European Journal of Agronomy 136 (2022) 126503

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Reducing pesticide use in vineyards. Evidence from the analysis of the French DEPHY network

Esther Fouillet[a,*], Laurent Delière[b], Nicolas Chartier[c], Nicolas Munier-Jolain[d], Sébastien Cortel[e], Bruno Rapidel[a,f], Anne Merot[a]

[a] ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, Montpellier, France
[b] INRAE, Bordeaux Sciences Agro, SAVE UE Vigne Bordeaux ISVV, F-3882 Villenave d'Ornon, France
[c] Institut de l'Elevage-Agrapole, 23 rue Baldassini, F-69364 Lyon Cedex 7, France
[d] Agroécologie, AgroSup Dijon, INRAE, Univ. Bourgogne, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France
[e] Chambre d'Agriculture Savoie-Mont-Blanc, 74000 Annecy, France
[f] CIRAD, UMR ABSys, F-34398 Montpellier, France

ARTICLE INFO

Keywords:
Pesticide reduction
Vineyard
TFI
Treatment frequency
Dose reduction
Agroecological transition
Substitution

ABSTRACT

High quantities of pesticides are applied on vineyards. For example, the average treatment frequency index (TFI) for French vineyards was 13.5 in 2016, whereas the average TFI for wheat (a major annual crop in France) was 4.9 in 2017. Reducing pesticide use is a key issue to improve viticulture sustainability. The aims of this study were (i) to analyse the evolution of pesticide use in vineyard farms voluntarily participating in a pesticide reduction programme, and (ii) to understand the options winegrowers used to reduce their pesticide use. We analysed data from the DEPHY farm network, including 244 cropping systems followed over 10 years and spread across 12 winegrowing regions. We used the TFI to assess the intensity of pesticide use. Mean pesticide use within the network decreased over the 10-year period and mostly concerned fungicide use. By analysing several indicators such as the number of treatments and the mean TFI per fungicide treatment, we were able to identify some of the management options mobilised for achieving this pesticide reduction. The use of biocontrol products and the reduction of sprayed doses were often associated with a low TFI. The analysis of yield evolution showed a significant mean reduction, although it was smaller than the TFI reduction. This raised the question of the impact of pesticide reduction on productivity. Further trade-off analyses are required in the future.

1. Introduction

The negative impact of pesticides on the environment and on human health is widely recognised today (Aubertot et al., 2005; Mailly et al., 2017; Momas et al., 2004; Wilson and Tisdell, 2001). Consequently, reducing pesticide use is a major issue to enhance agriculture sustainability. Debates about pesticide use also extend to the wine sector, as it is one of the most intensive agricultural sectors in terms of pesticide use (Urruty et al., 2016). The treatment frequency index (TFI, Pingault et al., 2008) is an indicator of pesticide use intensity, taking into account the number of treatments, the dose applied relative to a standard reference dose, and the proportion of the treated vineyard area. In 2016, the average TFI for French vineyards was 13.5, with an average of 20 treatments per year (Simonovici, 2019) whereas the average TFI for wheat (a major annual crop in France) was 4.9 in 2017 (Agreste, 2020).

Pesticide use in vineyard systems has many negative environmental impacts. Harmful consequences for soil biodiversity (Coll et al., 2011; Schreck et al., 2012) and detrimental effects on deep and surface water (Bony et al., 2008) are reported. Pesticides can also affect the physiological processes of grapevine, such as limiting photosynthesis (Petit et al., 2008). Herbicide use can lead to soil erosion and a reduction in biodiversity (Cerdà et al., 2021; Keesstra et al., 2019).

Moreover, winegrowers are directly exposed to pesticides during pesticide preparation and spraying (Tsakirakis et al., 2014), while pesticide drift towards housing near vineyards is often a subject of neighbourhood conflicts, because the potential impacts of pesticides on human health is currently a major concern in winegrowing regions (Baldi et al., 2001, 2012; Raherison et al., 2019; Thierry and Yengue, 2018). Because of water fluxes, pesticide residues can affect the quality of water far away from the fields where pesticides were applied (Rodrigo

* Corresponding author.
E-mail address: esther.fouillet@inrae.fr (E. Fouillet).

https://doi.org/10.1016/j.eja.2022.126503
Received 5 May 2021; Received in revised form 16 February 2022; Accepted 21 March 2022
Available online 30 March 2022

Comino et al., 2018).

The vineyard system faces strong pest and disease pressures. Downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), botrytis (*Botrytis cinerea*) and grape moth (*Eupoecilia ambiguella*) can cause major damage impacting the qualitative and quantitative characteristics of grapevine production (Fermaud et al., 2016). Among the pesticides used in France, 80% are fungicides, 15% insecticides and 5% herbicides (Mailly et al., 2017; Agreste, 2016). Grape moths (*Lobesia botrana*) and the leafhopper vector of Flavescence dorée (*Scaphoideus titanus*) are sprayed with insecticides. On average, 1–4 insecticides per year are sprayed (Pertot et al., 2017), representing around 15% of the total TFI. Treatments against the leafhopper vector of Flavescence Dorée (1–3 treatments depending on the winegrowing region) have been mandatory in France since 1994, which means that significantly reducing the insecticide TFI against the leafhopper vector will not be possible. Meanwhile, chemical treatments against grape moths can be more easily replaced with biocontrol (e.g. mating disruption).

If not controlled, downy mildew and powdery mildew can cause yield losses of up to 100% during a high disease pressure year (Fermaud et al., 2016). These diseases can also affect the photosynthetic rate and grape maturation (Jermini et al., 2010), and lead to off flavours and organoleptic defects in wines (Pons et al., 2018). The wrong choice of lever or poor management during the technical change can pose substantial risks (Merot and Smits, 2020).

