iVES OENO One vine & wine

DOI: https://doi.org/10.20870/oeno-one.2026.60.4.10041

OPEN ACCESS

VITICULTURE ORIGINAL RESEARCH ARTICLES

On-farm experimentation to reduce pesticide use in viticulture: evidence from Southwestern France

Mickaël Perez[1], Aurélie Metay[2,*], Raphaël Metral[2], Christian Gary[2], Pauline Lacapelle[1], Marie-Hélène Robin[3]

[1] VINOVALIE R&D, Saint-Sulpice-la-Pointe, France
[2] ABSys, Univ Montpellier, INRAE, CIRAD, Institut Agro, Ciheam-IAMM, Montpellier, France
[3] AGIR, INRAE, INPT, ENSAT, EI-PURPAN, Univ Toulouse, Castanet-Tolosan, France

Article number: 10041

*correspondence:
aurelie.metay@supagro.fr

Associate editor:
Michaela Griesser

Received:
21 April 2026

Accepted:
24 September 2026

Published:
28 October 2026

This article is published under the **Creative Commons licence** (CC BY 4.0).

Use of all or part of the content of this article must mention the authors, the year of publication, the title, the name of the journal, the volume, the pages and the DOI in compliance with the information given above.

ABSTRACT

Viticulture is typically associated with high pesticide use. However, strategies exist to reduce their use, such as substituting them with biocontrol products, though winegrowers still adopt them in limited numbers. On-farm experimentation (OFE) is a promising approach to promoting the transition towards low-pesticide viticultural systems. In this study, we assessed four innovative management strategies, co-designed with winegrowers in southwestern France and implemented through OFE: (i) 'IPM' (Integrated Pest Management), targeting a 50 % reduction in the total treatment frequency index (TFIt) compared to the French High Environmental Value (HEV) reference; (ii) '0RES' (Zero Residue), aiming for the same pesticide reduction as 'IPM' while ensuring no detectable pesticide residues in wine; (iii) 'BCT' (Biocontrol), relying exclusively on biocontrol products and plant extracts, with mandatory treatments against phytoplasma (*Candidatus Phytoplasma vitis*); and (iv) 'ORG2kgCo' (Organic with 2 kg Copper), an organic farming approach limiting copper application to 2 kg/ha/year. Nineteen winegrowers across three wine-growing regions implemented these strategies over two years (2021–2022). The strategies were evaluated under commercial vineyard conditions using a set of agronomic, environmental, and economic indicators, including disease severity, treatment frequency index (TFI), copper use, yield, and fungicide costs. Their performance was assessed by comparison with both the winegrowers' conventional practices and the French High Environmental Value (HEV) reference. Compared to the HEV reference, TFIt reductions averaged –32.1 % for 'IPM', –42.2 % for '0RES', and –87.8 % for 'BCT'. When compared to the winegrowers' conventional practices, reductions were lower: –17.9 % ('IPM'), –29.7 % ('0RES'), and –80.7 % ('BCT'). The decrease in pesticide use primarily resulted from a reduction in fungicide applications, achieved through two key technical levers: the use of a Decision Support System and the substitution of conventional fungicides with biocontrol products. The 'ORG2kgCo' strategy effectively maintained copper applications below the 2 kg/ha threshold. Except 'BCT', all management strategies successfully controlled disease, limited yield losses, and reduced fungicide costs. These findings demonstrate that pesticide use can be significantly reduced while maintaining satisfactory yields under real farm conditions. These results highlight that while full-scale adoption remains limited, targeted deployment and farmer-led experimentation can facilitate transitions to low-pesticide systems. However, further validation is needed across larger areas, with diverse grapevine varieties, different production objectives, and over multiple years with varying disease pressures. If confirmed, such strategies could accelerate the large-scale adoption of low-pesticide viticultural systems.

KEYWORDS: evaluation, biocontrol, disease control, grapevine

INTRODUCTION

Reducing pesticide use is a major challenge in agriculture due to environmental (*e.g.,* pollinator decline (Ali *et al.*, 2021)) and human health concerns (Inserm, 2021). In France, viticulture ranks among the most pesticide-intensive crops (Urruty *et al.*, 2016), with fungicides accounting for ~80 % of applications, followed by insecticides (15 %) and herbicides (5 %) (Mailly *et al.*, 2017). This reliance is driven by high disease and pest pressure, including downy mildew (*Candidatus Phytoplasma vitis*), powdery mildew (*Erysiphe necator*), botrytis (*Botrytis cinerea*), black rot (*Guignardia bidwellii*), and grape berry moths (*Eupoecilia ambiguella*, *Lobesia botrana*), which significantly affect yield and quality (Fermaud *et al.*, 2016). Despite the Ecophyto plan (Barzman & Dachbrodt-Saaydeh, 2011; Guichard *et al.*, 2017), pesticide use has remained relatively stable since 2009 (Mouly *et al.*, 2022; Phyteis, 2022).

Technical levers for pesticide reduction are commonly structured under the ESR framework (Hill & MacRae, 1996). Efficiency strategies rely on optimising dose, timing, and spraying quality using decision support systems (DSS) based on epidemiological models and climatic data (Mailly *et al.*, 2017; Davy *et al.*, 2020). These approaches can reduce pesticide use by 30–50 % (Delière *et al.*, 2018). Substitution involves replacing synthetic inputs with biocontrol solutions (Aveline *et al.*, 2022), including microorganisms, semiochemicals, and natural substances, though limitations persist, particularly for weed control. Redesign strategies include resistant cultivars and agroecological infrastructures, enabling major reductions in treatment frequency (Miclot *et al.*, 2022), but remain constrained by long-term system inertia (Mailly *et al.*, 2017).

The persistence of pesticide use reflects a socio-technical lock-in (Guichard *et al.*, 2017), reinforced by knowledge gaps, risk aversion, and organisational constraints (Aka *et al.*, 2018; Bakker *et al.*, 2021; Giampietri & Trestini, 2023). Participatory design and on-farm experimentation (OFE) have demonstrated their capacity to facilitate adoption by enhancing farmer engagement, experiential learning, and peer-to-peer diffusion (Catalogna *et al.*, 2018; Lacoste *et al.*, 2021; Toffolini & Jeuffroy, 2022; Fouillet *et al.*, 2022; Pant & Hambly Odame, 2009).

This study aims to answer the following research question: "What are the agronomic performances and associated costs of fungicides in co-designed management strategies?" The management strategies were co-designed through a participatory approach involving various stakeholders (Perez *et al.*, 2024). Their performance was then assessed through a two-year on-farm experiment (OFE) conducted in southwestern France, within a network of 19 winegrowers across three wine-growing regions. We hypothesised that reducing pesticide use could increase disease incidence, potentially lowering yield and raising fungicide costs, especially with biocontrol products. We evaluated whether co-designed strategies (i) reduced pesticide use (TFIt, TFIf, copper use), (ii) controlled diseases (intensity on leaves and grapes), and (iii) remained economically viable (yield, fungicide cost). After presenting the strategies and on-farm results, we assess their performance in reducing pesticide use and controlling diseases, and discuss improvement options and conditions for wider adoption.

MATERIALS AND METHODS

1. Study area

This study was conducted with the French cooperative VINOVALIE, the largest wine producer in South-West France, representing ~300 growers and 4000 ha out of 55,040 ha in 2021 (Interprofession des Vins du Sud-Ouest, 2024). The case study covered three PDOs (Cahors, Fronton, Gaillac), focusing on vineyards targeting 50–55 hl/ha, a yield level commonly achieved in these appellations. Vineyards are predominantly conventional, with ~20 % organic area. The climate is oceanic, with annual rainfall of 600–750 mm (1995–2022; Carretier, 2023). Rainfall peaks in January, April–May, and October–December (60–70 mm/month), and is lowest in February and July (40–45 mm). Summer storms increase pressure from downy mildew and black rot, often requiring intensive fungicide use. Consequently, the three PDOs show a TFIt above the French average (Prost, 2023), although VINOVALIE averages are similar (11.96 *vs* 12.4 in 2019). Growers typically apply 7–9 fungicide sprays, often combining two active ingredients. Inter-rows are alternately tilled and grass-covered, while under-vine areas receive 2–3 herbicide applications per season. Two insecticide treatments against *Scaphoideus titanus* are mandatory, often supplemented by one additional treatment for other pests or mating disruption.

2. Vintage characteristics

The two years experienced very different weather conditions. In 2021, a frost affected the whole of France, but only a few vineyards in the study were affected. In contrast with the data from 1995 to 2020, 2021 was wetter, with excess rainfall in May, June, and especially July (+80 mm in 3 months) (Carretier, 2021). On the contrary, 2022 was generally warmer and drier, in contrast to the data from 1995 to 2021. It suffered a rainfall deficit from May to August (–127 mm in 4 months), and average temperatures were 2.8 °C higher in July and 3.6 °C higher in August than normal over the last 26 years (Carretier, 2022). These characteristics had a strong influence on cryptogamic disease pressure. As confirmed by the Plant Health Newsletter (Bulletin de Santé du Végétal in French) published by the Chamber of Agriculture for both years, downy mildew pressure was average to high in 2021 in the three vineyards, whereas it was low in 2022. Black rot pressure was high in 2021 and low to medium in 2022. Finally, powdery mildew pressure was low to average in both years (Carretier, 2021; Carretier, 2022).

3. Characteristics of the co-designed management strategies and implementation by winegrowers

During the co-design workshops, a reduction in the use of all pesticides (including herbicides and insecticides) was initially discussed. However, within the on-farm experiment (OFE), winegrowers ultimately chose to implement only the disease management component, mainly due to equipment constraints (*e.g.,* lack of mechanical weeding tools). The tested management strategies are therefore innovative compared to current winegrowers' practices, as they were co-designed to substantially reduce pesticide use while remaining feasible under real farming conditions. These strategies, along with the set of indicators used for their assessment, were co-developed in 2019 through workshops involving five types of stakeholders: winegrowers, INRAE researchers, IFV engineers, VINOVALIE advisors, and the VINOVALIE Research & Development team (for more details, see Perez *et al.*, 2024).

Their performance was evaluated in a two-year on-farm experiment conducted within a network of nineteen winegrowers in south-western France, across three wine-growing regions. For the 'IPM' and '0RES' management strategies, the pesticide reduction targets were defined based on the Treatment Frequency Index (TFI) thresholds for High Environmental Value (HVE) certification (Ministère de l'Agriculture et de l'Alimentation, 2019). In this reference framework, the Total TFI (TFIt) is 14.98 and the Fungicide TFI (TFIf) is 11.37.

The four resulting management strategies were defined with the following objectives:

- 'Integrated Pest Management (IPM)': Reduction of TFIt (with biocontrol products not included in the TFIt calculation) by half as compared to the HEV reference (*i.e.*, down to TFIt max = 7.49 for the three PDOs), and prohibition of all carcinogenic, mutagenic and reprotoxic (CMR) pesticides,
- '0 Residu (0RES)': Same as 'IPM' with no pesticide residues in wines,
- 'Biocontrol (BCT)': exclusive use of biocontrol products (sulfur, potassium phosphonates) and plant extract (orange essential oil), with mandatory treatment against phytoplasma (*Candidatus Phytoplasma vitis*),
- 'Organic with 2 kg of copper (ORG2kgCo)': organic farming with a maximum copper use of 2 kg/ha/year. In Europe since 2018, the use of copper metal in agriculture (including Organic Agriculture) is limited to a maximum of 28 kg/ha/7years equivalent to 4 kg/ha/year.

