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ORIGINAL RESEARCH ARTICLE

To what extent can a phase-out of pesticides in viticulture be achieved? Learning from the efforts of a large farm network after 10 years

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ABSTRACT

In accordance with European Directive 2009/128/CE, France has set up national policies to curb the reliance of agriculture on phytosanitary inputs. The DEPHY network is one such initiative;, which has been designed to drive, support and document the fieldwork of 3,000 farms voluntarily taking part in a collective input reduction programme. This study aimed to describe the achievements of the network's viticultural sector, as its perennial crop is heavily reliant on pesticide applications. We chose a sample of 343 wine-growing systems across mainland France, analysed records of their vineyard operations from before they joined the network, and compared them to those from the 2017-2020 period. We used the Treatment Frequency Index (TFI) to assess pesticide reliance together with other techno-economical parameters: production costs, workloads, greenhouse gas emissions and disease control. A significant decrease in pesticide use was found over the whole study period, with, for instance, an average TFI reduction of 24 %, which is consistent with national objectives but unmatched outside of the network. We observed an overall shift towards pesticide inputs with lower repercussions on health or the environment, as well as different TFI reduction trajectories based on initial pesticide dependency. We described the alternative practices introduced to the systems, and our results suggest that reductions in pesticide use stem from quite small and minor changes made to the cropping systems. These new practices only slightly lowered the vineyards' technical and economical performances in specific situations involving an indepth revamping of the systems; e.g., conversion to organic viticulture. To increase pesticide phase-out, further research is needed on redesigning cropping systems, and on how to scale up the network's results to the national level.

KEYWORDS: viticulture, pesticide, demonstration farm, DEPHY, performance indicator, Treatment Frequency Index, agroecology

INTRODUCTION

In the late XIXth century, European viticulture was overwhelmed with pests and diseases originating from the American continent (e.g., powdery and downy mildews, phylloxera and grape black-rot). These pathogens caused severe harvest losses and large parts of the vineyard to be uprooted (Galet, 1991). Copper and sulphur were amongst the first pesticides employed to tackle these organisms, along with genetic engineering; for example, phylloxera-resistant rootstocks. A considerable number of synthetic plant protection products were developed in the latter half of the 20th century, which have improved protection efficiency, selectivity and convenience of use, and which are still unmatched by any other levers since their introduction. The introduction of synthetic herbicides to cropping systems and the leap in mechanisation further contributed to the simplification of vine cultivation (Boulanger-Fassier, 2008).

Given the persistence of the diseases and pests to which the vineyard is still subjected, modern protection methods still rely greatly on chemical inputs. The Treatment Frequency Index (TFI), which can be interpreted as the number of full-dose chemical treatments per unit area, is the main indicator used in France for measuring reliance on these inputs (Brunet *et al.*, 2008). During the 2019 season, the average TFI value for French vineyards was 12.4 (Simonovici and Caray, 2023), with over 80 % of this figure being associated with fungicide use (mostly against downy and powdery mildew) and insecticides accounting for 15 %. Despite only representing under 4 % of the national TFI, herbicides are still used on 70 % of France's viticultural area, being mostly applied under the vine row. In Organic Agriculture, in which the specifications prohibit the use of synthetic inputs, the average TFI is 8.1.

The European Directive 2009/128/CE introduced a framework for joint action to achieve the sustainable use of pesticides, requiring member States to implement national policies to reduce the use and impacts of pesticides (Barzman and Dachbrodt-Saaydeh, 2011). In France, the Government established the Ecophyto plan in 2008 (subsequently revised in 2015 and 2018) with the aim of acheiving a 50 % decrease in pesticide use by 2025. The plan includes the provision of funding for research on alternatives to phytosanitary products, and support for farmers in implementing measures to make this transition (Lamichhane *et al.*, 2019).

Launched in 2010, the DEPHY FERME network is one such initiative. It consists of around 250 groups, gathering 10 to 12 farmers each, who are from a given area and sector and all committed to reducing their input consumption. Initially having 1,900 members, the network was extended to 3,000 farms in 2016. To help them in their transition, each group is assigned an extensionist, who provides both individual and collective support. The collectives are scattered across the country and cover all French agricultural sectors: arable cropping, crop-livestock farming, arboriculture, market gardening, horticulture, tropical crops and winegrowing (Lapierre *et al.*, 2019). The wine-growing network comprised 280 farms when the network was created in 2010-2011, later increasing to 550 vineyards in 2016. These vineyards are located in each of the country's major wine-growing regions.

This article explores the evolution of pesticide-use within this network, as well as the associated impacts on vineyard environmental and economical parameters.

MATERIAL AND METHODS

1. The AGROSYST database

Data related to the network's members' vineyards are recorded yearly by the extensionists, and they are compiled on an online information system called "Agrosyst". These data are available on a specific scale: from several plots to the whole area of studied vineyards. For each individual, the study subject is therefore a homogenous set of plots, practices and equipment, accounting for a significant part of the vineyard's activity (if not all of it). In this paper, these "vineyard areas" are referred to as "wine-growing systems" (WS).

Agrosyst is an Information System developed by INRAE (French National Institute of Agronomic and Environmental Research) (Ancelet *et al.*, 2014). It is used to record the network's farm and field data and to calculate performance indicators related to pesticide use, and economic or environmental performances. These indicators are calculated using recorded data and a large amount of reference sources regarding prices, fuel consumption, approved pesticide doses and input composition (See Section 2.3 for details).

1.1. Vineyard operations

All the vineyard operations performed by the network's growers are entered into the database. Multiple details are stored, such as date of intervention, work rate, machinery used and inputs and doses, which can then be aggregated to create different performance indicators.

As well as being collected annually, these traceability data are also recorded for one to three years prior to a given member joining the network. These extra data are needed in order to be able to model an "initial point" (IP) of the wine-growing systems before they undergo DEPHY monitoring. Most of the network members joined the programme during two separate membership campaigns : either in 2012 or 2016; based on this, two IPs each spaninng a period of three years were defined: 2010/2011/2012 and 2014/2015/2016.

This study hence investigates the performances of the network's wine-growing systems, based on the evolution of their vineyard operations. The sample of studied WS comprised those for which traceability data were available from the IP and the 2017, 2018, 2019, 2020 seasons. Systems that left or joined the network during this time frame were filtered out, along with those for which data was missing or incomplete for at least one season.

As a result, a total of 343 wine-growing systems located in the nine main French wine-growing regions (Code Rural et de la pêche maritime, 2017) were studied:

Alsace-Lorraine (n = 21), Bordeaux-Bergerac (67), Bourgogne-Jura-Savoie (48), Champagne (18), Charentes (36), Languedoc-Roussillon (24), Rhône-Provence (50), Sud-Ouest (28) and Val de Loire (51). This distribution is not necessarily representative of French viticulture, but it does cover a wide range of its production. A map displaying the locations of the sample WS is provided in Supplementary Figure 1.

1.2. Pesticide reduction levers

Throughout the course of this article, we used the term "pesticide reduction levers" to refer to the tools, techniques and sets of practices deployed by the network winegrowers to reduce their TFIs.

In addition to recording the farming operations, the winegrowers indeed provide the network extensionists with descriptions of the pesticide reduction strategies they apply in their respective systems. To do so, they are asked to provide a yearly selection of the levers applied, from a drop-down menu on the aforementioned information system Agrosyst.

For the whole study period, data on pesticide reduction levers were available for 331 systems (out of 343), and a system was considered to carry out a lever if it was quoted at least once between 2017 and 2020. On Agrosyst, the displayed levers are categorised for each chemical type to be reduced (i.e., fungicide, insecticide, herbicide).