Technical levers can be mobilised to reduce pesticide use in vineyards. The ESR framework (Efficiency, Substitution, Redesign, see Hill and MacRae, 1996; Merot et al., 2019) can also be used to classify the changes implemented to reduce pesticide use according to the intensity of change (Wezel et al., 2014). Efficiency (E) corresponds to the reduction of inputs by making individual treatments more efficient, often resulting in a reduction in the amount of pesticide sprayed per unit area. Hill and MacRae (1996) consider efficiency (E) as the first step in a change process. Substitution (S) corresponds to the replacement of chemical inputs either by a non-chemical pest control method or by a chemical treatment with a lower environmental impact (in France, this can be a product from the official list of so-called biocontrol products, see below). Substitution is the second level in term of intensity of change after Efficiency and before Redesign (R). Redesign (R) corresponds to comprehensive changes made to the whole cropping system, most often combining several non-chemical pest management measures. Redesign impacts the whole cropping system and the use of production factors.

To reduce the use of fungicides after vineyards are planted, several levers can be activated. First, treatments can be optimised by adapting the dose and frequency of application (Efficiency) with the help of plant health reports or decision support systems. Most decision support systems rely on epidemiological models, mainly based on climate data. By integrating weather forecasts and epidemiological data, these models calculate the current or forecasted level of risk (Bleyer et al., 2011; Raynal et al., 2010; Viret et al., 2011). These models also include the effects of disease management strategies and are therefore used to establish recommendations for growers. Some authors have developed decision rules to help growers determine the start of spraying and adapt the maximal time lag after the application (Caffi et al., 2012; Carisse et al., 2009). Other decision support systems aim to integrate different disease risk indicators, such as phenological stage, rainfall, shoot growth, disease or outputs from a risk model (Davy et al., 2020; Delière et al., 2015; Kuflik et al., 2009). While other aims to adapt the amount of fungicide used to the canopy characteristics of the canopy and the phenological stage (Gil et al., 2011; Siegfried et al., 2007). Thiollet-Scholtus et al. (2019) and Deliere et al. (2013) designed and evaluated low-input vineyards that were mostly based on the use of decision support systems to achieve a reduction in both doses and the number of treatments. Pesticide use was reduced by 30–50% in these systems. Several studies have assessed the potential of TFI reduction while postponing the first fungicide treatment. The date of the first treatment against downy mildew will impact the number of treatments during the growing season (Chen et al., 2019). Delaying the first treatment against downy mildew could decrease the total TFI by up to 25% (Chen et al., 2020). A study by Mailly et al. (2017) also showed that the number of fungicide applications was reduced by half in winegrowing region when the first fungicide treatment was applied after 15 May. The date of the first treatment is a major lever to significantly decrease pesticide use in vineyards (Chen et al., 2020).

Another lever is the optimisation of spraying (Efficiency and Substitution). Spraying techniques are a key factor when it comes to environmental and human health risks. Pressure, air blast spraying and confined spraying can be used to prevent pesticides drifting into the atmosphere (Naud et al., 2018; Sinfort and Vallet, 2003). For example, the use of a side-by-side sprayer resulted in a 30% dose reduction while confined spraying cut the amount of product used by 50% (Delpuech and Carra, 2016). Winegrowers can also use recovery panels or side-by-side product applications for more efficient spraying. The optimisation of treatments and the postponement of the first fungicide treatment also impact operator health (Chen et al., 2020).

In addition, synthetic products are increasingly being replaced with biocontrol products (Substitution). In France, a list of authorised biocontrol plant protection products is updated annually (Ministère de l'Agriculture et de l'Alimentation, 2020). Biocontrol methods include mating disruption to disrupt reproduction of a target insect and the use of sulphur, natural defence stimulators, or *Bacillus thuringiensis*-based insecticides (Wezel et al., 2014). Most of these solutions are only partially effective; this means pest and disease pressure is reduced, but pests are not fully eradicated (Lamichhane et al., 2017).

Cropping system redesign entails more drastic changes in vineyards. For example, growers can plant grape varieties that are resistant or tolerant to downy and powdery mildew (Pertot et al., 2017). Moreover, some preventive practices such as the use of elicitors of plant defence mechanisms or thinning are also often mentioned to limit the development of cryptogrammic diseases by modifying the microclimate around the clusters (Valdés-Gómez et al., 2008; Pertot et al., 2017; Aveline et al., 2009). By studying trajectories of conversion to organic agriculture, Merot et al. (2020) showed redesign mostly contributed to pesticide reduction through the stop of herbicide and the change in the disbudding strategy, with a strong work reorganisation. Concerning fungicides, few practices associated with redesign exist except for elicitors or resistant grape varieties. Farmers are adapting their systems to changing conditions (pest pressure and climate) through innovation (Verret et al., 2020).