Two of the four management strategies ('IPM' and 'ORG2kgCo') were detailed in Perez *et al.* (2024). The 'IPM' management strategy co-designed during workshops for disease control is described in Figure 1. The '0RES' management strategy was similar to that of the 'IPM' management strategy, with the distinctive feature of positioning the molecules according to their 'tracing' power in the wines. The 'BCT' management strategy was developed around the use of several biocontrol products. The 'ORG2kgCo' management strategy was based on a modulation of the copper dose according to the phenological stage of the vine.

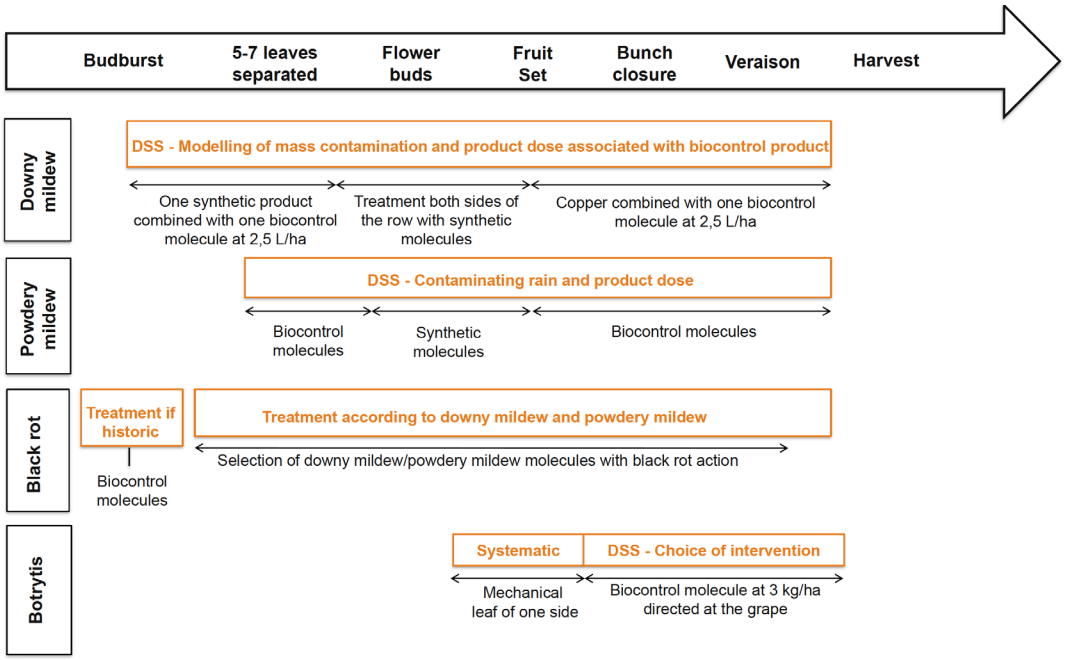


FIGURE 1. Schedule of disease control against downy mildew, powdery mildew, black rot, and botrytis of the 'IPM' management strategy as designed during the co-design workshop.

Treatments are positioned according to the vine's phenological stage. The decision rules for applying a treatment are shown in orange, and the product to apply or mechanical operation in black. The black lines delimit the period to apply this product. DSS = Decision Support System Decitrait (Davy *et al.*, 2020).

A total of nineteen winegrowers participated in the study, including twelve managing conventional vineyards and seven in organic systems (Table 1). Among the twelve conventional winegrowers, five adopted the 'IPM' strategy, five the '0RES' strategy, and two the 'BCT' strategy. These numbers remained stable between 2021 and 2022. In contrast, participation in the 'ORG2kgCo' strategy (organic systems) varied slightly over time, involving six winegrowers in 2021 and seven in 2022. 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 single field of at least 0.5 hectares.

TABLE 1. Repartition of the winegrowers involved during the two years of the experiment; each number indicates a different winegrower.

	Conventional			Organic
	IPM	0RES	BCT	ORG2kgCo
2021	N = 5	N = 5	N = 2	N = 6 n°8, n°11, n°14, n°17, n°21, n°24
2022	N = 5	N = 5	N = 2	N = 7 n°8, n°10, n°11, n°14, n°17, n°24, n°28

The choice of the field was a trade-off between the distance between the field and the shed, the representativeness of the vineyard field in the PDO production zone, and the field homogeneity. The field was divided into two parts: one was managed according to the co-designed management strategy (minimum 0.25 hectare) and the other was managed according to the usual strategy of the winegrower (VITI modality). Even though the two plots were close to each other, we excluded the side-by-side rows from the observations. The implementation of the management strategies was monitored during 2021 and 2022 through in-field meetings for pest and disease notations (see sampling method in Table 2).

4. Data collected to evaluate the performance of the management strategies

Various data were collected by the VINOVALIE R&D team in 2021–2022 throughout the growing season to compute agronomic, ecological, and economic indicators defined during the co-design workshop (Table 2). Strategy effectiveness was assessed using ratings at veraison, when leaves and grapes become less or no longer susceptible to disease, thus integrating whole-season effects. Other ratings were used to monitor implementation. Only downy mildew and black rot are presented, as powdery mildew was rarely observed.

TABLE 2. Collected data to calculate the performance indicators of the disease management strategies in the field network for each year.

Type of data	Data collection method	Data calculation method
Frequency and intensity of attacks of Downy mildew, Black-rot, Powdery mildew (%)	Rating on 100 leaves and 100 grapes on 4 plots per modality at fruit set, bunch closure, veraison, and harvest	For example, the frequency of attack of downy mildew on leaves on one plot: Frequency = number of leaves with downy mildew / 100 For example, the intensity of attack of downy mildew on leaves on one plot: Intensity = Intensity of attack on each leaf / 100
TFI (no-unit)	Farmers survey	TFI = ∑ (Dose_sprayedp / Dose_recommended*p*) × (Area_sprayed*p* / Area_total*p*) The TFI is equal to the sum of the TFI per treatment, where a treatment corresponds to a product *p* sprayed and a date of application. The dose sprayed per product corresponds to the Dose_sprayed*p*; the recommended dose for a product *p* for the target pest is the Dose_recommended*p*; the Area_sprayed*p* represents the surface area where the product was applied, and the Area_total*p* is the total surface area of the field where the treatment was sprayed (Pingault *et al.*, 2009).
Amount of copper applied (kg)	Farmers survey	
Yield (hL/ha)	Harvesting of each modality by machine or by hand	Depending on field constraints (size and heterogeneity), a sample of 20 to 50 vines is harvested by hand to determine the yield per vine (kg/vine). This yield per vine is multiplied by the planting density per hectare (vines/ha) to define the yield per hectare (kg/ha). Finally, this yield is converted into hectoliters per hectare (hl/ha) by multiplying by the winery's kg-to-hl converter.
Fungicide cost (in euros)	Farmers survey	Fungicide cost = ∑ (Price_fungicide × Dose_sprayed) + Price_spraying operation × Number_spraying operation Fungicide cost is equal to the sum of the cost of fungicides and the cost of spraying operation. The cost of fungicides is the product of the price of the fungicide (Price_fungicide) and the dose sprayed per product (Dose_sprayed). The cost of a spraying operation is the price of a spraying operation multiplied by the number of spraying operations. The price of the spraying operation is calculated taking into account labour and fuel for one hectare and is standardised at € 17.5 (IFV).

TFIt = Total Treatment Frequency Index, TFIf = Fungicide Treatment Frequency Index.

5. Data analysis

5.1. Calculated indicators

To analyse the effects of the disease management strategies on the performance of the cropping systems, we calculated twelve indicators (Table 3).

5.2. Statistical analyses

Differences among management strategies in TFI reduction, yield, and disease intensity were assessed using the Kruskal–Wallis test because the assumptions of normality and homogeneity of variances required for ANOVA were not met. When the Kruskal–Wallis test was significant ($p \leq 0.05$), pairwise comparisons were performed using Dunn's test with Bonferroni adjustment for multiple comparisons. Statistical analyses were conducted in R (version 4.5.0) using the stats package for the Kruskal–Wallis test and the rstatix package for Dunn's *post hoc* test. Each grower contributed a single vineyard plot; therefore, no within-grower clustering was present. The unequal number of plots among management strategies resulted in an unbalanced design, which was accommodated by the non-parametric analysis. To assess if the management strategies were economically acceptable, two bivariate figures have been produced, comparing the percentage reduction in yield and the percentage reduction in fungicide costs compared with the VITI modality, and the percentage reduction in the TFIf compared with the HEV reference or the percentage reduction in the amount of copper compared with the threshold of 4 kg/ha/year. For both graphics, a green box has been drawn to represent "win-win situations". To identify "win-win situations", we chose to focus on fungicide only, as the yield losses were mainly explained by diseases. For the first graph, the "win-win situation" represents a situation with TFIf or amount of copper reduced by at least 50 and yield loss below 10 % (see green box in Figure 5), and on the second graph, the "win-win situation" corresponds to a situation with TFIf or amount of copper reduced by at least 50 % and no increase in fungicide cost (see green box in Figure 6).

TABLE 3. Calculated indicators to evaluate the performance of the disease management strategies in the field network.

Indicator	hod	Threshold for evaluating the performance of the disease management strategies
Difference in average intensity for each disease on leaves and grapes compared to the usual practices of the winegrower (VITI modality)	Intensity of management strategy (%) - Intensity of VITI modality (%) at veraison stage	For each disease, the indicator is calculated on leaves and grapes separately. During the workshops, the threshold of "5 % more intensity" was defined as the limit that must not be exceeded for the strategy to be considered effective in controlling disease development.
Percentage reduction of TFIt compared to the VITI modality	((TFIt of management strategy – TFIt of VITI modality)/ TFIt of VITI modality) × 100	VITI modality
Percentage reduction of TFIt compared to the HEV reference	((TFIt of management strategy – TFIt of HEV reference)/ TFIt of HEV reference) × 100	During the workshops, the threshold of "50 % of HEV TFIt" was defined as the target to be reached for the management strategy in conventional viticulture to be considered effective in reducing pesticide use.
Percentage reduction of TFIf compared to the VITI modality	((TFIf of management strategy – TFIf of VITI modality)/ TFIf of VITI modality) × 100	VITI modality
Percentage reduction of TFIf compared to the HEV reference	((TFIf of management strategy – TFIf of HEV reference)/ TFIf of HEV reference) × 100	During the workshops, the threshold of "50 % of HEV TFIf" was defined as the target to be reached for the management strategy in conventional viticulture to be considered effective in reducing fungicide use.
Amount of copper applied (kg) on the 'ORG2kgCo' modality and VITI modality		2 kg copper/ha/year (this amount corresponds to half the amount of copper authorised per year in Europe since 2018)
Percentage reduction of copper use compared to VITI modality	((copper amount of management strategy – copper amount of HEV reference)/copper amount of HEV reference) × 100	VITI modality
Percentage reduction of copper use compared to European regulations	((copper amount of management strategy – copper amount of HEV reference)/copper amount of HEV reference) × 100	50 % of European regulation
Percentage reduction of yield compared to the VITI modality	((Yield of management strategy – Yield of VITI modality)/Yield of VITI modality) × 100	During the workshops, the threshold of "10 % loss" in relation to the VITI modality was defined as the limit not to be exceeded for the management strategy to be considered effective in maintaining yield.
Percentage reduction of the fungicide cost compared to the VITI modality	((Fungicide cost of management strategy – Fungicide cost of VITI modality)/Fungicide cost of VITI modality) × 100	VITI modality

TFIt = Total Treatment Frequency Index, TFIf = Fungicide Treatment Frequency Index, HEV = High Environmental Value.