1.3. Pest pressure and pest control:

Also collected yearly, this information is strictly evaluated by winegrowers as well:

They are requested to estimate the pressure of given relevant pests on their vineyard using a four-level scale: (i) None (absence), (ii) Low (no impact), (iii) Moderate (yield possibly affected), and (iv) High (assured impact on yield & margins).

For the same given pest, the network members are then asked to assess their pest control performance using a second scale based on the actual damage sustained: (i) No symptoms, (ii) Symptoms with no effects on yield or harvest quality, (iii) Symptoms with minor yield and quality impairment, and (iv) Economic losses caused by the pest.

The pests and diseases that the winegrowers report often vary with the local agro-climatic context of the wine-growing systems (WS); therefore, this study only addressed data for the two major ones: downy and powdery mildew. It was possible to analyse annual pressure for a maximum of 328 wine-growing systems. Protection performances were only analysed for the systems and years with moderate pressures at the least.

2. Description of performance indicators

2.1. Treatment Frequency Index (TFI)

The intensity of pesticide use is quantified using TFI, which is calculated for every pesticide treatment as follows:

$$Treatment\ TFI = \frac{Sprayed\ dose}{Approved\ dose} \times \frac{Sprayed\ area}{Total\ area}$$

The "approved dose" of a given substance for a given purpose is determined by the French National Agency for Social Security (ANSES, 2023). Those used in this study are the ones listed in 2022. The TFI score can be obtained for a whole viticultural season, by totalling the values of each treatment.

Hence, Total TFI was calculated for all plant protection products (PPPs) that had a marketing authorisation for a set period. In this study, partial TFIs were also calculated for the following categories:

- **Biocontrol TFI**: computed for PPPs listed under the 2022 French Ministry of Agriculture's inventory of "biocontrol products" (Direction générale de l'alimentation, 2022). The list contains "macro-organisms, microorganisms, natural substances, chemical mediators and defence elicitors" that do not pose major risks to human health (i.e., 27 hazard statements denied) or the environment (i.e., 2 statements denied). Most plant protection products approved in organic farming are featured on this list (e.g., sulphur), while others, like copper, pyrethrum and spinosad, are not.
- **TFI that excludes Biocontrol**: Total TFI - Biocontrol TFI.
- **Fungicide TFI (excluding biocontrol)**: computed for fungicidal PPPs (excluding those on the "biocontrol" list).
- **Insecticide TFI (excluding biocontrol)**: computed for insecticidal PPPs (excluding those on the "biocontrol" list).
- **Herbicide TFI (excluding biocontrol)**: computed for herbicidal PPPs excluding those on the "biocontrol" list).
- **CMR TFI**: computed for "Carcinogenic, Mutagenic, toxic to Reproduction" PPPs; namely those associated with at least one of the following hazard statements: H341, H350, H360, H360D, H360Df, H360FD, H361, H361d, H361f, H361fd and H362 (European parliament, 2008).
- **Standardised TFI**: for a given year, it is calculated as the quotient between a system's TFI (excluding biocontrol) and a reference value for its wine-growing area. It thus takes into account the local agro-climatic context while characterising pesticide use. References used are regional averages derived from ministerial surveys, conducted every three years in the whole country on a representative sample of 4,000 farms (Pujol, 2017; Ambiaud, 2015; Simonovici and Caray, 2023). During the studied time frame, regional averages were available for the 2010, 2013, 2016 and 2019 seasons. Consequently, standardised TFI was only calculated for these four year, including the IP of each WS (for which the multi-year average TFI was divided by the closest available reference).

2.2. Standardised TFI and system's pesticide-use intensity

A classification system based on standardised TFI was set up to sort the WS from least to most pesticide-intensive, while accounting for their production context. For a given year, they were divided into four classes of pesticide-use intensity: (i) non-efficient systems (standardised TFI ≥ 1), (ii) moderately efficient systems (1 > standardised TFI ≥ 0.75),

(iii) efficient systems (0.75 > standardised TFI ≥ 0.5), and (iv) very efficient systems (standardised TFI < 0.5). The threshold values that define these classes were arbitrarily chosen and represent a system's level of pesticide efficiency within its wine-growing region. The latter two threshold values also aim to highlight the most parsimonious systems, which are driving the sample towards national Ecophyto objectives for pesticide reduction: -25 % in 2020 and -50 % in 2025.

In addition, pesticide-use trajectories were determined for the whole study period using standardised TFI values for the Initial Point (IP) and the year 2019. These trajectories were studied based on four classes T1 to T4) shown in Table 1, rather than the 16 interactions of pesticide-use intensity. A summary table of these 16 interactions and their sizes are, however, provided in Supplementary Table 1. Our classification of pesticide-use trends, as shown in Table 1, is hence based on the standardised TFI value of 0.75, with the aim of identifying the systems that are in line with the 2020 Ecophyto objective. Indeed, the TFI of systems with values below this threshold were recorded as being at least 25 % lower than their regional average in 2019.

TABLE 1. Overview of the 4 standardised TFI trajectories between the IP and 2019.

Abv.	Pesticide-use trend	Standardised TFI at IP	Standardised TFI in 2019
T1	WS becoming inefficient	< 0.75	≥ 0.75
T2	WS staying efficient		< 0.75
T3	WS staying inefficient	≥ 0.75	≥ 0.75
T4	WS becoming efficient		< 0.75

2.3. Techno-economic performance indicators

As well as studying vineyard protection practices, we evaluated several metrics:

▸ **Phytosanitary expenses**: these reflect the purchasing costs in euros per hectare of plant protection inputs, applying national standard prices for a given year. The prices of phytosanitary products were extracted from the Agrosyst database and are based on estimations by TerrEtude (a firm specialising in market research) and prices provided by DEPHY farmers.

▸ **Mechanisation expenses**: these are a combination of both the fixed (e.g., depreciation, financial fees and insurance) and variable (e.g., fuel, maintenance and tyres) costs associated with a system's fleet of vehicles (manpower costs not included). They are shown in euros per hectare for a given year, and harvest was omitted from computations to avoid discrepancies induced by harvesting methods (i.e., manual or mechanical). Distinctive cost items and calculation methodology were estimated by the French chambers of agriculture (Hamiti and van Kempen, 2017).

▸ **Manual labour time** and **equipment operating time**: these two indicators refer to the amount of time spent per hectare carrying out manual or mechanised operations during the season. They were directly obtained from the records of the operations carried out by the sample wine-growing systems, which included the areas and workforce involved, and work rates per hectare. For the latter, the extensionists could either enter the growers' self-assessed times or use standard values (Hamiti and van Kempen, 2017). Manual labour time and equipment operating time are also expressed on an outside-of-harvest basis.

▸ **Greenhouse Gas emissions** (GHG): were also assessed using the "GEST'IM" reference framework (Gac *et al.*, 2010). They are expressed in kg of CO_2 equivalent, and do not take harvesting operations into account (see mechanisation expenses). Two types of emission were tracked separately: (a) Fuel-related emissions, which are a combination of direct ("on farm") and indirect emissions ("upstream"; e.g., fuel manufacturing) caused by fuel consumption, and, (b) indirect sources of crop protection input emissions; i.e., those associated with the production and supply of the applied plant protection products.

2.4. Statistical analysis

Graphs and statistical analyses were performed using R software (version 4.2.3) and the following packages: ggplot2 (Wickham *et al.*, 2016) and ggradar (Bion, 2023) to produce the graphs; ggh4x (van den Brand, 2023) and egg (Auguie, 2019) for the layout options, ggpubr (Kassambara, 2023) and multcompview (Graves *et al.*, 2023) for the statistical analysis, and dplyr (Wickham *et al.*, 2023) for data manipulation.

In order to compensate for annual variability, indicator trends over time were considered by comparing three-year average values: the initial point versus a 2018/2019/2020 mean; the results of this comparison were completed with paired statistical comparison of means (Student) or ranks (Wilcoxon), depending on data distribution. *Ad hoc* One-way ANOVA and Chi-square tests were also performed. For four previously mentioned tests an $\alpha = 0.05$ significance threshold was applied.