Herbicides account for a minor share of the total TFI but they have a major impact on the environment, and especially water quality (Louchart et al., 2001). Herbicides are used to control weed pressure, from sown or natural weeds. Weeds can compete with grapevines for water and mineral resources (Celette and Gary, 2013; Celette et al., 2009), which can result in lower yields. There is only one biocontrol product available to destroy plant cover – pelargonic acid, a contact herbicide – but it shows limited effectiveness (Cordeau et al., 2016). The most common alternative to herbicide use consists in weed management and cover cropping via tillage, mowing or rolling (Garcia et al., 2018). However, these practices involve a higher risk of soil compaction (Polge de Combret-Champart et al., 2013), nutrient competition (Celette and Gary, 2013) and an increase in costs and working time (Jacquet et al., 2019). Intercropping with a plant cover between rows or over the whole plot (including on-rows) is a growing practice within vineyards (Simonovici, 2019). Indeed, the use of herbicides in the inter-row has been largely reduced since 2000. Moreover, disparities are observed between regions in relation to pedoclimatic conditions (Mailly et al., 2017). Weed and disease pressures are mainly influenced by meteorological factors such as rainfall, air humidity and temperature. For an even more comprehensive system redesign, agroforestry or the use of animals to manage weeds in the vineyard are possible options, although these have obvious impacts at the farm level (Niles et al., 2018; Zhu et al., 2020). However, references and knowledge on these levers are lacking.

The abovementioned pest control methods can be combined to varying degrees and depending on the desired level of in-depth change during the transition towards more sustainable systems. Minor changes are related either to technical adaptations to enhance treatment efficiency and reduce doses, or to treatment substitutions using a given alternative control method. Major changes requiring a full farm-level redesign (R) may have more profound impacts on the cropping system. The transition towards more sustainable systems can be challenging for winegrowers because changes in practices are often complex to implement (Merot et al., 2019). Minor changes are more easily managed. The risk of yield losses is also limited, whereas more profound changes might present higher risks of yield losses, as in the case of conversion to organic farming (Deffontaines et al., 2020; Merot and Smits, 2020). Major system redesign that aims to reduce reliance on pesticides could also have consequences on workload and work organisation (Merot and Wery, 2017). Indeed, some practices increase working time (Merot et al., 2020) and mechanisation costs, which may or may not be offset by lower pesticide costs (Merot et al., 2019). Impacts of major changes on farm functioning and profitability may also be substantial when redesign involves combinations of levers rather than an isolated one (e.g. decision support systems at field and farm scale, combined with cover cropping and a resistant grape variety, see for example Métral et al., 2018; Delière et al., 2018; Thiollet-Scholtus et al., 2021).

In recent years, public policies have been created to support the transition towards low pesticide inputs. In France, the central government created the ECOPHYTO national action plan in 2008, with the objective of reducing pesticide use by half by 2025 (Barzman and Dachbrodt-Saaydeh, 2011). A network of demonstration farms, called the DEPHY farm network, was created in 2010 as a major initiative of this national action plan to promote and assess the implementation of practices to reduce the use of plant protection products. Today, this network provides a unique long-term perspective on the evolution of quite a large number of farms undertaking a transition process.

Within the DEPHY network, across all agricultural sectors, different types of levers are used in the pesticide reduction process. These levers can be classified according to their mode of action: cultural control, genetic control, biological control, biotechnical control, chemical control, chemical control and physical control (Deliere et al., 2016). The main technical levers employed to reduce pesticide use in vineyards are generally based on using decision support systems, reducing doses, and changing pulverisation methods (Chen et al., 2019; Mailly et al., 2017). In this study, we hope to identify new levers (rather than redesign).

This article aims to describe and analyse the trajectories of pesticide use in the DEPHY network demonstration vineyards, as well as to assess the trade-off between pesticide use and other farm performances. Our analysis first focuses on the assessment of changes in pesticide use using the TFI indicator and the different factors that influence pesticide use. Secondly, we analyse the management levers employed to reduce pesticide use. Finally, we examine the evolution of vineyard productivity and discuss how it relates to pesticide use reduction.

2. Materials and methods

2.1. DEPHY network and AGROSYST database

The main objective of the DEPHY network is to demonstrate the capacity of farms voluntarily participating in the network to reduce their pesticide use. The vineyard sector includes about 280 vineyards that joined the network between 2010 and 2012, and another 270 vineyards that joined in 2016. Vineyards are divided into 49 groups across the 12 main French winegrowing regions (Alsace, Bordeaux, Bouches-du-Rhône, Bugey-Savoie, Burgundy, Champagne, Charente, Côtes-du-Rhône, Gaillac, Languedoc, Loire-Valley, Provence). Each group of vineyards is coordinated by a network engineer who guides farmers in their pesticide reduction process and collects data using the AGROSYST system. The AGROSYST database gathers information collected every year on the practices and performances of cropping systems used on all network farms.

The cropping systems in the DEPHY network cover a wide range of production contexts. Data available for 303 vineyards (i.e. 55% of the network) reported the different levers mobilised in the DEPHY network. The main levers mentioned to reduce pesticide use are: soil management (cover cropping, soil tillage) against weeds (83%), pest monitoring (45%), insect mating disruption (24%), adaptation of the dose and frequency of fungicide spraying (79%), use of decision support systems (76% of the groups), and optimisation of spraying against fungal diseases (26%).

The AGROSYST database provides information about the cropping system: farm context (e.g. agricultural area, farm equipment), agricultural interventions and agronomic indicators such as yield. Other performance indicators, calculated from raw data, are available in the database. When joining the network, cropping system details were collected every year.

In this study, only the cropping systems of the farms that joined the network between 2010 and 2012 were analysed. Only those systems with at least six years of data were selected. In total, our study focuses on 12 winegrowing regions with a total of 244 cropping systems, after removing cropping systems with missing data or outliers (TFI > 30) (see Fig. 1). Data on the mode of production were also available and allowed us to classify cropping systems as conventional or organic farming (see supplementary material 1 for details on the variable used).

2.2. Indicator of pesticide use

We estimated the level of pesticide use by calculating the TFI. The TFI is the main indicator used within the DEPHY network to assess and monitor pesticide use. Contrary to other indicators such as the number of treatments, the TFI integrates the actual consumption of plant protection products, taking into account the actual applied dose relative to the full recommended dose (Brunet et al., 2008).