RESULTS

1. The four management strategies led to a significant reduction in pesticide use

1.1. Reduction of pesticide use in comparison with conventional viticulture

For the three conventional management strategies and over the two years, the average values of TFIt and TFIf of the VITI modality (usual strategy of the winegrowers) were lower than those of the HEV reference ('IPM' = 12.27, '0RES' = 12.49, and 'BCT' = 9.06, respectively, according to the management strategies versus 14.98) (Table 4). Only one winegrower in the 'IPM' group exceeded the values of the HEV reference (18.36 versus 14.98). The TFIt and TFIf of the three conventional management strategies were not significantly different (Kruskal test and Dunn test). The TFIt and TFIf were similar for the 'IPM' and '0RES' management strategies (TFIt = 12.27 and 12.49, respectively, and TFIf = 7.94 and 8.4, respectively). The values for the 'BCT' management strategy were lower (TFIt = 9.06) because, out of the two winegrowers in this group, one of them carried out few treatments, with a TFIt of less than 6 and a TFIf of less than 4 (Table 3). In general, the TFI values for a given modality were relatively stable, with coefficients of variation ranging between 17 % and 30 %.

1.2. A significant but limited reduction of the Total Treatment Frequency Index in comparison with the VITI modality and the HEV reference

All the winegrowers reduced their TFIt compared with their usual practice (VITI modality) over the two years except one winegrower. This winegrower made no difference between the two modalities. The reduction varied from 11.9 % to 88.5 % (Figure 2a). In comparison with the HEV reference, all winegrowers have successfully achieved a reduction in TFIt, with decreases ranging from 5.7 % to 93.3 %, except for one individual who had adopted the 'IPM' management strategy in 2021 (Figure 2b). This winegrower had a TFIt 7.3 % higher than the HVE reference (16.04 *vs* 14.98). Winegrowers who implemented the '0RES' management strategy appeared to reduce pesticide use more than those who implemented the 'IPM' management strategy, although this difference was not statistically significant. Winegrowers who implemented the 'BCT' management strategy, however, achieved a significantly greater reduction in TFIt than those implementing the two other strategies. On average, the 'IPM', '0RES', and 'BCT' management strategies reduced the TFIt by 32.1 %, 42.2 % and, 87.8 %, respectively, compared to the HEV reference (Figure 2b). The 50 % TFIt reduction target for the 'IPM' and '0RES' management strategies was barely reached in both years; it was achieved only twice out of 10 for the '0RES' management strategy (winegrowers n°12 and n°16 in 2022) and only three times out of 10 (winegrower n°15 in 2021 and winegrowers n°9 and n°13 in 2022).

1.3. A significant reduction of the Fungicide Treatment Frequency Index in comparison with the VITI modality and the HEV reference

Winegrowers who have implemented the 'BCT' management strategy have succeeded in using only biocontrol products for fungicides for both years. As a result, the TFIf reduction was equal to –100 % for the 'BCT' management strategy, and we have not included it in Figure 2c and d. For the other two management strategies, all the winegrowers succeeded in reducing TFIf (reduction by 19.2 % to 82.4 %) in comparison with the VITI modality, except the winegrower n°1 who implemented the 'IPM' management strategy (Figure 2c). As mentioned above, this winegrower made no difference between the two modalities. For the '0RES' management strategy, the TFIf ranged from 1.8 to 6.87 with an average of 4.68, while the TFIf for the 'IPM' management strategy varied from 1.39 to 9.9 with an average of 5.88. Winegrowers who implemented the '0RES' management strategy seemed to reduce fungicide use more than those who implemented the 'IPM' management strategy, but this difference was not significant (p-value = 0.6) (Figure 2d). Winegrowers who implemented the '0RES' management strategy reduced TFIf by an average of 58.8 % compared with the HEV reference, while those who implemented the 'IPM' management strategy achieved a 48.3 % reduction. This difference can be explained by the high variability in fungicide use reduction due to two winegrowers in the 'IPM' group: winegrower n°1 in both years and winegrower n°9 in 2022 (Figure 2d), who did not reduce their fungicide use as much as other winegrowers in the 'IPM' group.

TABLE 4. TFI intervals of the VITI modality by conventional management strategies in 2021 and 2022. TFIt (total) and TFIf (fungicides) are not significantly different (Kruskal test and Dunn test) between management strategies.

Management strategy	Total Treatment Frequency Index				Fungicide Treatment Frequency Index				Amount of data in the two years
	Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation	
IPM	8.7	18.36	12.27	2.79	5.17	12.05	7.94	2.34	10
0RES	8.67	14.93	12.49	2.15	5.58	10.53	8.4	2.04	10
BCT	5.95	11.42	9.06	2.35	3.79	8.10	6.79	2.01	4

IPM = Integrated Pest Management, 0RES = 0 Residu, BCT = Biocontrol.

1.4. Reduction in the amount of copper used in organic viticulture

In this group, five winegrowers participated for two years, while three were present for only one year (n°21 in 2021, n°10 and n°28 in 2022), accounting for a total of 13 winegrower-year pairs over the two years. All the winegrowers used less copper than the European regulations (4 kg/ha/year) in the two modalities (Figure 3). The amount of copper applied in the VITI modality varied from 0.72 kg/ha/year to 3.74 kg/ha/year, with an average of 2.38 kg/ha/year and a standard deviation of 1.32 kg/ha/year (in these data, conventional winegrowers n°8 and n°28 have been excluded). The 'ORG2kgCo' management strategy enabled all winegrowers to apply no more than 2 kg of copper per hectare, except winegrower n°14, who used over 7 g. This target was met in both a high rainfall year (2021) and a moderate rainfall year (2022). All winegrowers whose VITI modality was organic viticulture reduced, over the two years, the amount of copper applied in the 'ORG2kgCo' modality compared with their VITI modality by 13.1 % to 50 % (Figure 3).

2. Three management strategies resulted in satisfactory disease control

In this section, winegrowers n°8 and n°28 have been removed from the 'ORG2kgCo' management strategy sample because, as mentioned above, their VITI modality was run under conventional viticulture. In both years, all the winegrowers succeeded in controlling diseases on their VITI modality. The intensity of attack by downy mildew and black rot did not exceed 7 % on leaves and grapes (Table 5). The averages in the VITI modality for winegrowers belonging to the 'IPM', '0RES', and 'ORG2kgCo' groups were below 1.2 %, while those for winegrowers from the 'BCT' group were higher (Table 4). Powdery mildew was only observed on grapes in one field in both years. This field belonged to winegrower n°5, who had implemented the 'BCT' management strategy. The powdery mildew intensity in the VITI modality was 3.78 % in 2021 and 5.54 % in 2022. According to the winegrower, this field has a very strong history of this disease.

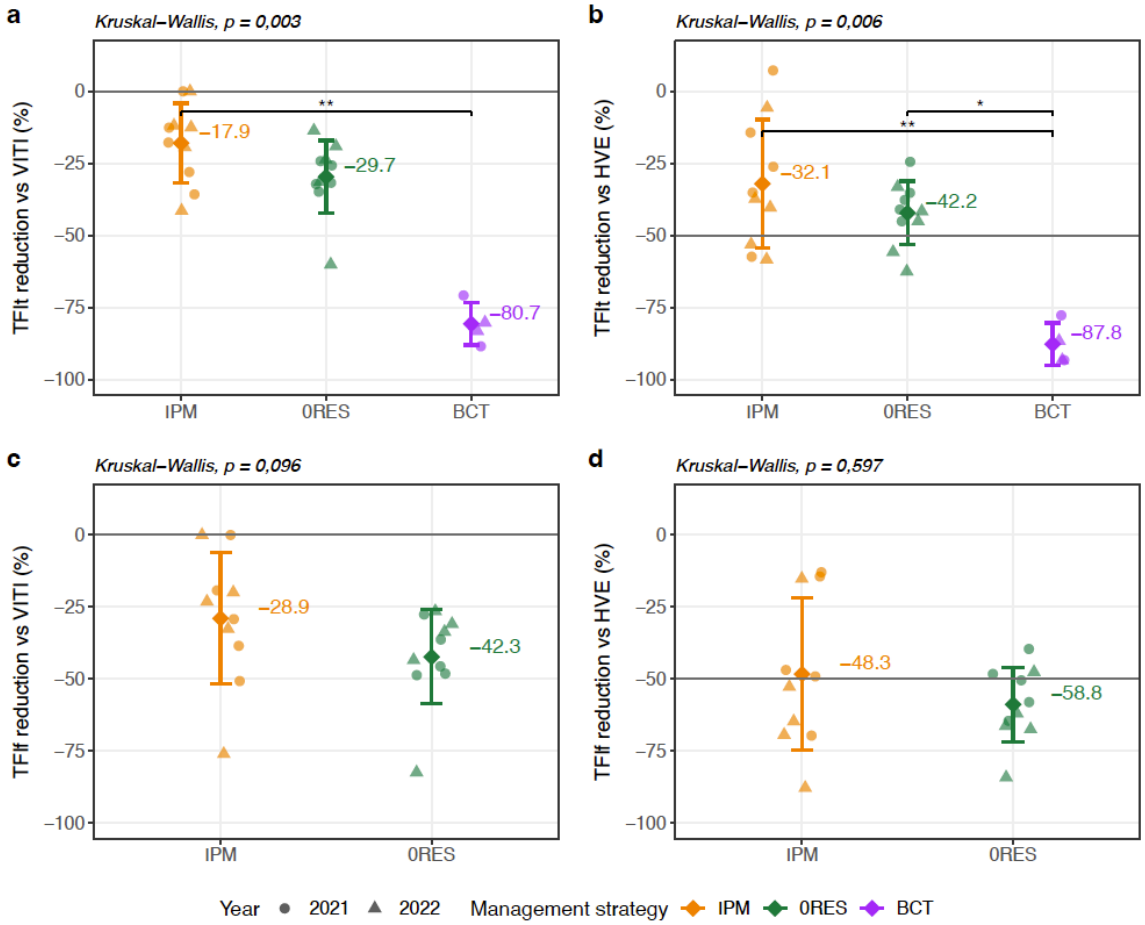


FIGURE 2. Reduction of the Total TFI (TFIt) in percent according to the management strategies compared to the VITI modality (a) and compared to the HEV reference (b), and reduction of the fungicide TFI (TFIf) in percent according to the management strategies compared to the VITI modality (c) and compared to the HEV reference (d).