3. Data accessibility

Part of the data used in the present study has been stored in the "Recherche Data Gouv" repository. This open-access anonymised dataset of cultural operations and performance indicators for the 343 sampled wine-growing systems is accessible via the following DOI: https://doi.org/10.57745/2HITDV.

RESULTS

1. Pesticide use reduction levers:

In order reduce their fungicide use, the network winegrowers primarily adopt techniques and tools for adjusting either the first treatment date or the applied doses: Reduced doses (quoted by 76 % of wine-growing systems), Vineyard inspections (63 %), Spraying techniques and equipment (45 %), Decision support systems (31 %), or Fragmented plot protection (30 %). They also introduce preventive practices aimed at reducing the vine's sensitivity to disease: Foliage thinning such as disbudding or leaf removal (59 %), and Vigour reduction induced through grass cover, fertilisation or pruning (37 %). About half of the respondents stated that they use alternative protection agents (e.g., biocontrol and natural defence stimulators) as a replacement for conventional molecules. In addition, a smaller number of winegrowers (9 %) said that they cut off infected aerial plant organs as a sanitary measure: inoculum removal. Finally, we noted that more strategic approaches were still rarely chosen by network members, such as the planting of resistant varieties (2 %). A barplot visualisation of these results is available in Supplementary Figure 2a.

To reduce insecticide use, the dominant strategy also aimed at achieving greater input efficiency; for example, applying treatments when pest outbreaks were confirmed through vineyard inspections involving, for example, counting or trapping (65 %). In the same vein, optimised spraying techniques and equipment were used in certain systems (17 %). The type of products used was also often highlighted as a means of reduction, specifically Mating disruption agents (19 %) and Alternative protection agents (14 %), like biocontrol or kaolin clay. Finally, some levers sought to decrease agroecosystem sensitivity, either by using agroecological infrastructures to cause natural regulation (21 %) or by restraining the vine's vegetative growth via vigour reduction (14 %) or foliage thinning (18 %). A barplot of these results is available in Supplementary Figure 2b.

For weed control, fewer alternative techniques are available to winegrowers. Mechanical weeding (84 %), such as tillage, mowing and ploughing, and sown or spontaneous cover crops (59 %) were found to be by far the most common techniques in the network. Although the range of existing solutions is limited, these two techniques can be widely applied by the winegrowers (varying with type of machinery used or the species sown, for example). Conventional farming systems also implemented herbicide reduction measures, such as reducing the sprayed area (30 %), or applying reduced doses to an equivalent area (26 %). In addition, 27 % of the surveyed systems claimed to have replaced at least one chemical suckering treatment with a manual or mechanical operation. Lastly, less established techniques are being marginally pioneered in the network, such as the targeted grazing of weeds by small cattle (1 %). A barplot of these results is available in Supplementary Figure 2c.

2. Overall pesticide-use trends

The mean total TFI significantly decreased between the IP and the 2018-2019-2020 average: it dropped from an initial mean value of 12.4 to 10.6 (i.e., a 14.5 % reduction, $p < 0.001$). Over this time frame, it declined for 236 winegrowing systems (around 70 % of the sample). The values were, however, found to be highly dispersed in each of the two periods (IP: min = 0.5 and max = 28.1; 18-19-20 average: min = 0.6 and max = 22.7). Yearly fluctuations also occured, with some of the highest scores being recorded in the 2018 season for most WS (Figure 1a).

Figure 1b shows the weight of non-biocontrol fungicides in the treatments. The average fungicide TFI value can be seen to be 8.42 at IP (biocontrol excluded), which equates to 67 % of the average total TFI over the same period (Figure 1a). A substantial inter- and intra-annual heterogeneity of TFI fungicide values can also be observed, but the mean score decreased by 25 % between IP and the last three years (Supplementary Table 2).

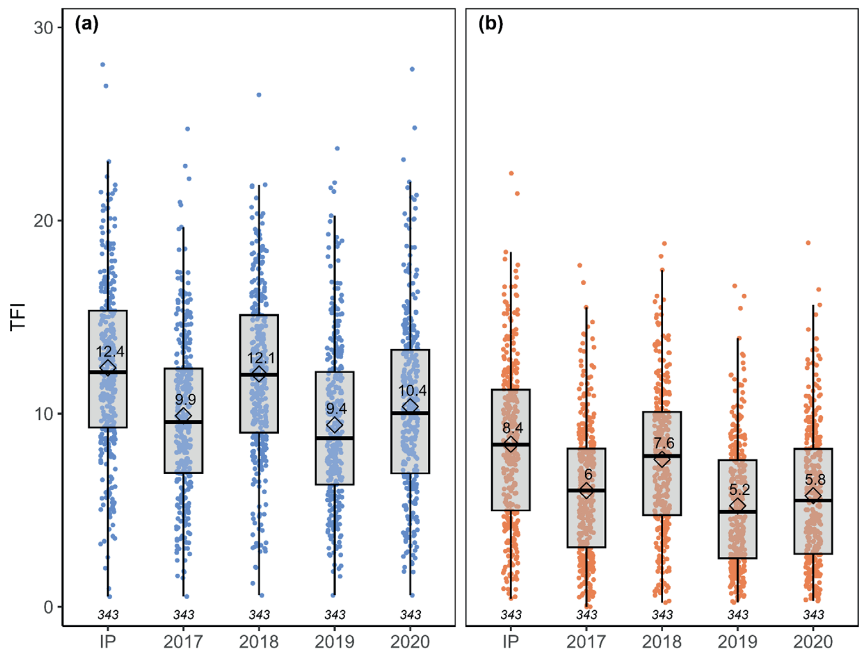

FIGURE 1. (a) Total TFI, and (b) Fungicide TFI (biocontrol excluded) values for the sampled winegrowing-systems at the Initial Point and from 2017 to 2020.

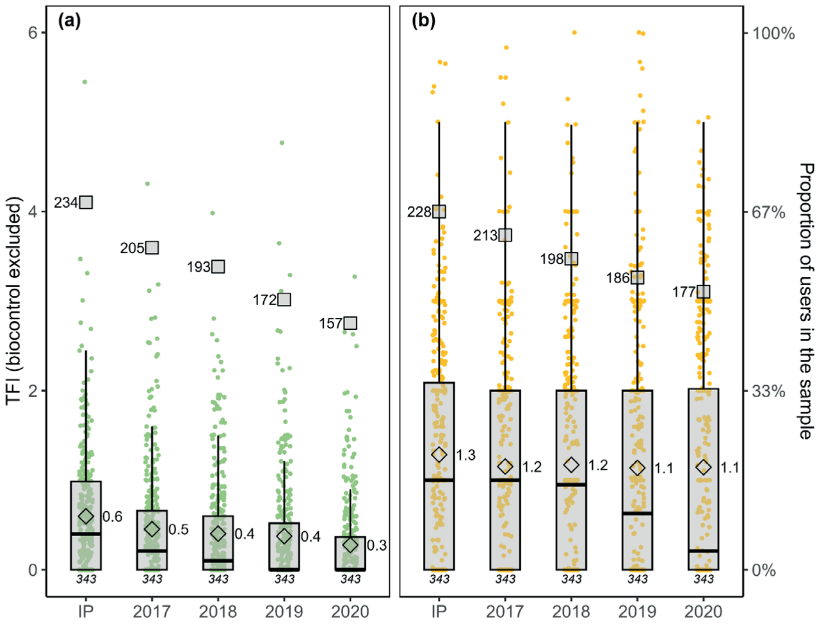

FIGURE 2. TFI values (biocontrol excluded) and number of (a) herbicide and (b) insecticide users in the sample at the Initial Points and from 2017 to 2020. The number of herbicide users is shown as an absolute value on the graph and as a proportion of the total sample (n = 343) on the right-hand axis.