Different methods are possible for calculating the TFI. The differences between these methods are derived from the recommended dose, either established by product or by targeted pest or disease. To obtain a detailed TFI for our study, we calculated the TFI with the applied dose expressed as a fraction of the dose recommended to control specific targeted pests or diseases and by the proportion of sprayed area (see detailed variable in supplementary material 1).

$$\mathrm{TFI} = \sum (\mathrm{Dose\_sprayed}_p \,/\, \mathrm{Dose\_recommended}_p) \times (\mathrm{Area\_sprayed}_p \,/\, \mathrm{Area\_total}_p)$$

Eq(1): Calculation of the TFI (Pingault et al., 2008) *for a given year at the cropping system scale. The TFI equals the sum of the TFI per treatment, where one treatment corresponds to one product P sprayed and one date of application. The dose sprayed per product corresponds to Dose_sprayed; the recommended dose for a product P for the targeted pest is Dose_recommended; Area_sprayed represents the surface area where the product was applied and Area_total is the total surface of the field where the treatment was sprayed.*

We used the recommended doses per product and per target pest/disease from the e-phy database published by the French Ministry of Agriculture in 2020 (Ministère de l'Agriculture et de l'Alimentation, 2021) for all 10 years of the study, so that variations in the TFI would not be due to variations in dose regulations during this period. For 3% of the treatments, we could not locate the product in the official databases. Those treatments were arbitrarily allocated a TFI of 1.

The TFIs per treatment were summed up to assess pesticide use over each growing season. First, the TFIs for the whole year were calculated as the sum of the TFI per treatment for all interventions performed.

We differentiated between three partial TFIs: fungicide TFI (TFI_f), herbicide TFI (TFI_h) and insecticide/acaricide TFI (TFI_i), which were

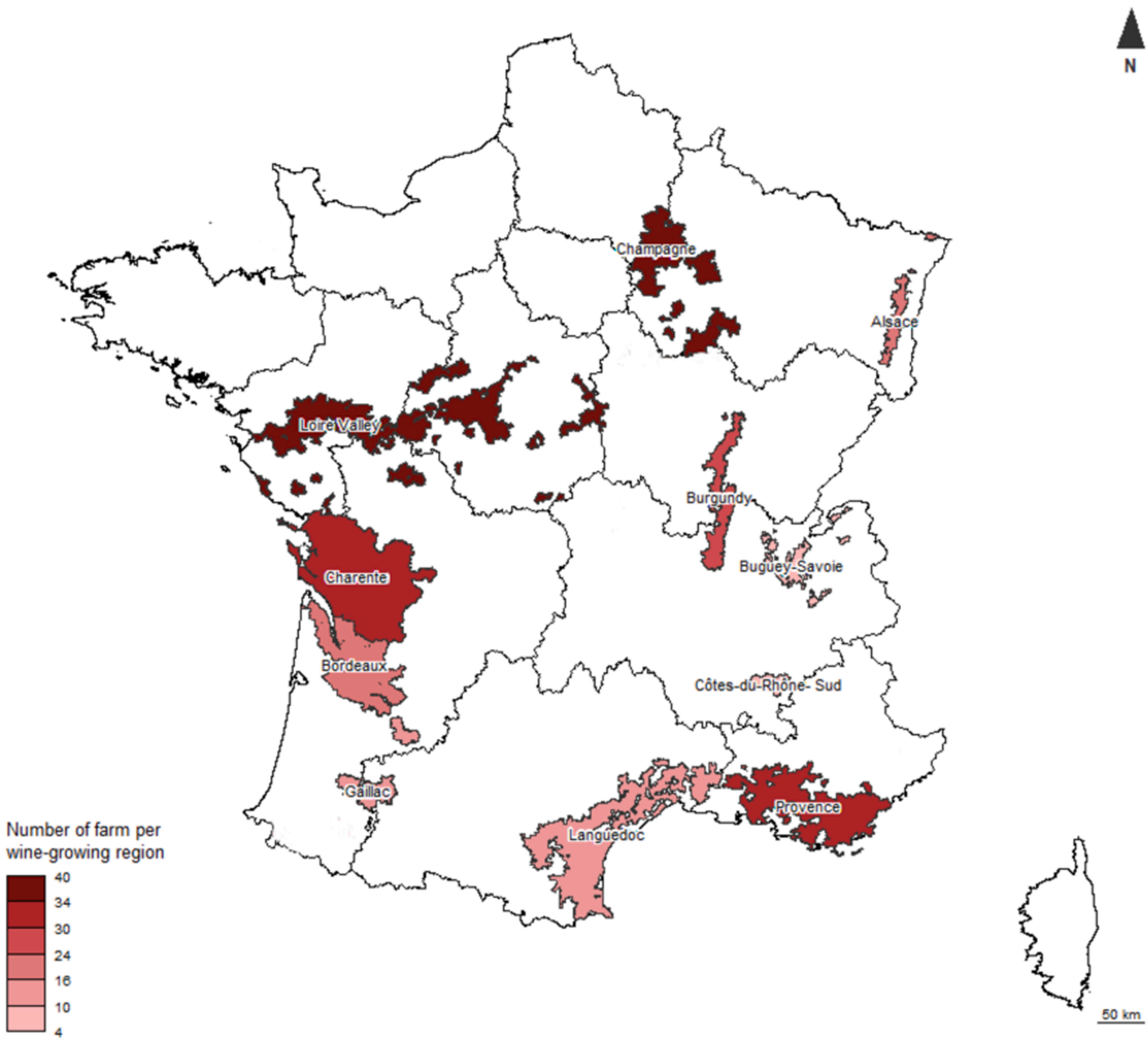

Fig. 1. Locations of the DEPHY network demonstration farms studied depending on the wine-growing region. Provence includes Var, Vaucluse and Bouches-du-Rhône. Winegrowing region are coloured according to the number of DEPHY-farms engaged in the region.

added together to obtain the sum of all TFIs per treatment for the three types of pesticides.