The TFIf reduction was equal to −100 % for the 'BCT' management strategy, so it has not been shown in Figure 2c and d. Years are represented by a circle for 2021 and a triangle for 2022. Each dot (n = 24 for Figure 2a and b, and n = 20 for Figure 2c and d) represents a couple (winegrower and year). The grey circle represents the average by management strategy, with its standard deviation. In Figure 2a and c, the green line represents a non-reduction in TFIt compared with the VITI modality. In Figure 2b and d, the green line represents the target of 50 % TFI reduction (TFIt = 7.49). IPM = Integrated Pest Management, 0RES = 0 Residu, BCT = Biocontrol, HEV = High Environmental Value.

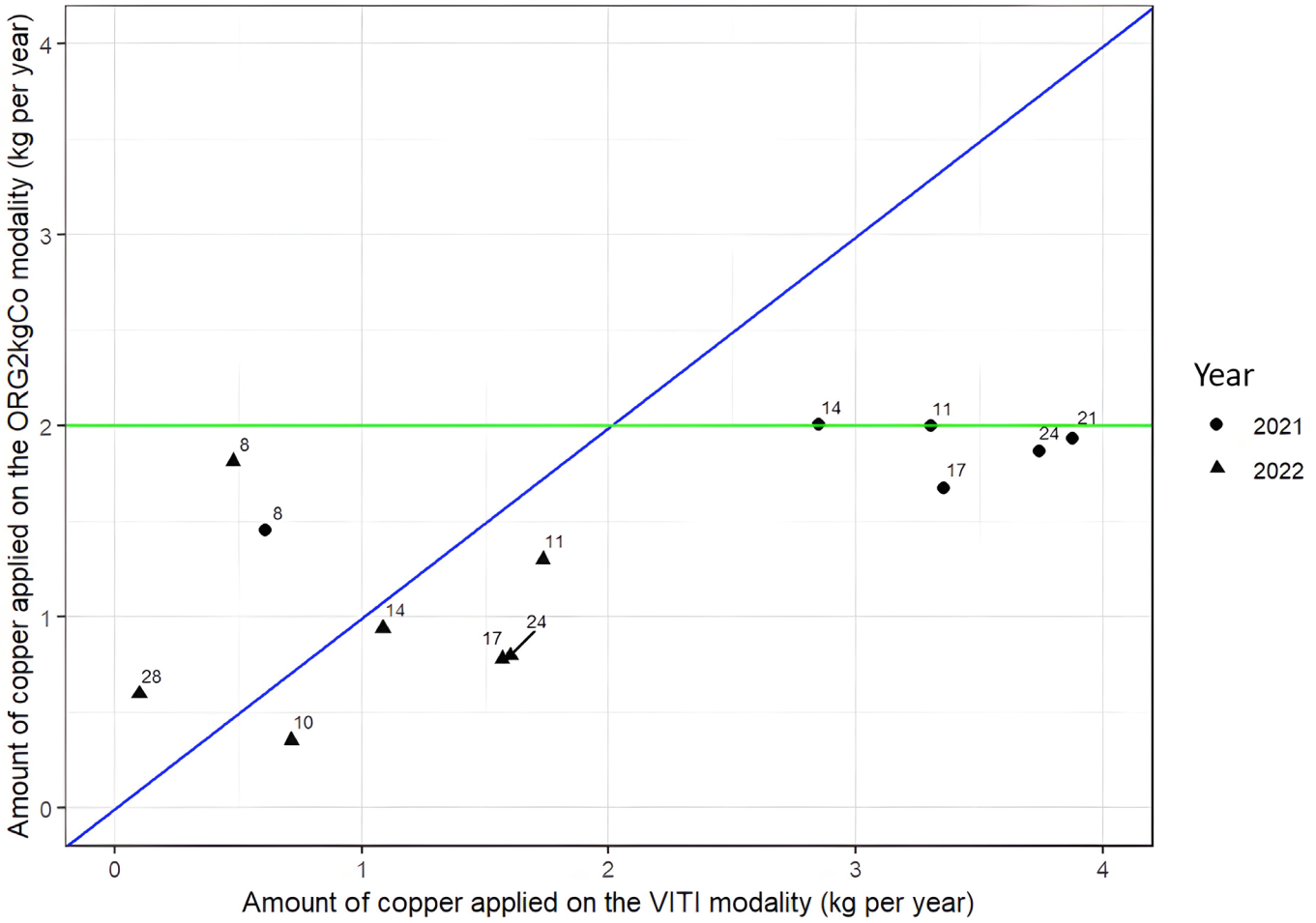


FIGURE 3. Comparison of the quantity of copper (kg per year) applied to the VITI modality compared to the quantity applied to the ORG2kgCo modality in 2021 (circle) and in 2022 (triangle).

Each dot (n = 13) represents a couple (winegrower and year). The blue x = y line shows whether the 'ORG2kgCo' modality allowed a reduction in the amount of copper applied compared to the VITI modality, while the green line shows the management strategy target of 2 kg of copper per year per hectare. ORG2kgCo = Organic with 2 kg of copper.

TABLE 5. Downy mildew and black rot intensities (in percentage) at the veraison stage of the VITI modality for each management strategy group in 2021 and 2022.

Management strategies groups	Downy mildew intensity (%)								Black rot intensity (%)							
	Leaves				Grapes				Leaves				Grapes			
	Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation
IPM	0	4.76	1.19	1,80	0	0.56	0.06	0,18	0	0.02	0.00	0,01	0	2.63	0.36	0,81
0RES	0	4.40	0.77	1,49	0	0.00	0.00	0,00	0	0.05	0.00	0,01	0	0.13	0.02	0,04
BCT	0	6.95	2.49	3,21	0	3.09	0.77	1,54	0	0.01	0.00	0,00	0	6.97	2.07	3,29
ORG2kgCo	0	0.68	0.16	0,25	0	0.02	0.00	0,01	0	0.31	0.06	0,11	0	2.94	0.63	1,00

For each winegrower, the experimental field was divided into two parts: one managed according to the co-designed management strategy (either 'IPM', 'ORES', 'BCT', or 'ORG2kgCo') and the other managed according to the usual strategy of the winegrower (VITI modality). IPM = Integrated Pest Management, ORES = 0 Residu, BCT = Biocontrol, ORG2kgCo = Organic with 2 kg of copper.

The 'IPM', '0RES', and 'ORG2kgCo' strategies caused only slight increases in downy mildew relative to VITI (Figure 4). For 'IPM', leaf damage ranged from 0–4.26 % (mean 1.04 %) and grape damage from 0–1.18 % (mean 0.13 %). For '0RES', values ranged from 0–10.18 % on leaves (mean 1.70 %) and 0–0.06 % on grapes. Isolated increases occurred for n°18 in 2022 under 'IPM' (+2.8 points) and n°20 in 2021 under '0RES' (+5.78 points). 'BCT' controlled downy mildew in 3/4 cases, but n°19 in 2022 showed severe increases (leaves: 36.53 %, +29.6 points; grapes: 32.85 %, +29.8 points). Powdery mildew was only observed for n°5: under 'BCT', it increased in 2021 (+3.46 points; 7.23 % *vs* 3.77 %) but decreased in 2022 (−2.23 points; 3.31 % *vs* 5.54 %). 'ORG2kgCo' showed low downy mildew (leaves: 0–4.8 %, mean 0.56 %; grapes: 0–0.02 %), with one increase for n°21 in 2021 (+4.13 points). Black rot on leaves remained ≤ 0.10 % across all strategies. On grapes, 'IPM' and '0RES' maintained intensities < 2 % without increases. 'BCT' was highly variable: good control for n°5 (minor increase of +5.45 points in 2021), but poor for n°19 (28.67 % in 2021; 20.05 % in 2022), likely due to field history. 'ORG2kgCo' controlled black rot overall, with slight increases in 2021 for n°14 (+2.62 points) and n°21 (+4.58 points).

3. A compromise between reducing pesticide use, preserving yield, and controlling fungicide cost

This section quantifies the consequences of the four management strategies, firstly on yield and secondly on the fungicide cost.

To perform the analysis, six winegrowers were removed from the first analysis (Figure 5): for the 'IPM' management strategy, winegrower n°1 was removed as he did not make a difference between the two modalities; for the 'ORG2kgCo' management strategies, three couples were removed because yield data could not be collected and three others because

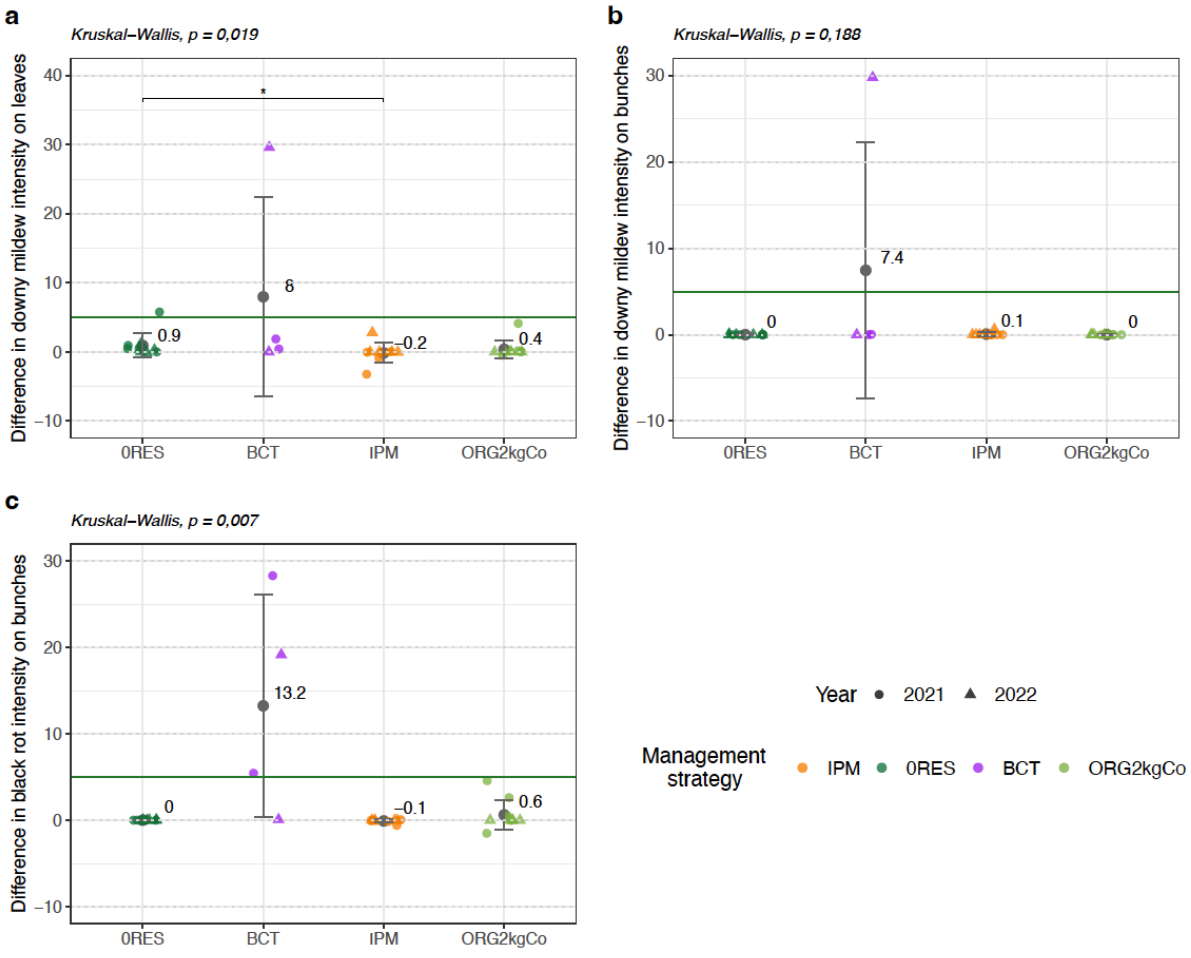


FIGURE 4. Differences (Intensity of management strategy – Intensity of VITI modality) in downy mildew intensity on leaves at the veraison stage according to the management strategies compared to the VITI modality (a), difference in downy mildew intensity on grapes at the veraison stage according to the management strategies compared to the VITI modality (b), and difference in black rot on grapes at the veraison stage according to the management strategies compared to the VITI modality (c).