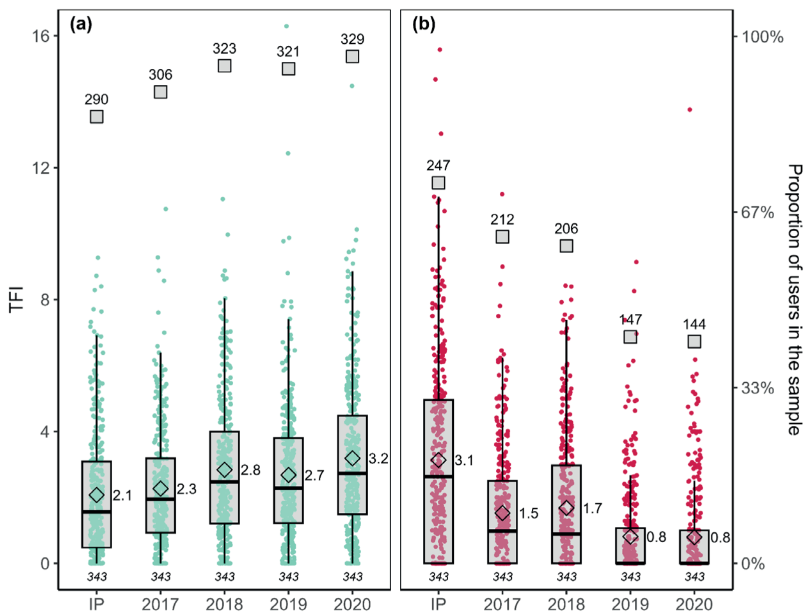

FIGURE 3. TFI values and number of users of (a) biocontrol and (b) CMR products in the sample, for initial points and from 2017 to 2020. The number of herbicide users is shown as an absolute value on the graph and as a proportion of the total sample (n = 343) on the right-hand axis.

Despite herbicide representing a much lower proportion of the treatments (3.5 %), its TFI also dropped significantly between IP and the 2018, 2019, 2020 average ($p < 0.001$). The average TFI value of the whole sample decreased by 0.25 points from one study period to the next; i.e., by 40 % (Supplementary Table 2). One-third of the systems initially using herbicides had stopped doing so by 2020 (77/234) (Figure 2a). 146 WS were using weed-killers during each studied year (Supplementary Figure 3a), yet their mean herbicide TFI still fell by 25 % between IP and 2018-2020 ($p < 0.001$).

The insecticide TFI (biocontrol excluded) decreased significantly as well, but less steeply than that of the fungicides and herbicides: -11 % on average ($p < 0.001$). In 2020, the number of systems using these products was 22 % lower than at IP (Figure 2b). Nearly two thirds of the WS that had stopped using insecticides during the study period said they carried out "vineyard inspections" to avoid having to apply unnecessary treatments (23/36). Meanwhile, the average TFI of the 135 systems that kept using insecticides did not significantly evolve between the beginning and end of the study period (Supplementary Figure 3b).

Meanwhile, the adoption of biocontrol can be seen to increase, both in terms of number of users and Treatment Frequency Index (Figure 3a). Over the study period, the average TFI of biocontrol substances rose by 0.83 points ($p < 0.001$); i.e., by about 40 % (Supplementary Table 2). They incidentally became more widespread, with 96 % of the systems applying at least one in 2020.

It thus follows that when considering the evolution of conventional products only (i.e., excluding biocontrol) a significant 25 % reduction in TFI ($p < 0.001$) can be observed. The mean value for the whole sample indeed dropped from 10.3 at IP to 7.7 from 2018 to 2020 (Supplementary Table 2).

The proportion of WS using "Carcinogenic - Mutagenic – Reprotoxic" products declined from 72 % at IP to 42 % in 2020 (Figure 3b). Despite high values still being observed in 2018, the mean treatment frequency index for these products decreased by almost a third over the course of the study period ($p < 0.001$). Likewise, for the 113 systems that used these products every year, the CMR TFI fell sharply, with a 50 % decrease in the average value ($p < 0.001$) (Supplementary Figure 3c).

All the partial TFI average values for the IP and the 2018-2019-2020 period are summarised in Supplementary Table 2.

3. Pesticide Use Intensity (PUI) and reduction trajectories:

Based on their standardised TFI values at IP (biocontrol excluded), the sampled WS were distributed as follows:

- 29 % of wine-growing systems were initially "non-efficient": standardised TFI ≥ 1 (98/343),
- 25 % were "moderately efficient" systems: 1 > standardised TFI ≥ 0.75 (86/343),
- 21 % were "efficient" systems: 0.75 > standardised TFI ≥ 0.5 (72/343),
- 25 % were "very efficient" systems: standardised TFI < 0.5 (87/343).

The average decrease in TFI that occurred between IP and 2018-2020 was found to differ depending on the initial chemical use level. Significant decreases were achieved by the initially "non-efficient", "moderately efficient" and "efficient" systems. By contrast, those who were "very efficient" when they first joined the network did not undergo a significant TFI decrease (Table 2). When comparing these reduction dynamics (Anova, $p < 0.001$), it appears that WSs with high initial pesticide use are likely to achieve a more

TABLE 2. Mean TFI values (biocontrol excluded) of the four PUI sub-samples at the start (IP) and end (18/19/20) of the study period.

Initial Pesticide - Use Intensity	Initial point	18/19/20 average	Test performed	p-value	Mean difference	Pairwise difference comparisons
Non-efficient	14.92	9.90	Student	< 0.001	-5.02	c
Moderately efficient	12.44	9.28	Student	< 0.001	-3.16	b
Efficient	8.83	7.35	Student	< 0.001	-1.49	a
Very efficient	4.20	3.99	Student	= 0.43	-0.21	a

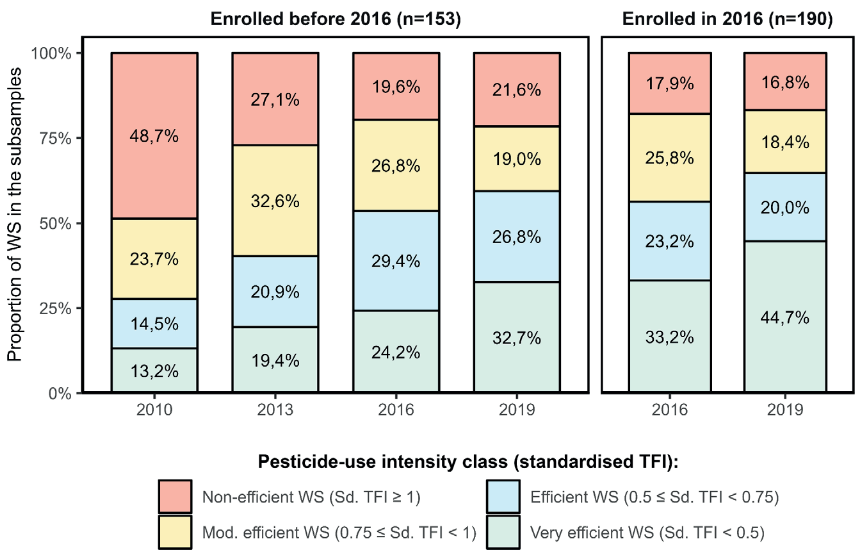

FIGURE 4. Proportions of the sample wine-growing systems in each pesticide-efficiency category for each ministerial survey. Number of WS within a category is shown as a percentage of the total number of wine-growing systems from the first enrollment period and the second one in 2016.

substantial decrease than the others. Although significant, the decreases in TFI shown by the initially "efficient" WSs are more tenuous: the distribution of their TFI differences (18/19/20 - IP) is not statistically dissimilar ($p = 0.066$) to that of the "very efficient" systems, which maintained their TFI at a low level.