Since treatment dates are recorded in the database, we were also able to calculate partial TFIs by phenological periods or by month. We calculated the average TFI_f per treatment according to three main phenological periods. The three periods considered are April-May as the pre-flowering period; June as the flowering and fruit set period and July-August as the ripening period.

The list of biocontrol products authorised by the Ministry of Agriculture includes macroorganisms, microorganisms, natural substances, pheromones and elicitors that have no apparent negative impact on health or the environment. These products were excluded from the TFI calculation. The TFI including the biocontrol product was calculated separately following the principle of equation 1.

To compare the DEPHY network with national trends, we used the average TFI from the three national surveys carried out in 2010, 2013 and 2016 by the French Ministry of Agriculture's Department of Statistics and Prospective Services in the main French winegrowing regions as a reference. This database provides a representative view of cropping practices in France's different winegrowing regions. Data are collected every three years at the field scale and surveys are carried out on a representative sample of 4000 farms. The data we used here were limited to the TFI in each winegrowing region in 2010, 2013 and 2016. Data from 2019 are not available yet.

A normalised TFI was calculated corresponding to the ratio between calculated TFI and average TFI from the national surveys.

For each cropping system, the 'Initial Point' was defined as the average practices during the three years immediately preceding the year when farmers joined the DEPHY network. For the systems entering the network in 2010, the 'Initial Point' corresponded to years 2008–2010, while for the systems entering the network in 2011, the 'Initial Point' corresponded to years 2009–2011. Practices at the 'Initial Point' were therefore not affected yet by the changes favoured by the network activities. Practices were described at the cropping system level, i.e. for all field plots of a given farm managed with the same consistent strategy (either at the plot level, i.e. all details of the crop management sequences described for each plot, or directly as a cropping system synthetic crop management sequence representing all variants of crop management across the plots of the cropping system).

Because some of the pesticide-reduction solutions can rely on dose reduction and/or a change in application frequency, three complementary indicators were assessed (at the cropping system level) to better characterise the crop protection changes:

- The number of treatments corresponding to the number of treatments during a growing season whatever the date of intervention.
- The average TFI_f per treatment representing the ratio between TFI_f divided by the number of treatments.
- The number of product applied containing carcinogenic, mutagenic, or toxic for reproduction (CMR)

Finally, we also used the Yield ($hl.ha^{-1}$) available in the database, to assess if trade-offs were made between pesticide reduction and agricultural performance.

2.3. Statistical analysis

To assess the evolution over time of each indicator, two different methods were used.

First, linear mixed-effects models were used to assess if there was an evolution of a studied variable over time (modEq(2))(Zuur et al., 2009). We assumed that the studied variable X varied over time and by winegrowing region. Winegrowing Region was integrated as a fixed effect to collect the slope and intercept coefficients and cropping system followed over the time was integrated as a random effect.

$$\text{mod} = \text{lmer}(X \sim \text{Year} * \text{Winegowing Region} + (1+\text{Year}=\text{cropping system}))$$

Eq(2): Linear models used to visualise the evolution of a variable X over the 10 years of the study taking into account the winegrowing region effect (Winegrowing Region). The copping system effect followed over time is integrated as a random effect. The equation is formulated using the language of the lme4 package of the R software.

Normality and heteroscedasticity were verified to validate the statistical analysis (Zuur et al., 2009). We then used an ANOVA on each variable to test the significance of the fixed variables (Year and Winegrowing_Region) effect. A classical 0.05 level of significance was considered.

Secondly, to assess if a variable evolution occurred after a vineyard joined the network, we calculated the difference between the Final Point (2017, 2018 and 2019) and the Initial Point for each vineyard. A t-test was performed for each winegrowing region to see if the delta Final Point-Initial Point was significantly different from zero.

Statistical analysis was conducted using the R-software version 3.6.2 and the R package *Tidyverse* (Wickham et al., 2019), *lme4* (Bates et al., 2015) and *broom* (Robinson et al., 2022). The boxplot and graph were created using the *ggplot2* package (Wickham 2009). The cartography was made using the package *sf* (Pebesma, 2018) and *cartography* (Giraud and Lambert, 2018).

3. Results

3.1. Pesticide use over time in the DEPHY-Network

TFI significantly decreased over the 10 years ($p < 0.001$) in the DEPHY-network (Fig. 2A). The TFI difference between the Initial Point and the Final Point (2017, 2018, 2019) indicates an average reduction of 33%. Considerable variability among the cropping systems could be noted each year. At the Initial Point, the average TFI value was 12.1 $\pm$ 6.3 whereas the TFI value was 8.1 $\pm$ 4.6 at the Final Point. The TFI varied between 1.7 and 29.2 at the Initial Point and between 0.5 and