Years are represented by a circle for 2021 and a triangle for 2022. Each dot (n = 34) represents a couple (winegrower and year). The grey circle represents the average by management strategies, with its standard deviation. The green line represents the limit of the difference in intensity (5 points) defined as acceptable by the winegrowers during the co-design workshop. IPM = Integrated Pest Management, 0RES = 0 Residu, BCT = Biocontrol, ORG2kgCo = Organic with 2 kg of copper.

the VITI modality was in conventional agriculture. As a result, a total of 29 couples were used for this initial analysis (Figure 5). All VITI modalities achieved their yield targets for both years, except vineyards that were frozen in 2021. Taking all management strategies into account, 13 out of 29 couples (44.8 %) combined a reduction in pesticide use with yield preservation (dot in the green box in Figure 5).

The 'IPM' management strategy produced yields equivalent to the VITI modality while reducing the TFIf. Winegrower n°16 in 2022 was the only one to have experienced a yield loss of more than 10 % (–13.8 %), but the target yield was achieved. Moreover, in Figure 5, half of the points are in the green box, and two are very close to the 50 % TFIf reduction limit. One winegrower in 2022 even managed to reduce his TFIf by 75 % while remaining below the –10 % yield loss limit compared with the VITI modality (winegrower n°13), and one winegrower (n°9 in 2021) was away from both limits because of a limited reduction in TFIf and a yield gain.

The '0RES' management strategy achieved more contrasting results in terms of maintaining yields acceptable to winegrowers. Two winegrowers (n°12 and n°26 in 2021) suffered a significant loss of yield compared to the VITI modality (Figure 5). However, this loss was not directly correlated with a greater incidence of grape disease and the target yield was achieved. Moreover, for winegrower n°12, this difference is observed in favour of the '0RES' modality in 2022 without any difference in the presence of disease. Three points are between –15 % and 2–0 % of yield reduction (winegrower n°23 in 2021 and winegrowers n°16 and n°20 in 2022), and winegrower n°26 in 2022 is very close to 1–0 %. Of these 4 situations, only winegrower n°23 in 2021 did not achieve the target yield because the field had been affected by frost. Finally, 4 out of 10 situations (2 in 2021 and 2 in 2022) managed to combine a 50 % reduction in the use of fungicides with the preservation of yields (yield reduction of under 10 %) (Figure 5).

The 'BCT' management strategy resulted in yield losses highly variable from one winegrower to another. Only one in 4 situations resulted in a "win-win situation". This variation was explained by the difference in powdery mildew and black rot damage observed. For winegrower n°19, the yield loss was 64.8 % in 2021 and 68.4 % in 2022, while for winegrower n°5 the loss was 22.1 % in 2021 and 5.1 % in 2022 (Figure 5).

The 'ORG2kgCo' management strategy limited yield loss compared with the VITI modality, while reducing copper quantity. In fact, 4 out of 7 points are in the green box (57.1 %), and n°10 in 2022 is very close to the yield loss limit of –10 % compared with the VITI modality (Figure 5). Winegrower n°10 is the only one that did not succeed in maintaining yield, with a loss of around 20 %, but the target yield was achieved (Figure 5).

On average, the fungicide cost of the VITI modality of each winegrower varied according to management strategies tested by the winegrower: 448.7 €/ha for management strategy 'IPM', 521.2 €/ha for '0RES', 415.7 €/ha for 'BCT', and 378.5 €/ha for 'ORG2kgCo', respectively. Taking all management strategies into account, 21 out of 32 couples (65.6 %) combined a reduction in pesticide use with controlling fungicide cost (dot in the green box in Figure 6).

The results of the 'IPM' management strategy varied. In the majority of cases, the implementation of this strategy resulted in a reduction in fungicide cost (from –7.5 % to –36.5 %) linked to a reduction in TFIf (Figure 6). However, three situations resulted in a minor increase in cost from 0.5 % to 18.3 %. On average, the 'IPM' management strategy resulted in a 9.1 % reduction in the cost of fungicides, with a standard deviation of 16.6 % (in these data, winegrower n°1 was excluded because he did not implement the management strategy).

The implementation of the '0RES' management strategy has not resulted in any increase in the cost of fungicides, with a reduction in the TFIf (Figure 6). All winegrowers who implemented the '0RES' management strategy reduced their fungicide costs (from –6.1 % to –71.3 %). On average, the '0RES' management strategy resulted in a 26.2 % reduction, with a standard deviation of 18.3 %, in the cost of fungicides.

The implementation of the 'BCT' management strategy has led to an increase in the fungicide cost (Figure 6). On average, the increase in fungicide cost incurred by winegrowers when 'BCT' was implemented was 40.6 % with a standard deviation of 39.3 %. The increase varied from 6.4 % to 94.6 %.

The 'ORG2kgCo' management strategy resulted in a reduction in fungicide costs each time (Figure 6). This decrease varied from –6.6 % to –31.3 % with an average of –15.8 % and a standard deviation = 7.8 % (in these data, winegrowers n°8 and n°28 have been excluded because their VITI modality was in conventional viticulture).

DISCUSSION

The management strategies studied in this article have yielded compelling results in fostering more sustainable viticulture, both environmentally and economically (maintaining yields and lowering fungicide costs), while concurrently meeting consumers' demand. In the following section, we first examine the efficiency of the management strategies in reducing pesticide use and how they could be improved. Subsequently, we will examine the feasibility of implementing these strategies on a larger scale. Finally, we will evaluate the pros and cons of on-farm experimentation.

1. Co-designed management strategies have successfully reduced pesticide use (TFIt) by decreasing fungicide use (TFIf)

The implementation of the 'IPM' and '0RES' management strategies resulted in an average reduction in TFIt of 32.1 % ('IPM') and 42.2 % ('0RES'), respectively, compared with the HEV reference. The reduction target for these two management strategies (a 50 % reduction in TFIt, excluding biocontrol products from the TFI calculation, relative to the HEV reference) was not fully achieved. Nevertheless, this reduction is encouraging compared with the results obtained

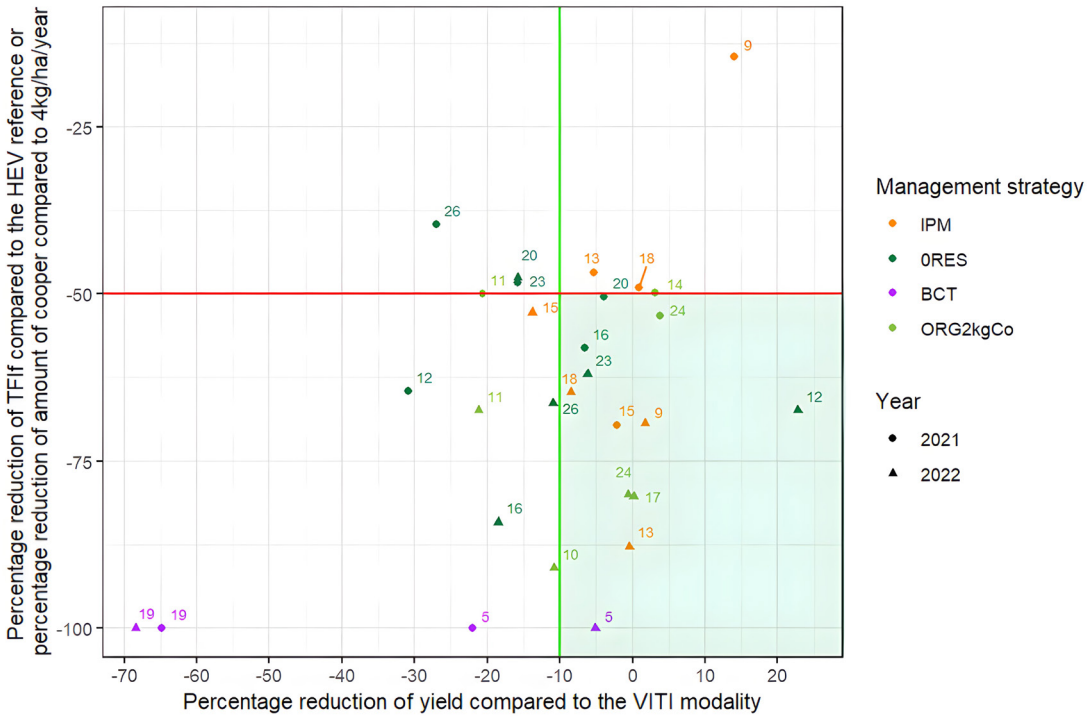


FIGURE 5. Comparison of the percentage of yield reduction compared to the VITI modality and the percentage of TFIf reduction compared to the HEV reference, or the percentage reduction in the amount of copper compared to 4 kg/ha/year.

Each dot (n = 29) represents a couple (winegrower and year). The red line represents the target of 50 % TFI reduction or 50 % amount of copper reduction (2 kg/ha/year). The green line represents the limit of the yield loss percentage (–10 %) defined as acceptable by the winegrowers during the co-design workshop. The green box represents a "win-win situation": TFIf or amount of copper reduced by 50 % and yield loss below 10 %. IPM = Integrated Pest Management, 0RES = 0 Residu, BCT = Biocontrol, ORG2kgCo = Organic with 2 kg of copper, HEV = High Environmental Value.