Figure 4 depicts the evolution of the percentage of WS in each PUI group for each of the 2010-2013-2016-2019 growing seasons. It shows a sharp increase in "non-efficient" systems, and in turn an increase in the "very efficient" ones. From 2016 onwards, the "efficient" (blue) and "very efficient" (green) systems constitute the majority of the sample (62 % in 2019 overall). In this graph, the long-standing systems of the network are shown separately from those that joined in 2016. This helps to display the proportion of efficient systems in a more constant population, and to better describe the impact of network monitoring.

By dividing the 343 wine-growing systems among four trajectories of standardised TFI evolution (Table 1), we obtained the following distribution over the study period:

i. 7 % (26/343) of systems were "becoming inefficient" between IP and 2019 (T1).

ii. 39 % (133) were "staying efficient" (T2)

iii. 30 % (103) were "staying inefficient" (T3)

iv. 24 % (81) were "becoming efficient" (T4).

These four categories can be linked to quite distinct production methods (Figure 5). The inefficient systems (whether they become or remain so) mostly applied conventional agriculture (T1 + T3) and often relied on herbicides for weed management; however, a substantial number of them had ceased to use herbicides by 2020, but maintained a conventional production system in most cases. The WSs that stayed input-efficient (T2) were predominantly organic (65 %). In addition, nearly a third of the T2 conventional growers underwent a conversion, resulting in 100 out of 133 systems being organic in 2020. The systems that became efficient (T4) had the highest conversion rate (25 %). The remaining T4 systems were essentially conventional, of which about half were herbicide-free.

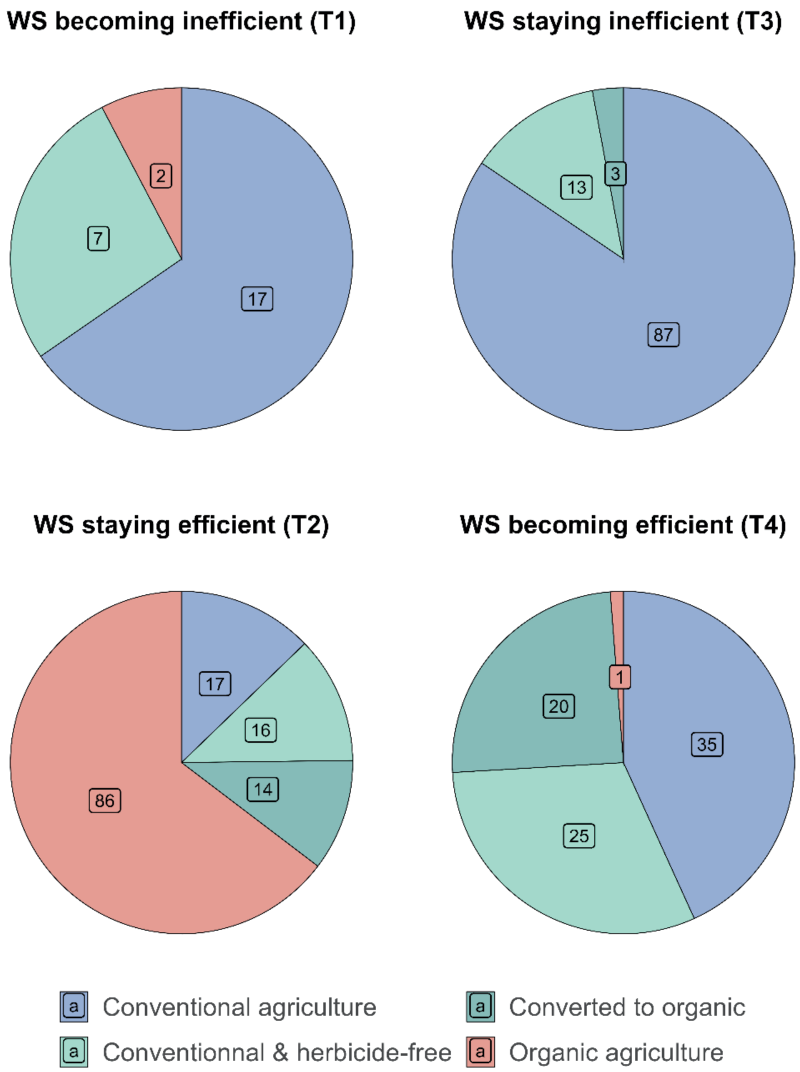

FIGURE 5. Number of WS per production method in 2020 in each of the four standardised TFI trajectories.

4. Impact of TFI trajectory on techno-economic performances

For each of the four described trajectories, the evolution of several technical and economic performances was analysed. Variations between IP and 18/19/20 mean values of 8 indicators were plotted as radars in Figure 6. This analysis was also carried out on all 16 temporal interactions between the four PUI classes; the results are not discussed in this paper but can be found in Supplementary Table 3.

Unsurprisingly, the total TFI of the systems that became inefficient rose (+25 %, $p < 0.001$), and it decreased for those that became efficient (-30 %, $p < 0.001$). However, for the WSs that stayed inefficient and efficient (T3 and T2) the average score dropped (-11 % ($p < 0.001$) and -12 % ($p < 0.001$) respectively). The same trends were also observed when the biocontrol products were omitted from the calculation: the average TFI values only increased for the T1 subset (+19 %, $p < 0.001$), and fell for the remaining three. Both herbicide and CMR TFI significantly declined across all four trajectories, but more so for T2 and T4, with an average decrease of over 60 %.

Regarding the production costs, phytosanitary expenses evolved with TFI. They on average increased in the systems that had become inefficient (+28 %, $p < 0.01$) and decreased in the others. Substantial savings were thus made by wine-growing systems that had become efficient (T4), with this cost item decreasing by an average of 40 % ($p < 0.001$). The differences in average mechanisation costs were less marked, decreasing by 6 % in categories T1 and T3 (non-significant), and increasing by 5 % (ns) and 20 % (ns) in T2 and T4 respectively. Although not significant, the latter increase is still noteworthy, as it is mainly linked to a greater dispersion of values over the 2018-2019-2020 period.

