vineyards (Montaigne *et al.*, 2016). The stakeholders involved in the co-evaluation workshop consistently considered that these two management strategies were feasible.

Lastly, this participatory approach allowed a significant reduction in the use of pesticides thank to by the individual support provided to the winegrowers. First, the individual interview before the beginning of the treatment campaign gave the opportunity to re-explain the management strategies, which improved the winegrowers' understanding. Second, the regular individual contacts during the campaign through numerous phone calls and in-field meetings reassured the winegrowers on the implementation of the management strategies and facilitated the use of the DSS as previously mentioned. This need for ongoing support is important, especially in the first years of adopting the management strategy (Puech *et al.*, 2021).

Relevance and limitations of the method for large-scale adoption of these management strategies

The objective of this paper was to present the participatory approach, how it involved winegrowers, and how its application over one year contributed to a reduction in pesticide use and stimulated winegrowers to continue the experiment.

On this basis, the results showed that the participatory approach enabled the winegrowers to get involved in the process and to achieve a significant reduction in pesticide use. However, this implementation and the associated results may vary according to climate and the disease pressure of the year. For instance, if the year's fungal pressure had been lower, the reduction in TFI and copper could have been greater. In contrast, if the implementation of management strategies had caused some damage, the satisfaction of the stakeholders would have probably been lower. This seasonal change in pesticide use and in the willingness to reduce pesticide use has already been observed in various studies (Larsen *et al.*, 2019; Hossard *et al.*, 2022). Thanks to our method, we designed management strategies with explicit decision rules, which enabled adjustment to the year's disease pressure. To consolidate these results, the strategies co-designed as part of this project will be evaluated over a 3-year period. There is also the possibility of modelling fungal pressure and associated damage to consider a wider range of situation [*e.g.* for wheat (Robin *et al.*, 2013)]. If the implementation of the co-designed management strategies is successful, the final objective is their dissemination to a wider audience among the winegrowers' partners already involved in the trial, and to a larger number of winegrowers of the cooperative. Given that our sample of partner winegrowers has an initial TFI equivalent to the average TFI of winegrowers of the cooperative and the average TFI of French winegrowers, we assume that these results can be generalized and disseminated to a larger number of the cooperative's producers. However, some subzones are not represented in the network of fields examined in this study, so the dissemination of management strategies in these subzones should be carried out with caution. All involved winegrowers succeeded in reducing pesticide use and were satisfied with the results obtained. However, they were not ready yet to expand the implementation of management strategies to their whole farm, as they prefer to wait for more long-term assessments results. This problem of upscaling innovative practices to the farm has already been identified, and was explained by the higher risk of yield losses associated with their implementation and confidence in these practices built over time (Puech *et al.*, 2021).

To facilitate the transfer to non-participating winegrowers, a communication of the results was made to all winegrowing members of the cooperative, including field visits in July and an oral presentation at harvest review meetings organised by VINOVALIE advisors in each vineyard. We plan to continue such visits, as demonstrations on *pilot* farms to motivate other farmers has been shown to be effective because it allows them to see results in their production situation (Le Bellec *et al.*, 2012). In addition to these actions, the implementation of an insurance system to cover the risk of crop damage due to cryptogamic diseases linked to the reduction of phytosanitary inputs, as proposed by Raynal *et al.* (2022), could help to encourage the reduction of pesticide use. Note that winegrowers also cultivate grapes destined to produce Protected Geographical Indication (PGI) wines with different growing methods and yield objectives than the PDO fields. The management strategies are tested on PDO fields and their implementation without testing on PGI fields could be too risky (the targeted yield is higher on PGI fields, *i.e.*, 120 hl/ha *versus* 50-55 hl/ha). To avoid this, an experiment as carried out on PDO fields could be established on PGI fields.

The participatory approach has led to a reduction in fungicides, but not in herbicides and insecticides. We assume that the initial objective was too ambitious to work on the reduction of all three types of treatments simultaneously, in a short period of time. Moreover, the reduction of herbicides and insecticides may require the redesign of cropping systems to introduce biodiversity (*e.g.* hedges, covercrops), which entails more drastic changes in vineyards (Fouillet *et al.*, 2022).

Conclusions

The proposed participatory approach combines the involvement of a diversity of stakeholders, the co-design of two management strategies for disease, insect, and weed control in vineyards, the implementation of the management strategies by 11 winegrowers in a field on their farm, and their co-evaluation by the stakeholders. This participatory approach enabled the co-design of management strategies that allow a significant reduction in the use of pesticides. The implementation of the IPM management strategy resulted in an average 25% reduction of the TFI compared to HEV standard TFI and the winegrowers who tested ORG2kgCo managed not to exceed the set limit of 2kg of copper per year. This participatory approach involved winegrowers at the centre of the whole process to reduce pesticide use. The participatory approach could be transposed to other winegrowing areas, as management strategies are site-specific, especially for crops such as vines, where fungi are the main issue. It remains to be seen whether this participatory approach will allow the adoption of management strategies within the cooperative in the future.

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