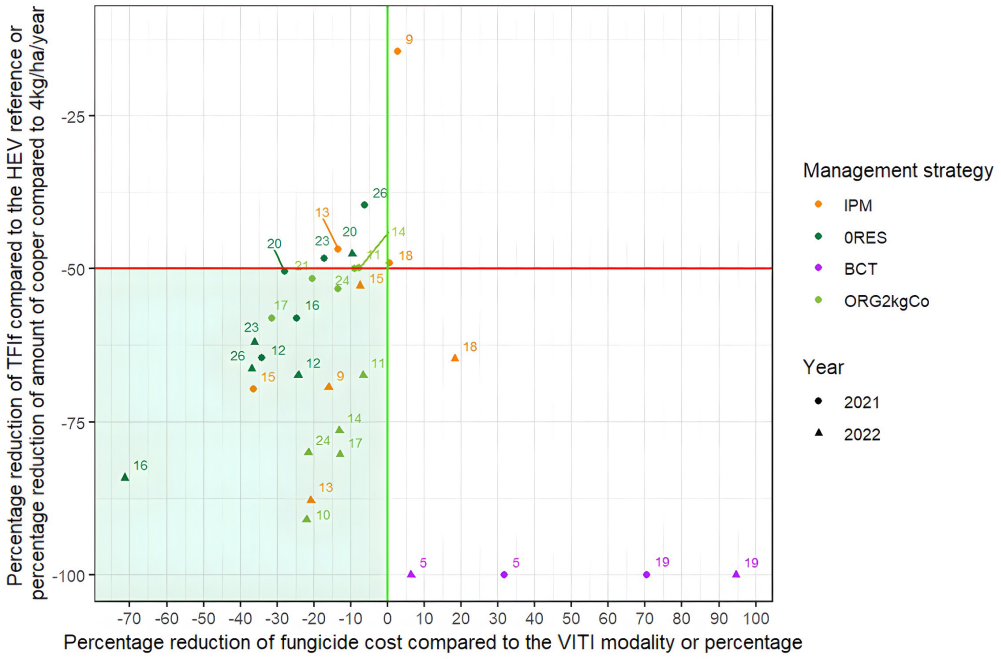


FIGURE 6. Comparison of the percentage of fungicide cost reduction compared to the VITI modality and the percentage of TFIf reduction compared to the HEV reference, or the percentage reduction in the amount of copper compared to 4 kg/ha/year.

Each dot (n = 32) represents a couple (winegrower and year). The red line represents the target of 50 % TFI reduction or 50 % amount of copper reduction (2 kg/ha/year). The green line represents the limit of no increase in fungicide cost. The green box represents a «win-win» situation: TFIf or amount of copper reduced by 50 % and no increase in fungicide cost. IPM = Integrated Pest Management, 0RES = 0 Residu, BCT = Biocontrol, ORG2kgCo = Organic with 2 kg of copper, HEV = High Environmental Value.

from management strategies co-designed within the DEPHY EXPE ECOVITI project (combining in-station and on-farm experimentation) conducted from 2013 to 2018 in various French wine-growing regions. In this project, the average reduction in TFIt compared with the regional reference was 40 % in the Alsace vineyard (Thiollet-Scholtus *et al.*, 2019), 50 % in the Bordeaux vineyard (Delière *et al.*, 2018), and 65 % in the Gaillac vineyard (Serrano *et al.*, 2019). Similarly, in the 'DEPHY FARM' project, winegrowers' groups obtained across several French winegrowing regions a 33 % reduction in total pesticide use and 39 % for fungicides, over 10 years of on-farm experimentation (Fouillet *et al.*, 2022). However, unlike the present study, these management strategies (implemented in the DEPHY EXPE ECOVITI and 'DEPHY FARM' projects) also aimed to reduce the use of herbicides and insecticides (Delière *et al.*, 2018; Fouillet *et al.*, 2022; Serrano *et al.*, 2019; Thiollet-Scholtus *et al.*, 2019). By contrast, in the present study, pesticide use was reduced exclusively through decreases in fungicide applications, which may explain why the target of a 50 % reduction in TFIt was not achieved in most cases. The 'IPM' and '0RES' management strategies have led to a reduction in fungicides (reduction from 19.23 % to 87.8 %). Winegrowers decided to focus on the reduction of fungicide use, as simultaneously reducing both herbicides and insecticides was too ambitious within a short timeframe. The two measures used were: optimisation of the timing, dose, and frequency of pesticide application (Efficiency (E)) and substitution of synthetic products for biocontrol products (Substitution (S)). As a result, Redesign (R), *e.g.,* planting resistant varieties or modifying the training system, was not explored during the co-design workshops. However, Redesign is often considered the most efficient way to reduce the use of fungicides. Indeed, numerous studies have shown that the use of resistant varieties leads to a significant reduction in the use of fungicides (Delière *et al.*, 2018; Thiollet-Scholtus *et al.*, 2021). Since 2021, VINOVALIE winegrowers have already cultivated resistant varieties and have succeeded in drastically reducing the use of fungicides.

To achieve the TFIt reduction target, it seems necessary to reduce the use of herbicides and insecticides. Herbicides could be reduced or even suppressed. One management option available to winegrowers is to control inter-row vegetation through mowing or tillage (Garcia *et al.*, 2018), in vineyards where slope conditions allow these practices. (Biddoccu *et al.*, 2016). This lever generally generates an increase in working time and cost, slowing down its large-scale deployment (Fouillet *et al.*, 2022; Serrano *et al.*, 2019). For insecticides, the use of clay for green leafhopper (*Empoasca vitis*) management, as envisaged in the codesign of management strategies, is an effective alternative (Tacoli *et al.*, 2017). It is already widely used in organic farming. In conventional farming, its deployment is limited by the fear of mechanical damage to sprayers expressed by VINOVALIE winegrowers.

The 'BCT' management strategy allowed a significant average reduction in the TFIt (89.4 %) because all the fungicides used were biocontrol products. The 'ORG2kgCo' management strategy limited the amount of copper applied under the set limit of 2 kg/ha. In addition, the implementation of the 'ORG2kgCo' management strategy has enabled winegrowers to apply a lower amount of copper than winegrowers in the 'DEPHY FARM' network in 2021 and 2022 (Cellule d'Animation Nationale DEPHY Ecophyto, 2021; Cellule d'Animation Nationale DEPHY Ecophyto, 2022).

2. Co-designed management strategies have successfully controlled diseases

The two years during which the management strategies were evaluated were characterised by contrasting disease pressures: downy mildew pressure was average in 2021 and low in 2022, while black rot pressure was high in 2021 and average in 2022. In these changing conditions, the four management strategies successfully controlled diseases, except the 'BCT' management strategy, with a reduction in pesticide use as mentioned above.

The 'IPM' and '0RES' management strategies allowed good control of downy mildew on the leaves, with an average attack intensity of 1.37 % (ranging from 0 % to 10.18 %). They provided very good control of downy mildew and black rot on grapes, with an average attack intensity of 0.07 % (ranging from 0 % to 1.18 %) and 0.16 % (varying from 0 % to 2.04 %), respectively (Figure 4). These results are consistent with previous studies on this subject in PDO vineyards (Delière *et al.*, 2018; Thiollet-Scholtus *et al.*, 2019).

The 'BCT' management strategy substantially reduced pesticide use but showed highly variable disease control (Figure 4), with downy mildew ranging from 0–36.53 % on leaves and 0–32.85 % on grapes, and black rot on grapes from 0.12 % to 28.67 %. Such variability is consistent with reported fluctuations in biocontrol efficacy and the limits of relying solely on these products (Zanzotto & Morroni, 2016). The strategy – excluding both copper and resistant varieties – was particularly ambitious. Improving reliability likely requires combining complementary biocontrol agents (*e.g.,* mixtures targeting different infection stages) and integrating decision support tools based on weather-driven infection risk models to optimise timing and frequency of applications. Previous studies achieved more stable control by combining biocontrol with resistant varieties (DEPHY EXPE ECOVITI Project, France) or low-dose copper (Bleyer *et al.*, 2020). These approaches suggest that hybrid strategies may enhance robustness while maintaining low pesticide use.

The 'ORG2kgCo' management strategy enabled very good control of downy mildew on the leaves (the intensity of attack varied from 0 % to 0.22 %), except in two vineyards with an intensity of attack of 4.8 % and 17.54 %, respectively, and in all the vineyards concerning the grapes (Figure 4). This effectiveness might be compromised if downy mildew pressure is high, as has been observed in previous studies (Delière *et al.*, 2018; Schumacher *et al.*, 2022; Serrano *et al.*, 2019). The effectiveness of this management strategy against black rot on grapes was more variable, with two vineyards with an attack intensity close to 5.5 % and one severely affected field with an attack intensity of 48.77 %.

The two vineyards most affected belong to two winegrowers not involved in organic farming (Figure 4). They sought to determine whether a conversion to organic farming was feasible. Indeed, as noted by Merot *et al.* (2020), such a transition requires significant adaptation and may result in increased disease incidence during the initial years.

3. In most situations, co-designed management strategies have successfully maintained yields while reducing the cost of fungicides

The 'IPM' and '0RES' strategies maintained yields while reducing fungicide costs (Figures 5 and 6). Yield losses were limited, with cost reductions of 9.1 % and 26.2 %, respectively. This aligns with studies showing pesticide reductions without yield penalties and with lower costs (Delière *et al.*, 2018; Serrano *et al.*, 2019; Thiollet-Scholtus *et al.*, 2019), including in arable systems (Lechenet *et al.*, 2017). In contrast, 'BCT' increased fungicide costs by 40.6 % due to higher biocontrol prices (Figure 6). 'ORG2kgCo' reduced costs by 15.8 % but reached only 88 % of target yield (Figure 5). Performance variability was highest for 'BCT', with yield changes from −5.1 % to −68.4 % relative to VITI, mainly due to disease damage. This variability underscores the role of site conditions and technical expertise. In low-copper systems, Delière *et al.* (2018) reported lower yields (62 %), whereas Serrano *et al.* (2019) and Thiollet-Scholtus *et al.* (2019) found yields closer to targets. The slight reduction under 'ORG2kgCo' may reflect a learning phase with reduced copper inputs; performance often improves with experience (Merot & Smits, 2020). Results should be interpreted cautiously due to on-farm experimental constraints. Pooling two climatically contrasting years may mask inter-annual variability, further amplified by heterogeneous conditions (varieties, practices, equipment). Averaging disease intensity can generate unrealistic values, especially compared with high-pressure years such as 2021. Year-specific analyses or a well-characterised reference year would strengthen interpretation. Overall, despite variability and methodological limits, co-designed strategies tested on farms can reduce fungicide use and costs while maintaining acceptable yields in most cases.