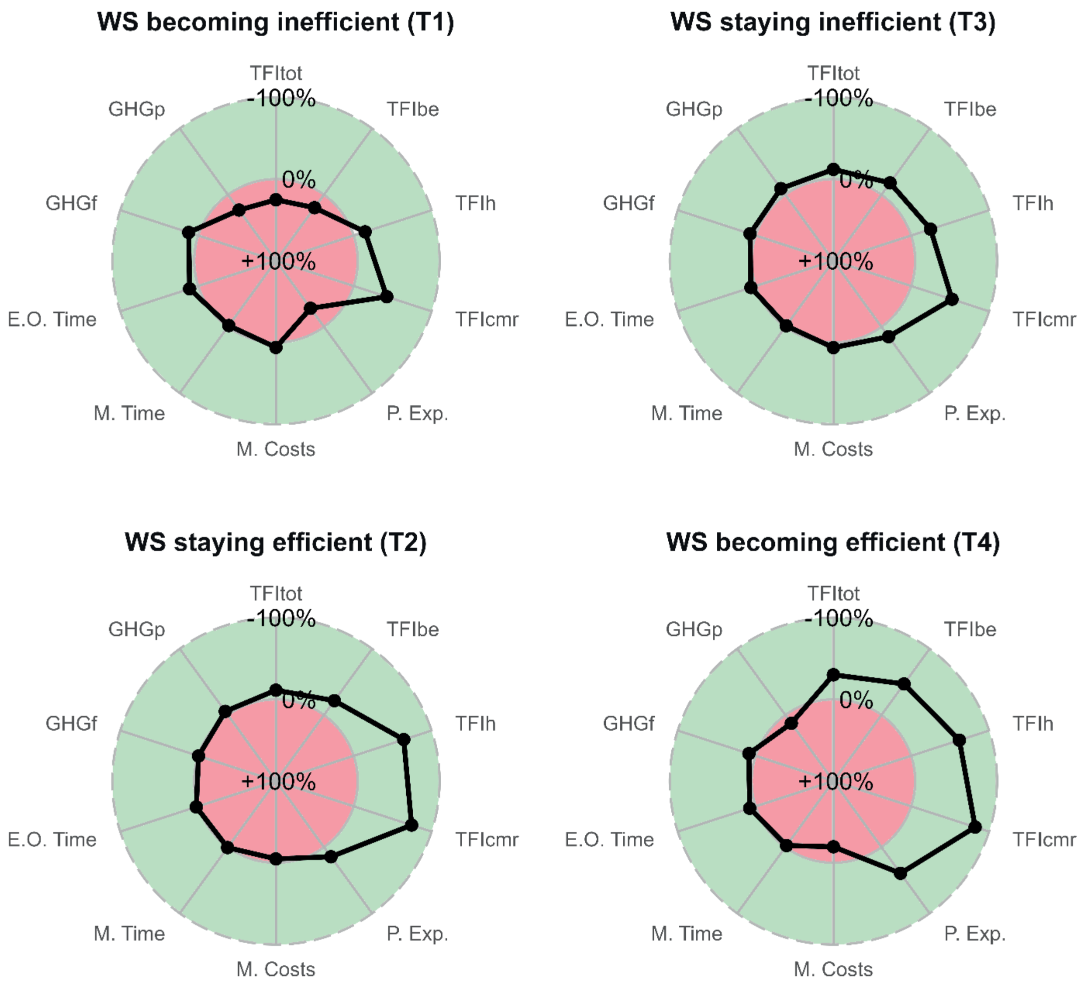

FIGURE 6. Evolution of performance indicators in the 4 standardised TFI trajectories. Changes in each indicator are expressed as the variation rate (%) between the average values for the 18-19-20 period and the IP.

For a considered indicator, the further a point from the radar's centre, the greater the decrease in the sample's average value over the time frame. Displayed indicators are (clockwise): Total TFI (TFItot), Biocontrol-excluded TFI (TFIbe), herbicide TFI (TFIh), CMR TFI (TFIcmr), Phytosanitary expenses (P. Exp.), Mechanisation costs (M. Costs), Manual labour time (M.Time), Equipment operating time (E.O. Time), Fuel-related GHG emissions (GHGf) and Input-related GHG emissions (GHGp).

TABLE 3. Disease pressure scale for downy and powdery mildew, and associated number of respondent WSs from 2017 to 2020.

Disease	Pressure	2017	2018	2019	2020
Downy mildew *(Plasmopara viticola)*	None (absence)	11 %	4 %	24 %	23 %
	Low (presence but no impact)	**60 %**	14 %	**57 %**	28 %
	Moderate (yield possibly affected)	26 %	24 %	17 %	25 %
	High (impact on yield & margins)	3 %	**58 %**	2 %	24 %
Powdery mildew *(Erysiphe necator)*	None (absence)	29 %	37 %	23 %	17 %
	Low (presence but no impact)	49 %	50 %	46 %	36 %
	Moderate (yield possibly affected)	17 %	8 %	25 %	**33 %**
	High (impact on yield & margins)	5 %	5 %	6 %	14 %

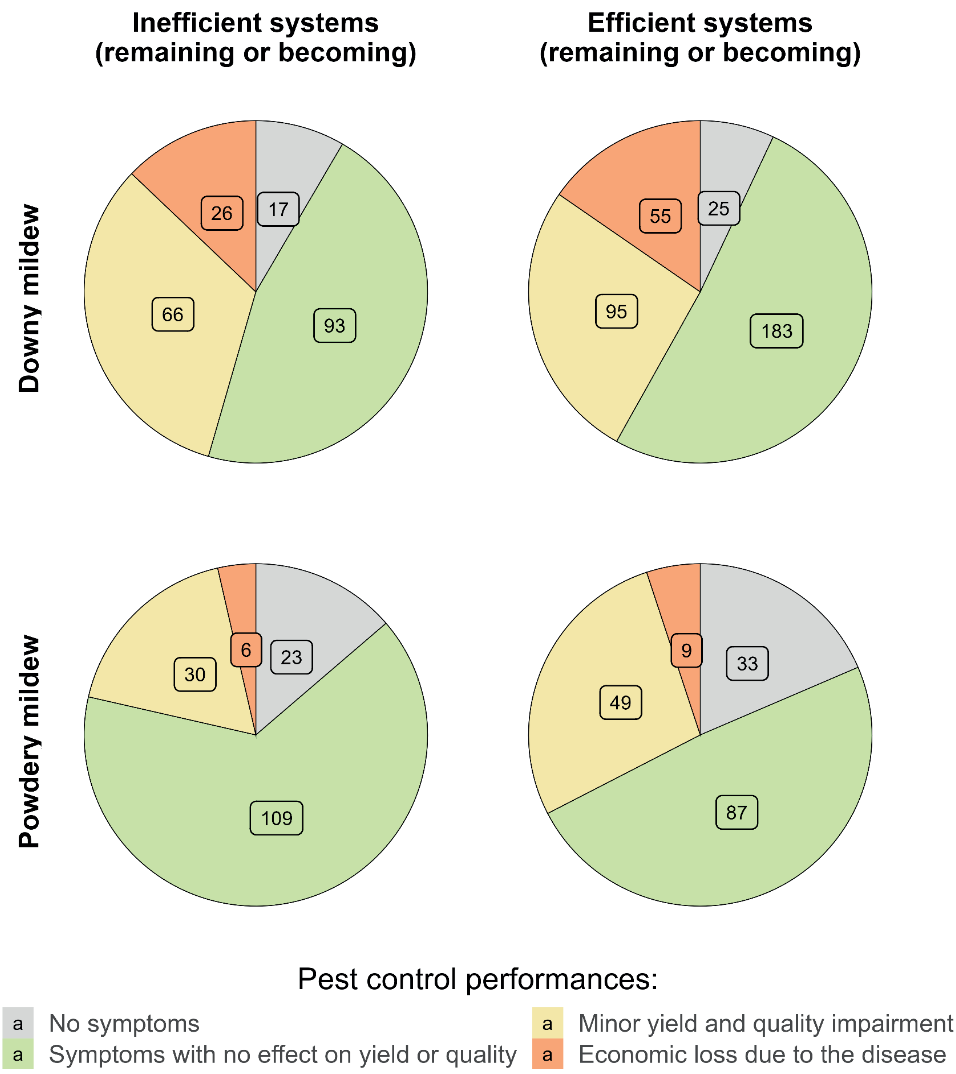

FIGURE 7. Distribution of efficient and inefficient systems over the four control levels of fungal diseases for the years with medium or high pest pressure over the 2017-2020 period.

The two upper pie charts depict protection performances against downy mildew (*Plasmopara viticola*) under substantial pressure conditions and the two lower ones depict powdery mildew control (*Erysiphe necator*).

Average manual labour times were more or less steady, with values increasing very slightly in each trajectory, though never significantly (between +0.5 and +3 %). Equipment operating time only showed significant evolution for the T3 (-6 %, $p < 0.05$) and T4 (-7 %, $p < 0.05$) systems.