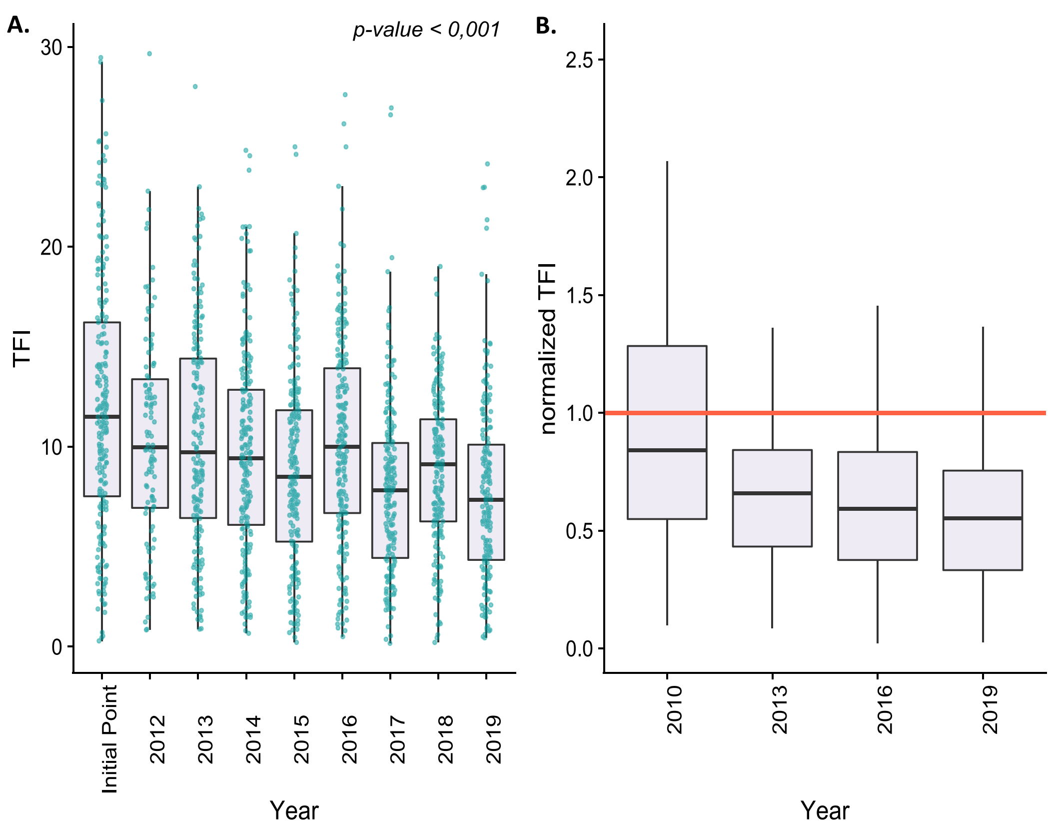

Fig. 2. Evolution of the treatment frequency index (TFI) over 10 years in the DEPHY network. A. Box plot representing the evolution of the TFI over 10 years. B. Box plot representing the normalized TFI with data from the French Ministry of Agriculture's Department of Statistics and Prospective Service's database from 2010, 2013, 2016 and 2019; we compared 2010 with the Initial Point. Outliers are not represented. Whiskers display the 5th and 95th percentiles. Horizontal bars indicate the first quartile, median and third quartiles. The p-value correspond to the results of the linear model (see Eq(2)).

24.1 at the Final Point. The year effect was statically verified ($p < 0.001$).

The normalised TFI shows trends in pesticide use, excluding the 'noise' due to inter-annual variations in climate conditions and pest pressure, and excluding regional differences (Fig. 2B). At the Initial Point, the mean normalised TFI was close to 1. This result indicates that the cropping systems within the DEPHY network had similar initial TFIs compared to representative vineyards sampled in the French Ministry of Agriculture's Department of Statistics and Prospective Service database. However, high variability was observed: the normalised TFI varied between 0.1 and 2.72. In 2013 and 2016, the median of the normalised TFI dropped below 1, close to 0.75. In 2019, the median of the normalized TFI was 0.55. The DEPHY network has sustained the pesticide reduction at a higher rate than the general population of wine growers in France. The variability decreased compared to 2010, with TFI ranging from 0.09 to 1.5 in 2013 and from 0.08 to 1.66 in 2016. The variability increase in 2019 with TFI from 0.03 to 2.1 in 2019.

3.2. TFI factors of variability

3.2.1. Winegrowing region

A variety of TFI evolutions can be observed among winegrowing regions (Fig. 3). The TFI at the Initial Point varied widely depending on the winegrowing regions. Some regions such as Charente and Loire Valley had a high level of pesticide use at the Initial Point (higher than 15). Meanwhile, Gaillac and Languedoc had a low TFI when they joined the network (below 10). The evolution of TFI by winegrowing region differed from one region to another. The regional effect was significant ($p < 0.001$, see supplementary material 2).

Some regions managed to significantly reduce the TFI (Alsace, Charente, Bordeaux and Loire Valley) according to the linear model ($p < 0.001$) and the t-test ($p < 0.01$). Loire Valley was the region with the highest TFI reduction (−66%).

InCôtes-du-Rhône, the linear model shows a significant TFI decrease ($p < 0.05$).

In Provence, the t-test between the Initial Point and the Final Point shows a significant TFI decrease. In Provence, the difference between the TFI at the Initial Point and 2012 was − 37.4%.

In Bouches-du-Rhône, Bugey-Savoie, Champagne neither of the two tests showed no significant evolution ($p > 0.05$). The average TFI decreased slightly, but not significantly ($p = 0.09$). The lowest TFI reduction average (−5.5%) was observed in Bugey-Savoie. In Gaillac, a TFI increase was observed, from 8.7 in 2010–10.4 in 2019, i.e. + 19.2% (p-value <0.05).