4. Discussion about On-Farm Experimentation

On-farm experimentation (OFE) presents three main risks. First, outcomes depend on farmers' engagement: initial objectives (reducing all pesticides) were narrowed to fungicides, and some data (*e.g.,* working time) could not be collected, a known limitation (Carton *et al.*, 2022). Second, data loss may occur due to implementation errors or farmer dropout, requiring sufficiently large samples. Third, implementing strategies and collecting data are time-consuming, limiting scalability. Some design choices also constrain interpretation. Only one grape variety per vineyard and PDO vineyards were studied, although varietal susceptibility differs (Galet, 1977) and PGI systems may face higher disease pressure (Goulet *et al.*, 2006; Serrano *et al.*, 2019). Field selection prioritised representativeness over high-risk situations, possibly underestimating impacts. Only volunteer growers participated, often already using fewer inputs (Perez *et al.*, 2024), and some strategies (*e.g.,* 'BCT') were tested on few farms. Disease severity was assessed at veraison to attribute symptoms better and avoid confounding effects at harvest (Alabi *et al.*, 2016). Yield and fungicide costs were used to assess acceptability; additional indicators were excluded due to data constraints (Thiollet-Scholtus *et al.*, 2021).

Despite these limits, in our case, OFE was particularly relevant for reducing pesticide use because it involves mainstream winegrowers under real production conditions. It ensures that co-designed strategies are technically feasible, economically viable, and adaptable to local contexts, while increasing the credibility and transferability of results. Working with typical growers demonstrates that pesticide reduction is achievable within standard systems and constraints, and fosters learning and peer exchange, supporting wider adoption.

5. Perspectives for further adoption of the management strategies

After two years of experimentation, the winegrowers remain hesitant to implement the new management strategies across their entire vineyard. The rationale behind this reluctance is the perceived high risk associated with the strategies, which outweighs the potential for increased earnings. The challenge of scaling up innovative practices on the farm has been recognised, and it has been elucidated that the apprehension stems from the elevated risk of yield losses coupled with the need for confidence in the efficiency of these practices, as highlighted in previous studies (Chèze *et al.*, 2019; Puech *et al.*, 2021). As soon as this risk-taking is limited and yields can be maintained, winegrowers are prepared to adopt low pesticide-use practices (Chèze *et al.*, 2019). Concerning the 'IPM', '0RES', and 'ORG2kgCo' management strategies, an intermediate stage considered by the winegrowers could be to deploy the management strategies on the scale of several vineyards (5–10 % of their farm) which would be treated independently of the rest of their farm. This stage could be extended by a further 3 years, allowing the strategies to be tested over several years with different disease pressures (especially strong ones) and to observe their long-term effects. The diversity of grape varieties, PDO specifications, and production objectives represented in this study also highlights that the transferability of these management strategies cannot be assumed to be uniform across vineyards. Winegrowers are therefore likely to require evidence of the effectiveness and reliability of these strategies under their own production conditions before adopting them on a larger scale, as has also been reported for other viticultural innovations (Tabouret, 2019). Further on-farm evaluation across a wider range of viticultural contexts would strengthen confidence in their applicability and facilitate their wider adoption. It would also enable winegrowers to observe the behaviour of management strategies with different grape varieties and different production objectives (PDO and PGI), which would be representative of the rest of their farm. As mentioned earlier, the management strategies are tested on PDO

vineyards, and their implementation without testing on PGI vineyards could be too risky. Finally, this step would permit studying the impact of these strategies on winegrowers' working time, which has not been addressed in this study. However, for the 'BCT' management strategy, it would be necessary to continue experimentation on a field scale to improve its effectiveness before considering a transfer to a larger scale. Indeed, the results of this strategy vary greatly from year to year and from winegrower to winegrower. The aim would be to continue on a small scale (0.5 hectares in this study) to study this variability over several years and to be able to assess it before a larger-scale transfer.

To streamline the dissemination of findings to winegrowers not actively engaged in the study, annual communication of results is extended to all cooperative members. This includes on-site visits in July, along with an oral presentation during the harvest review meetings conducted by VINOVALIE advisors in each vineyard. We intend to persist in conducting these visits, utilising 'pilot' farms as demonstrative platforms. Past experiences have demonstrated the effectiveness of such demonstrations in motivating other farmers by providing tangible results within their specific production contexts (Le Bellec *et al.*, 2012). It is noteworthy that winegrowers often employ pesticides as an insurance mechanism, yet this does not necessarily translate to a commensurate increase in their overall income (Menapace *et al.*, 2013). To encourage them to reduce their pesticide use, a significant financial incentive through a 'production-risk premium' seems necessary (Chèze *et al.*, 2019). In addition to awareness-raising actions, the introduction of an insurance system covering the risk of crop damage due to cryptogamic diseases linked to the reduction in plant protection inputs, as proposed by Raynal *et al.* (2022) could help to encourage a reduction in the use of pesticides. This positive incentive would be more interesting than a negative incentive through an increase in pesticide prices. It has been shown that a very large change in price is needed to bring about a relatively small change in the quantity of pesticides (Ayouba & Vigeant, 2020).

CONCLUSION

In this study, we showed that three co-designed management strategies in conventional viticulture ('IPM', '0RES', and 'BCT') led to substantial reductions in pesticide use in 2021 and 2022 compared with both current winegrower practices (VITI modality: −11.9 % to −88.5 %) and the HEV reference (−5.7 % to −93.3 %). Similarly, the 'ORG2kgCo' strategy in organic viticulture reduced copper use by 13.1 % to 50 % compared with current practices, ensuring that the target of 2 kg/ha/year – representing a 50 % reduction relative to European regulations – was not exceeded. Except for the 'BCT' strategy, the co-designed systems were generally effective in controlling disease, limiting yield losses, and reducing fungicide costs. These results are encouraging for potential transfer to PDO vineyards. In contrast, the performance of the 'BCT' strategy was too variable to support direct recommendation, highlighting the need for further improvement of its technical reliability.

A key strength of this study lies in the use of on-farm experimentation with volunteer winegrowers operating under real production constraints. The strategies were implemented in commercial vineyards, on small plots embedded within farmers' vineyards, and managed with their own equipment and decision rules. This context inevitably introduces variability (*e.g.,* differences in varieties, sprayers, and local conditions) and contrasts with the level of control achieved in factorial experimental designs. However, it also provides a more realistic assessment of the agronomic and economic performance of innovative systems, as well as their practical feasibility and acceptability.

Such an approach is particularly relevant in a context where farmers are often risk-averse regarding pesticide reduction. By testing co-designed strategies directly on their own farms, winegrowers can progressively assess and adapt these systems, thereby reducing perceived risk and facilitating adoption. To support wider implementation, further research should evaluate these strategies at larger spatial scales, across a broader range of grapevine varieties and production objectives, and over multiple years with contrasting disease pressures.

ACKNOWLEDGEMENTS

The authors thank all the winegrowers for their involvement in this study. The authors also thank the French ANRT (Association Nationale de la Recherche et de la Technologie) and the VITI OBS project funded by the Occitanie Region for their support of this study. The authors thank the editors of Oeno One and the anonymous reviewers for improving the article.

REFERENCES

Aka, J., Ugaglia, A. A., & Lescot, J.-M. (2018). Pesticide Use and Risk Aversion in the French Wine Sector. Journal of Wine Economics, 13(4), 451-460. https://doi.org/10.1017/jwe.2018.55

Alabi, O. J., Casassa, L. F., Gutha, L. R., Larsen, R. C., Henick-Kling, T., Harbertson, J. F., & Naidu, R. A. (2016). Impacts of grapevine leafroll disease on fruit yield and grape and wine chemistry in a wine grape (Vitis vinifera L.) cultivar. PLoS One, 11(2), e0149666.

Ali, S., Ullah, M. I., Sajjad, A., Shakeel, Q., & Hussain, A. (2021). Environmental and Health Effects of Pesticide Residues. In Inamuddin, M. I. Ahamed, & E. Lichtfouse (Éds.), Sustainable Agriculture Reviews 48 (Vol. 48, p. 311-336). Springer International Publishing. https://doi.org/10.1007/978-3-030-54719-6_8

Aveline, N., Dupin, S., Becquet, L., & Cayla, L. (2022, mai). Le biocontrôle en viticulture : Recherche et expérimentations. https://www.vignevin.com/wp-content/uploads/2023/06/itineraires_biocontrole_web.pdf

Ayouba, K., & Vigeant, S. (2020). Can We Really Use Prices to Control Pesticide Use? Results from a Nonparametric Model. Environmental Modeling & Assessment, 25(6), 885-900. https://doi.org/10.1007/s10666-020-09714-w

Bakker, L., Sok, J., Van Der Werf, W., & Bianchi, F. J. J. A. (2021). Kicking the Habit : What Makes and Breaks Farmers' Intentions to Reduce Pesticide Use? Ecological Economics, 180, 106868. https://doi.org/10.1016/j.ecolecon.2020.106868

Barzman, M., & Dachbrodt-Saaydeh, S. (2011). Comparative analysis of pesticide action plans in five European countries. Pest Management Science, 67(12), 1481-1485. https://doi.org/10.1002/ps.2283

Biddoccu, M., Ferraris, S., Opsi, F., & Cavallo, E. (2016). Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North–West Italy). Soil and Tillage Research, 155, 176-189.

Bleyer, G., Lösch, F., Schumacher, S., & Fuchs, R. (2020). Together for the Better : Improvement of a Model Based Strategy for Grapevine Downy Mildew Control by Addition of Potassium Phosphonates. Plants, 9(6), 710. https://doi.org/10.3390/plants9060710

Carretier, D. (2021). BSV BILAN 2021. EDITION MIDI-PYRENEES GAILLAC.

Carretier, D. (2022). BSV BILAN 2022. EDITION MIDI-PYRENEES GAILLAC.

Carretier, D. (2023). BSV BILAN 2023. EDITION MIDI-PYRENEES GAILLAC.

Carton, N., Swiergiel, W., Tidåker, P., Röös, E., & Carlsson, G. (2022). On-farm experiments on cultivation of grain legumes for food – outcomes from a farmer–researcher collaboration. Renewable Agriculture and Food Systems, 37(5), 457-467. https://doi.org/10.1017/S1742170522000102

Catalogna, M., Dubois, M., & Navarrete, M. (2018). Diversity of experimentation by farmers engaged in agroecology. Agronomy for Sustainable Development, 38(5), 50. https://doi.org/10.1007/s13593-018-0526-2

Cellule d'Animation Nationale DEPHY Ecophyto. (2021). Bilan de Campagne 2021 Filière Viticulture.

Cellule d'Animation Nationale DEPHY Ecophyto. (2022). Bilan de Campagne 2022 Filière Viticulture.