Fuel-related GHG emission levels stayed roughly the same. However, the systems that stayed inefficient (T3) noticeably reduced their levels by 7 % on average ($p < 0.05$). Input-related emissions increased by 23 % ($p < 0.05$) for the systems becoming inefficient, whose average TFI rose. The input-related emission levels of the systems that stayed inefficient (T3) and efficient (T2) also seemed to evolve alongside the TFI, with average level reductions of 9 % and 5 % respectively (ns). Lastly, despite considerable TFI reduction being achieved by WS T4, no significant evolution of their input-related emissions was observed, but on average they nonetheless rose (+13 %, ns).

5. Fungal diseases pressure and pest control performances

For the 2017-2020 seasons, yearly disease pressure data were analysed across 308 to 328 systems for the two major vineyard diseases (Table 3). In the whole of this sample, high annual variability in the perceived risk can be observed. For instance, far more growers reported downy mildew pressure to be high in 2018 than in 2017 and 2019, which is in line with the characteristics of each year.

Based on this information, a sub-sample was selected to investigate the systems' protection performances against these pathogens. For both diseases, only the pairs system * year with high or moderate pressure were considered to analyse disease protection performances in that order.

Thus, in order to perform a X^2 analysis with sufficient sample size, vineyard disease control performance data of efficient (T2 + T4) and inefficient (T1 + T3) systems were compared (Figure 7). For downy mildew, the pie charts show a similar distribution, which is uncorrelated with pesticide efficiency ($p > 0.05$). Both charts show that around 55 % of mildew pressure situations were handled without any impact on the yield. Meanwhile, for powdery mildew, the differences in distribution are more marked ($p < 0.05$), with mildly detrimental symptoms occurring more often in the efficient systems. Harvest losses caused by this disease are, however, scarcer than those caused by downy mildew, occuring in 23 and 37% of the pressure situations of the inefficient and efficient systems respectively.

DISCUSSION

Our results show that the DEPHY vineyards managed to substantially decrease their pesticide use. Biocontrol products aside, a significant 24 % decrease in TFI was found between the time the members joined the network and the 2018 to 2020 years. Similar results were obtained for the subset of systems that joined the network in 2016 (-23 %) and for those formerly involved (-28 %).

However, divergent trends were observed, which depended on pesticide-use intensity before joining the network. The sharpest reductions were recorded for systems whose initial usage rates were intense: on average, the WSs that scored a higher TFI than their regional reference had since undergone a considerable 34 % reduction. By contrast, the mean TFI value of the systems whose initial pesticide reliance was low (TFI < 0.5 * regional reference) did not further decrease.

These decreases in TFI applied to every chemical product type, excluding biocontrol; i.e., fungicides, insecticides and herbicides. Mainly used to protect vineyards against downy (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*) (Delière *et al.*, 2015), fungicides showed the biggest reduction, accounting for 84.6 % of the overall decrease in TFI. With regards to insecticides, a much lower reduction in TFI was found, mostly due to treatments against the leafhopper vector of "*flavescence dorée*" (*Scaphoideus titanus*) being mandatory; (Ay and Gozlan, 2020). In 2018, the compulsory control area covered 75 % of French vineyards (Barthelet *et al.*, 2020), which were required to apply 0 to 3 anti-vector treatments. In the analysed dataset, there were only three wine-growing areas to which these measures did not apply: Alsace-Lorraine, Champagne and Val-de-Loire. These treatments can therefore locally represent a large and irreducible share of the insecticide TFI, if not all of it. Other arthropod pests (e.g., grapevine moth and leafhoppers) are often controlled using several alternative methods, namely mating disruption pheromone dispensers (Lucchi *et al.*, 2018), bio-insecticides (Ruiz de Escudero *et al.*, 2007) or preventive barrier agents (Tacoli *et al.*, 2017). The overall herbicide TFI was associated with a dual trend of an increasing number of systems that stopped using herbicides altogether and a reduced usage by those still relying on them, with a decrease in the area where they were applied. This decrease can be attributed to the scheduled or already implemented withdrawal of a large number of compounds from the market, as well as to the availability of effective non-chemical solutions, such as tillage and growing cover-crops (Merot *et al.*, 2019; Fouillet *et al.*, 2022; Fouillet *et al.*, 2023). Soil management based on the latter techniques has proven to bring multiple benefits for biological activity and biodiversity preservation (Giffard *et al.*, 2022), as well as grape quality (Fleishman *et al.*, 2023; Wheeler and Pickering, 2003).

The TFI that we used to measure dependency on Plant Protection Products (PPP) is an overall pesticide consumption indicator that does not take into account the various impacts of specific products on health and the environment. Nevertheless, beyond the described decreases, our results also revealed two major patterns: an increased use of products with low adverse impacts on health or the environment (see biocontrol list), alongside a reduction in the use of CMR-classified products.

Biocontrol products are most likely used as substitutes for some conventional inputs, as their utilisation was seen to increase while the TFIs of the conventional products decreased. Most of these biocontrol products are sulphur-based fungicides, which are used to combat powdery mildew. Also registered as "biocontrol" but not fulfilling organic specifications, potassium and disodium phosphonates are also frequently applied against downy mildew. These inorganic substances have been used for a long time in viticulture, and winegrowers are familiar with their effects and application requirements, hence they are easily promoted by salespeople and advisors (Villemaine *et al.*, 2021). The health hazards of plant protection products for exposed individuals have been documented by diverse sources, in particular with regard to various cancers and neurodegenerative diseases (Talibov *et al.*, 2022; Pouchieu *et al.*, 2018; Renier *et al.*, 2022). In our results, the use of CMR-classified products, which raise the greatest concerns in this respect, is subject to a substantial drop. As with herbicides, many WS stopped using them during the course of the study period, while others reduced application rates. These changes occurred across all TFI trajectories, including systems that remained inefficient (-52 % CMR TFI) and became inefficient (-42 %). These changes seem to be occurring outside of the network too, since a similar trend in national PPP sales has been reported over the last decade (Parisse, 2023). As well as the increasing awareness of winegrowers about the danger of such products, this trend may also be being driven by regulatory changes; the established or planned suspension of several molecules during the study period (e.g., mancozeb, myclobutanil and oryzalin) might indeed have impacted the growers' CMR use. Environmental certifications may also have contributed to this downturn, with the recent and rapidly spreading "High Environmental Value" government label (HVE) prohibiting the use of CMR-classified products (Ministère de l'Agriculture et de la Souveraineté Alimentaire, 2023).

In the literature, pesticide reduction trajectories have been suggested to be heterogeneous and gradual, rather than linear. They consist of successive agronomic-coherence phases, during which new techniques are introduced to cropping systems (Chantre *et al.*, 2015). The intensity of a reduction trajectory is the result of different strategies, and is determined by the potential for reduction and previous achievements (Fouillet *et al.*, 2023). In the case of viticulture, TFI reductions are strongly influenced by spatial and temporal effects, in particular structural differences between wine-growing areas and variations in weather and fungal pressure (Fouillet *et al.*, 2022). In our results, the higher TFI values in the 2018 season coincide with a stronger downy mildew pressure on a national scale. As well as TFI, these fluctuations also affect the environmental performances of the wine-growing system, especially because of fuel consumption (Beauchet *et al.*, 2019). In an attempt to overcome this variability, we made some methodological adjustments to our results: the changes over time were quantified by comparing the three-year averages, the wine-growing systems were classified according to standardised TFI to account for their agro-climatic context, and performance evolutions were expressed as variation rates instead of absolute values. However, the adjusted data only provide a limited description of pesticide consumption trajectories and associated consequences. Our results show only two distinct time frames and they omit the intermediate steps of the longstanding network WSs. Additionally, their interpretation may have been marginally compromised by threshold effects.