Within each winegrowing region, high intra-annual variability was also observed. In Bordeaux and Champagne, for example, the TFI at the Initial Point varied from 2.1 to 23.2 and from 2.1 to 19.3, respectively. Meanwhile, the regions Gaillac, Languedoc and Bouches-du-Rhône showed a lower intra-annual variability.

3.2.2. Production mode

A significant decrease in the TFI has been observed since 2010 for conventional and organic farming ($p < 0.001$ for organic farming and $p < 0.001$ for conventional farming). At the Initial Point, the TFI of conventional cropping systems was higher than the TFI of organic cropping systems ($p < 0.001$). The TFI was from 11.9 ± 5.4 for the conventional cropping system and 6.7 ± 5.6 for the organic cropping system. Despite the differences in value, the TFI trajectories for the two production modes were similar, with declines after the vineyards joined the network and peaks in 2016 and 2018. The TFI decrease observed in organic farming (−45.9%) was significantly steeper than the decrease observed in conventional systems (−26.8%) ($p < 0.001$).

An increase in the number of organic farming systems was observed between the Initial Point and 2019 (see supplementary materiel 3 and supplementary material 4). At the Initial Point, 11.6% systems were organic versus 18.8% in 2019. The conversion rate among the network

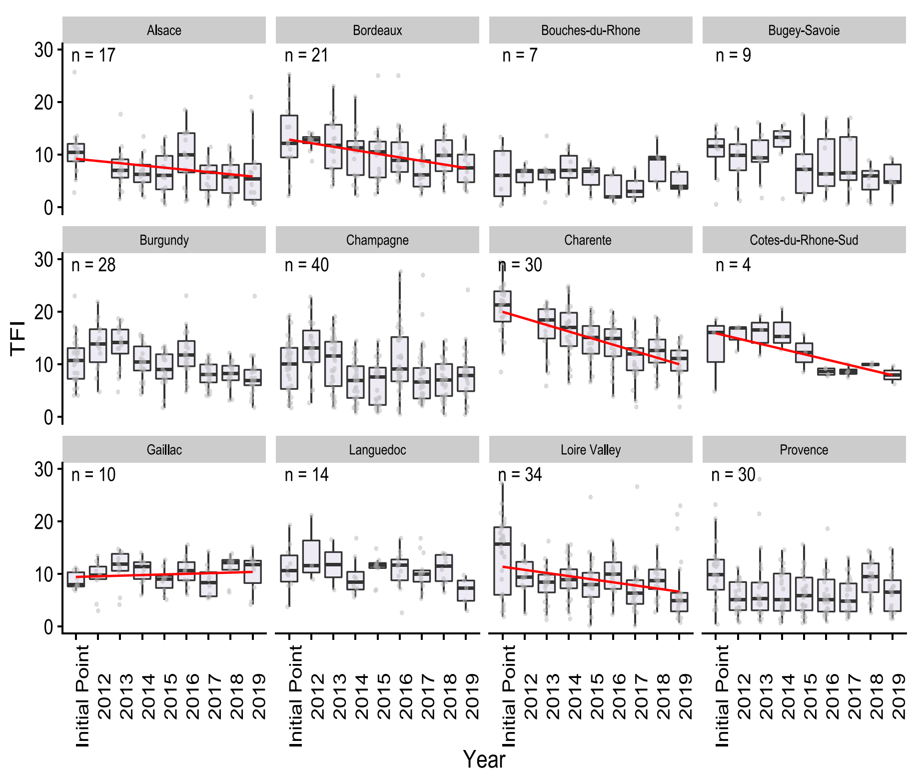

Fig. 3. Evolution of the Treatment Frequency Index (TFI) over the 10 years depending on the wine-growing region. Outliers are not represented. Whiskers display the 5th and 95th percentiles. Horizontal bars indicate first, median and third quartiles. N represents the number of cropping systems engaged in the DEPHY-network in each wine-growing region. The red line corresponds to the linear trend of TFI over time for the winegrowing region with a significant TFI evolution (see Eq(2)).

winegrowers increased after 2016. A total of 9.5% of the cropping systems converted to organic farming during the 10 years of the study: 2.1% of the cropping systems before 2015 and 7.4% of the cropping systems between 2016 and 2019. Some 17.6% were still in conversion in 2019.

3.2.3. Evolution of partial TFI

We observed a stagnation in the insecticide TFI but a significant decrease in the fungicide and herbicide TFI in the DEPHY network (Fig. 4).

Fungicides were the most sprayed pesticides (Fig. 4A) to control downy mildew and powdery mildew. They accounted for 86% of the total TFI in 2010 and 83% in 2019. A substantial, statistically significant reduction of 27% in fungicide use was observed between the Initial Point and the Final Point ($p < 0.001$). The average TFI_f was 10.1 ± 5 in 2010 and 7.3 ± 5.8 in 2019. Inter-annual variability was also observed and was very high for the TFI_f, with two spikes in 2016 and 2018. In 2016, the mean TFI_f was 8.5 ± 4.3 and 7.55 ± 3.1 in 2018. However, looking at the coefficient of variation (CV) over time and space, we observed that the inter-annual variability was higher than the intra-annual variability (see supplementary material 5). Looking at the CV over time (i.e. inter-annual variability), the minimal CV was 41.4 in 2018 and the maximum CV 79.8 in 2019. If we compare to the CV over space (i.e. intra-annual variability), it varied from31.4 for Côtes-du-Rône and 58.9 in Champagne.

Insecticide use over the 10 years did not show any significant evolution with the linear model ($p = 0.76$) (Fig. 4B) and ranged from 0.82 to 1.03. Insecticides accounted for 5.5% of the total TFI when the vineyards joined the network and 10.4% in 2019. The TFI_i presented a very low inter-annual and intra-annual variability. At the Initial Point, the TFI_i was from 0.9 ± 1.1 and in 2019 from 1.1 ± 1.3.