Chèze, B., David, M., & Martinet, V. (2019). Understanding farmers' reluctance to reduce pesticide use : A choice experiment. Ecological Economics, 167, 106349. https://doi.org/10.1016/j.ecolecon.2019.06.004

Davy, A., Raynal, M., Vergnes, M., Debord, C., Codis, S., Naud, O., Deliere, L., Fermaud, M., Roudet, J., Metral, R., Bouisson, Y., Davidou, L., Guilbault, P., Dupin, S., Genevet, B., Mahieux, V., Baron, M., & Perot, S. (2020). DeciTrait® : Un OAD pour la protection de la vigne. Innovations Agronomiques, 79, 89-99. https://doi.org/10.15454/7FK8-GT23

Delière, L., Guimier, S., Petitgenet, M., Goutouly, J. P., Vergnes, M., Dupin, S., Davidou, L., Christen, M., Rochas, A., & Guilbault, P. (2018). Projet EcoViti Aquitaine : Performances de systèmes viticoles à faible niveau d'intrants phytopharmaceutiques dans le vignoble bordelais. Innovations Agronomiques, 70, 37-53pp. https://doi.org/10.15454/3WLRXP

Fermaud, M., Smits, N., Merot, A., Roudet, J., Thiéry, D., Wery, J., & Delbac, L. (2016). New multipest damage indicator to assess protection strategies in grapevine cropping systems : An indicator of multipest damage in grapevine. Australian Journal of Grape and Wine Research, 22(3), 450-461. https://doi.org/10.1111/ajgw.12238

Fouillet, E., Delière, L., Chartier, N., Munier-Jolain, N., Cortel, S., Rapidel, B., & Merot, A. (2022). Reducing pesticide use in vineyards. Evidence from the analysis of the French DEPHY network. European Journal of Agronomy, 136, 126503. https://doi.org/10.1016/j.eja.2022.126503

Galet, P. (1977). Les maladies et les parasites de la vigne, Volume 1. Impr. du Paysan du Midi.

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H., & Metay, A. (2018). Management of service crops for the provision of ecosystem services in vineyards : A review. Agriculture, Ecosystems & Environment, 251, 158-170. https://doi.org/10.1016/j.agee.2017.09.030

Giampietri, E., & Trestini, S. (2023). Pro-Environmental Viticulture : Status Quo and Perspectives from Prosecco Winegrowers in Italy. Sustainability, 15(2), 1073. https://doi.org/10.3390/su15021073

Goulet, É., Cady, E., & Chrétien, P. (2006). Sensibilité de la vigne face aux maladies cryptogamiques : Utilisation croisée d'une cartographie des terroirs viticoles et d'une enquête parcellaire. VIe Congrès International des terroirs viticoles.

Guichard, L., Dedieu, F., Jeuffroy, M.-H., Meynard, J.-M., Reau, R., & Savini, I. (2017). Le plan Ecophyto de réduction d'usage des pesticides en France : Décryptage d'un échec et raisons d'espérer. Cahiers Agricultures, 26(1), 14002. https://doi.org/10.1051/cagri/2017004

Hill, S. B., & MacRae, R. J. (1996). Conceptual Framework for the Transition from Conventional to Sustainable Agriculture. Journal of Sustainable Agriculture, 7(1), 81-87. https://doi.org/10.1300/J064v07n01_07

Inserm. (2021). Pesticides et effets sur la santé : Nouvelles données. Collection Expertise collective. Montrouge : EDP Sciences.

Interprofession des Vins du Sud-Ouest. (2024). Economie. Vignobles du Sud-Ouest. https://www.vignobles-sudouest.fr/economie/

Lacoste, M., Cook, S., McNee, M., Gale, D., Ingram, J., Bellon-Maurel, V., MacMillan, T., Sylvester-Bradley, R., Kindred, D., Bramley, R., Tremblay, N., Longchamps, L., Thompson, L., Ruiz, J., García, F. O., Maxwell, B., Griffin, T., Oberthür, T., Huyghe, C., … Hall, A. (2021). On-Farm Experimentation to transform global agriculture. Nature Food, 3(1), 11-18. https://doi.org/10.1038/s43016-021-00424-4

Le Bellec, F., Rajaud, A., Ozier-Lafontaine, H., Bockstaller, C., & Malezieux, E. (2012). Evidence for farmers' active involvement in co-designing citrus cropping systems using an improved participatory method. Agronomy for Sustainable Development, 32(3), 703-714. https://doi.org/10.1007/s13593-011-0070-9

Lechenet, M., Dessaint, F., Py, G., Makowski, D., & Munier-Jolain, N. (2017). Reducing pesticide use while preserving crop productivity and profitability on arable farms. Nature Plants, 3(3), 17008. https://doi.org/10.1038/nplants.2017.8

Mailly, F., Hossard, L., Barbier, J.-M., Thiollet-Scholtus, M., & Gary, C. (2017). Quantifying the impact of crop protection practices on pesticide use in wine-growing systems. European Journal of Agronomy, 84, 23-34. https://doi.org/10.1016/j.eja.2016.12.005

Menapace, L., Colson, G., & Raffaelli, R. (2013). Risk Aversion, Subjective Beliefs, and Farmer Risk Management Strategies. American Journal of Agricultural Economics, 95(2), 384-389. https://doi.org/10.1093/ajae/aas107

Merot, A., & Smits, N. (2020). Does Conversion to Organic Farming Impact Vineyards Yield? A Diachronic Study in Southeastern France. Agronomy, 10(11), 1626. https://doi.org/10.3390/agronomy10111626

Merot, A., Fermaud, M., Gosme, M., & Smits, N. (2020). Effect of Conversion to Organic Farming on Pest and Disease Control in French Vineyards. Agronomy, 10(7), 1047. https://doi.org/10.3390/agronomy10071047

Miclot, A. S., Delmotte, F., Bourg, J., Mazet, I. D., Fabre, F., & Delière, L. (2022). Four years of monitoring of disease-resistant grapevine varieties in French vineyards. BIO Web of Conferences, 50, 02008. https://doi.org/10.1051/bioconf/20225002008

Ministère de l'agriculture et de l'alimentation. (2019). Une certification environnementale pour les exploitations agricoles.

Ministère du Partenariat avec les territoires et de la Décentralisation, le ministère de la Transition écologique, de l'Énergie, du Climat et de la Prévention des risques et le ministère du Logement et de la Rénovation urbaine. (2022). Publication des ventes de produits phytopharmaceutiques en 2022 (données définitives). https://www.ecologie.gouv.fr/actualites/publication-ventes-produits-phytopharmaceutiques-2022-donnees-definitives

Mouly, M., Garnault, M., Aulagnier, A., Barbu, C., Gallien, M., Boussada, V. G., ... & Ecophyto, C. (2022). Éléments d'analyse de l'évolution des indicateurs de ventes des produits phytopharmaceutiques en France. Données 2020 (Doctoral dissertation, Inrae).

Pant, L. P., & Hambly Odame, H. (2009). The promise of positive deviants : Bridging divides between scientific research and local practices in smallholder agriculture. Knowledge Management for Development Journal, 5(2), 160-172. https://doi.org/10.1080/18716340903201504

Perez, M., Hossard, L., Gary, C., Lacapelle, P., Robin, M.-H., & Metay, A. (2024). A participatory approach to involve winegrowers in pesticide use reduction in viticulture in the south-western region of France. Italian Journal of Agronomy, 18(4). https://doi.org/10.4081/ija.2023.2209

Phyteis. (2022, juillet). Légère hausse des volumes de phytopharmaceutiques vendus en 2021 sous l'impulsion des produits utilisables en agriculture biologique.

Pingault, N., Pleyber, É., Champeaux, C., Guichard, L., & Omon, B. (2009). Produits phytosanitaires et protection intégrée des cultures: l'indicateur de fréquence de traitement. Notes et études socio-économiques, 32, 61-94.

Prost, C. (2023). Enquête Pratiques culturales en viticulture en 2019 IFT et nombre de traitements Données révisées (Rapport Technique 4; Chiffres & données). Ministère de la transition et la cohésion des territoires.

Puech, C., Brulaire, A., Paraiso, J., & Faloya, V. (2021). Collective design of innovative agroecological cropping systems for the industrial vegetable sector. Agricultural Systems, 191, 103153. https://doi.org/10.1016/j.agsy.2021.103153

Raynal, M., Davadan, L., Lely, D., Magot, C., Gizardin, F., Taillée, M., & Robichon, G. (2022). Experimentation in the vineyard of an insurance protocol to cover the harvest's risk of damage due to cryptogamic diseases linked to the reduction of phytosanitary inputs. BIO Web of Conferences, 50, 04008. https://doi.org/10.1051/bioconf/20225004008

Schumacher, S., Mertes, C., Wohlfahrt, Y., Kaltenbach, T., Schwab, S., Eisenmann, B., Kauer, R., Bleyer, G., Berkelmann-Loehnertz, B., & Fuchs, R. (2022). VITIFIT : Aiming for copper reduction in organic viticulture - Improvement of established strategies and new techniques for plant protection against Plasmopara viticola. BIO Web of Conferences, 50, 03008. https://doi.org/10.1051/bioconf/20225003008

Serrano, E., Petit, A., Gaviglio, C., Gontier, L., Dufourcq, T., Cogo, R., Massol, T., Mora, J., Rafenne, X., & Cichosz, B. (2019). Ecoviti Sud-Ouest : Performances de systèmes viticoles innovants à faible niveau d'intrants phytopharmaceutiques sur le bassin de production Sud-Ouest. Innovations Agronomiques, 76, 254-272pp.

Tabouret, S. (2019). Setting up a "good" experimentation: the case of vine varieties testing in Languedoc. Open Agriculture, 4(1), 275-283.

Tacoli, F., Pavan, F., Cargnus, E., Tilatti, E., Pozzebon, A., & Zandigiacomo, P. (2017). Efficiency and Mode of Action of Kaolin in the Control of Empoasca vitis and Zygina rhamni (Hemiptera : Cicadellidae) in Vineyards. Journal of Economic Entomology, 110(3), 1164-1178. https://doi.org/10.1093/jee/tox105

Thiollet-Scholtus, M., Muller, A., Abidon, C., Audema, P., Bailly, C., Chaumonnot, S., Grignion, J., Keichinger, O., Klein, C., Koller, R., Langenfeld, A., Ley, L., Lemarquis, G., Nassr, N., Nibaudeau, R., Rabolin-Meinrad, C., Ribeiro, S., Schneider, C., & Weissbart, J. (2019). Performances multicritères de systèmes viticoles à réduction drastique d'intrants dans le vignoble alsacien (PEPSVI). Innovations Agronomiques, 76, 219-236pp. https://doi.org/10.15454/MGHRXL

Thiollet-Scholtus, M., Muller, A., Abidon, C., Grignion, J., Keichinger, O., Koller, R., Langenfeld, A., Ley, L., Nassr, N., Rabolin-Meinrad, C., & Wohlfahrt, J. (2021). Multidimensional assessment demonstrates sustainability of new low-input viticulture systems in north-eastern France. European Journal of Agronomy, 123, 126210. https://doi.org/10.1016/j.eja.2020.126210

Toffolini, Q., & Jeuffroy, M.-H. (2022). On-farm experimentation practices and associated farmer-researcher relationships : A systematic literature review. Agronomy for Sustainable Development, 42(6), 114. https://doi.org/10.1007/s13593-022-00845-w

Urruty, N., Deveaud, T., Guyomard, H., & Boiffin, J. (2016). Impacts of agricultural land use changes on pesticide use in French agriculture. European Journal of Agronomy, 80, 113-123. https://doi.org/10.1016/j.eja.2016.07.004

Zanzotto, A., & Morroni, M. (2016). Major biocontrol studies and measures against fungal and oomycete pathogens of grapevine. In S. Compant & F. Mathieu (Éds.), Biocontrol of major grapevine diseases : Leading research (1re éd., p. 1-34). CABI. https://doi.org/10.1079/9781780647128.0001