When analysing this dataset, it did not seem appropriate to explore links between lever implementation and TFI evolutions. Data on applied levers only cover the 2017-2020 period and does not offer comparison with practices predating the network admission. Furthermore, information about the implementation of alternative practices was reported directly by the winegrowers using a non-exhaustive drop down menu and comprising an inconsistant number of respondents. It was therefore difficult to accurately determine whether certain practices were mobilised or not in a given wine-growing system, and the lack of contextual information on the actual deployment conditions meant that it was not possible to reliably compare vineyard performances. Further research using more indepth analyses would be required to exploit these data on such a large scale. We chose to give an overview of the techniques used in the network, which proved useful for interpreting some of our findings.

Most of the mentioned levers are part of efficiency strategies, aiming to optimise pesticide application. For instance, the network's winegrowers apply decision support systems that are widely available in Europe (Bregaglio *et al.*, 2022) in order to determine whether treatment is required and the dose to be used. Confined spraying is also carried out to minimise chemical load (Pergher *et al.*, 2013) and environmental drift. These techniques are generally time-efficient and do not always entail high financial costs, making them easier to adopt. The improved efficiency of fungicide use has in fact been found to be the main driver of TFI reductions upon network entry (Fouillet *et al.*, 2022). Vegetation management practices (e.g., disbudding and leaf thinning) are also applied to favour air circulation in the fruit-bearing zone, thus contributing to the prevention of epidemics (Austin and Wilcox, 2011) and increasing product penetration. These practices were presumably widely adopted by the WS, even before they joined the network, as they also contribute to grape quality. As a result, the averaged workload and mechanisation costs showed little change, despite the substantial reductions in TFI. TFI trajectories therefore mainly have impact on performances directly linked to pesticide consumption, such as phytosanitary expenses. Input-related greenhouse gas emissions also seem to decrease alongside TFI. Such emissions are directly derived from the quantity of active substance applied per treatment, which can vary a lot across PPPs for an identical TFI score. For instance, inorganic fungicides, such as sulphur and copper, tend to generate more indirect GHG emissions (Cech *et al.*, 2022) as their maximal approved doses are higher. Copper and sulphur are predominant in a number of low-TFI strategies, especially organic ones, which may account for the increased indirect emissions in T4 systems.

Even though the share of herbicides in treatments is very much minor (3.5 % of total TFI), levers designed to replace them are mostly mechanical (tillage, mowing, cover crops), and can therefore lead to drastic changes to farm work patterns (Jacquet *et al.*, 2021; Merot *et al.*, 2019). Once again, a greater variability in the performance trends (mechanisation expenses, equipment operating time, fuel-related GHG emissions) of the T4 WSs was observed, since these more WSs stopped using herbicides than the other trajectories.

Conversion to organic farming appeared to be a major cause for pesticide use reduction. In our analysis, 25 % of WS that became pesticide-efficient had carried out a conversion during the study period. Due to specifications prohibiting all synthetic inputs, organic conversion leads to the exclusion of all herbicides and CMR products, which are considered the most harmful to health and environment (European Parliament, 2008), and to significant decreases in TFI. Making this transition is nonetheless demanding, as it inevitably affects both the farm's production factors (Merot *et al.*, 2019) and the complexity of its cropping systems (Merot and Wery, 2017). While organic practices have a positive influence on agroecosystem biodiversity and production quality (Döring *et al.*, 2019), they do not improve the overall multi-functionality of the farms (Ostandie *et al.*, 2022). In addition, this production approach is still dependant on specific PPPs, such as copper to control downy mildew. Given the environmental concerns associated with copper (Lamichhane *et al.*, 2018), reducing or eliminating this mineral input is a major challenge for organic winegrowers. Extensive research is being carried out into potential alternatives (Dagostin *et al.*, 2011), but few solutions are currently available.

Having set out to achieve a 50 % reduction in pesticide use by 2025, the Ecophyto plan has often been criticised for failing to deliver results (Guichard *et al.*, 2017). However, the results of efforts underway in the DEPHY network show that a decrease is achievable in viticulture. After a few years of monitoring, most of the studied systems ranked among the most efficient farms in their wine-growing area: half (168) have exceeded the Ecophyto plan's 2020 intermediate reduction target (-25 %), and over a third (64) has already undergone a reduction that meets the 2025 goal (-50 %). Credit for these achievements should partly be given to the actual network operation; firstly, because its winegrowers are committed to using less plant protection products, and secondly, because they receive both collective and individual support through peer experience sharing. Such schemes are well matched with farmers' expectations, as they are more inclined to change their practices when encouraged by successful examples and collective dynamics (Bjørnåvold *et al.*, 2022).

To date, whether in viticulture or other sectors, the DEPHY network's TFI reductions have not been reflected in the national PPP sales trends (Parisse, 2023). Scaling up these results hence remains a key challenge for the ECOPHYTO plan, which raises questions about the effectiveness of other policies for curbing pesticide use. Lee *et al.* (2019) have identified different policy instruments that tend to produce effective pesticide reduction when applied in mix; these include diversified regulatory tools involving decentralised measures and a plurality of involved stakeholders, and which are designed to encourage farmer engagement. The strengthening of national legislation, underpinned by experiences from the network and other successful initiatives, could therefore be an initial step towards better skill transfer. At European level, the adoption of the "Sustainable Use of Pesticides Regulation" proposal indicates further tightening of the current directive, and standardisation across all Member States (European commission, 2022). Through their diversity and combined activities, the French territorial food governance organisations (e.g., institutes, designations, trade unions and consular chambers) provide a framework that is steering a transition towards environmental sustainability (Ruggieri *et al.*, 2023). These stakeholders could mobilise the DEPHY network's outputs and apply them as tools for generating change in farm practices by transferring both accumulated reference data and skills. With the contributon of committed farmers and support from a wide range of local stakeholders, the DEPHY network could thus pave the way to effectively making the transition.

Despite the network's results providing good grounds for initiating a far-reaching reduction in pesticides, they also highlight several limitations; for example, we observed that farms with low initial input rates experienced difficulties in further reducing their TFIs. Whether within or beyond the network, the measures taken do not appear to be sufficient enough to achieve the most ambitious objectives, like the European "green deal" (Rossi, 2020), or to eventually phase out all pesticides; this would require more emphasis on redesigning cropping systems (Hill and MacRae, 1996). For instance, crop diversification (e.g., by applying viti-forestry, inter-row cultivation and viti-pastoralism), alternative pruning and varietal resistance are rarely implemented by winegrowers, for such practices lead to radical transformation of the production system. Very low-input systems designed around them do, however, exist, but these remain experimental or marginal (Molitor *et al.*, 2022; Thiollet-Scholtus *et al.*, 2021), and their adoption is hampered by persistent socio-technical barriers, such as regulations, equipment, production costs and designation specifications (Montaigne *et al.*, 2021). Lastly, such a transition should also involve the food value chains (e.g., agricultural suppliers, breeders, processors and distributors), whose capacity for innovation and market influence are key drivers of change (Meynard *et al.*, 2017). With more commitment from all value chain actors, additional mitigation levers could be deployed on a landscape scale (Jacquet *et al.*, 2022); for example, area-wide mating disruption, biological regulations or crop mix diversity.

CONCLUSION

Our analysis of the DEPHY network data revealed that winegrowers have successfully undergone a transformation in terms of their use of plant protection products. We described different trajectories, most of which shared a significant TFI decrease paired with a shift to less harmful products. Few impacts on technical and economic parameters were observed overall, as most introduced practices do not seem to radically revamp the farming systems. Some technical parameters were however affected (e.g. mechanisation costs), when more far-reaching changes occurred (e.g., conversion to organic), which highlights the need for further research, since redesigning cropping systems appears to be the next step for further reducing pesticide dependency. Over the few years of study, the efforts of the DEPHY network winegrowers resulted in TFI reductions that matched public policy objectives and were financially and technically sustainable for the winegrowers. The knowledge gained from these projects now needs to be effectively relayed, so that these results may be applied on a wider scale.

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