Among the cropping systems using herbicides, the linear model showed a significant decrease in the TFI_h: from 1.4 ± 1.4–1 ± 1.1 ($p < 0.001$) (Fig. 4C). The sprayed areas were not always representative of the entire plot. The reduction rate of 58% for TFI_h over the 10 years was sharper compared that for fungicides and insecticides. This percentage corresponds to the total use of herbicides, and also includes winegrowers who do not use herbicides. An early drastic decrease was observed from 2010 and 2012. On average, TFI_h accounted for 8.5% of the total TFI in 2010 and 4.8% in 2019. The intra-annual variability was higher at the Initial Point, rising from 0 to 5 while the TFI_h varied from 0 to around 2 in the following years.

In addition, the percentage of cropping systems using herbicides decreasing considerably, from 88.8% at the Initial Point to 51.3% in 2019 (Fig. 4C). This decrease was mainly observed early after vineyards joined the DEPHY network between the Initial Point and 2013.

3.3. Exploring pesticide reduction levers

3.3.1. Change in the type of product used

The use of biocontrol products increased significantly in the DEPHY network over the 10 years of the study ($p < 0.001$) (Fig. 5). The TFI $_{biocontrol}$ rose from 2.5 at the Initial Point to 3 in 2019. Biocontrol use increased by 20% between 2010 and 2019. Moreover, the number of cropping systems using biocontrol products increased between 2010 and 2019. At the Initial Point, 35.2% of the cropping systems used biocontrol products versus 80.9% in 2019. A shift was observed between 2010 and 2012 indicating that biocontrol was adopted early after inclusion in the network. Although biocontrol product use rose, this did not account for the entire decrease in pesticide use, since the increase in the TFI $_{biocontrol}$ was well below the total decrease in the TFI quantifying reduced pesticide use.

We observed a significant decrease in the number of treatment regardless of the type of pesticides ($p < 0.001$, see supplementary material 6). At the Initial Point, the mean number of treatment was 14.4 $\pm$ 5.1 and 13 ± 5 in 2019. Among the cropping systems which still use herbicides, the number of herbicide treatments held stable at around 2.1 over the 2010–2019 period. At the DEPHY-network scale, the number of herbicide treatments significantly decreased ($p < 0.001$). There was no significant evolution of the quantity of glyphosate sprayed in cropping

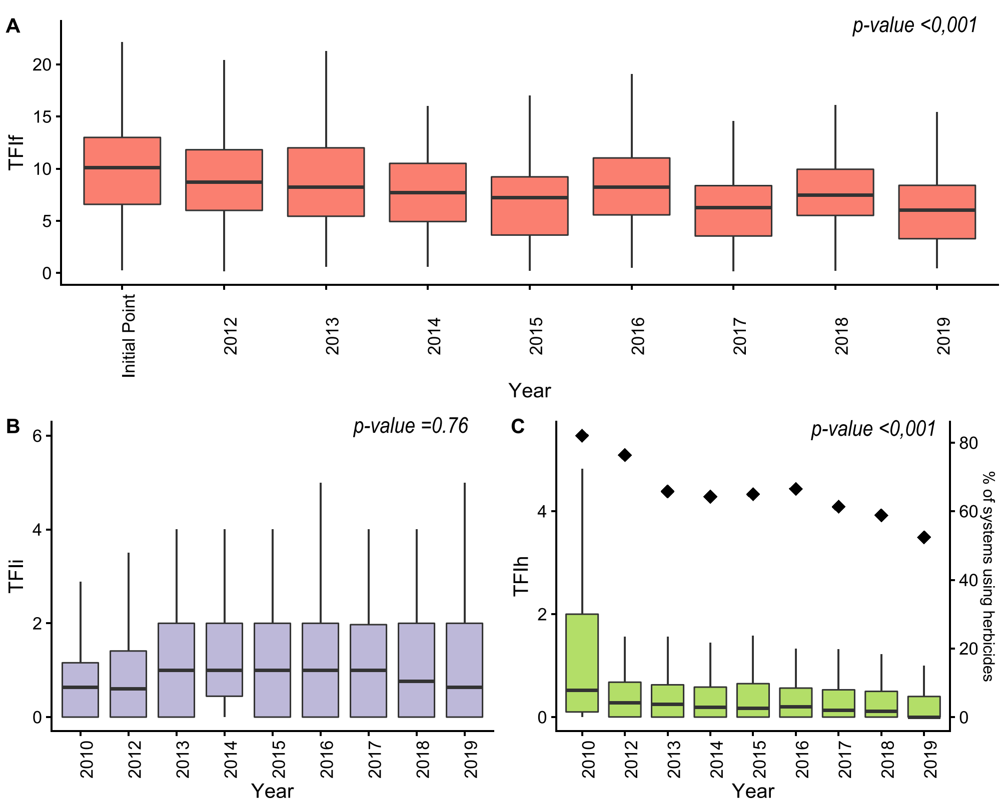

Fig. 4. Evolution of the partial TFI over the 10 years of the study. (A.) Evolution of the fungicide TFI (TFI_f). (B.) Evolution of the insecticide TFI (TFI_i). (C.) Box plot (left axis) representing the evolution of herbicide TFI (TFI_h) and point plot (right axis) representing the evolution of the percentage of systems using herbicides. Outliers are not represented. Whiskers display the 5th and 95th percentiles. Horizontal bars indicate the first, median and third quartiles. The p-value correspond to the results of the linear model (see Eq(2)).

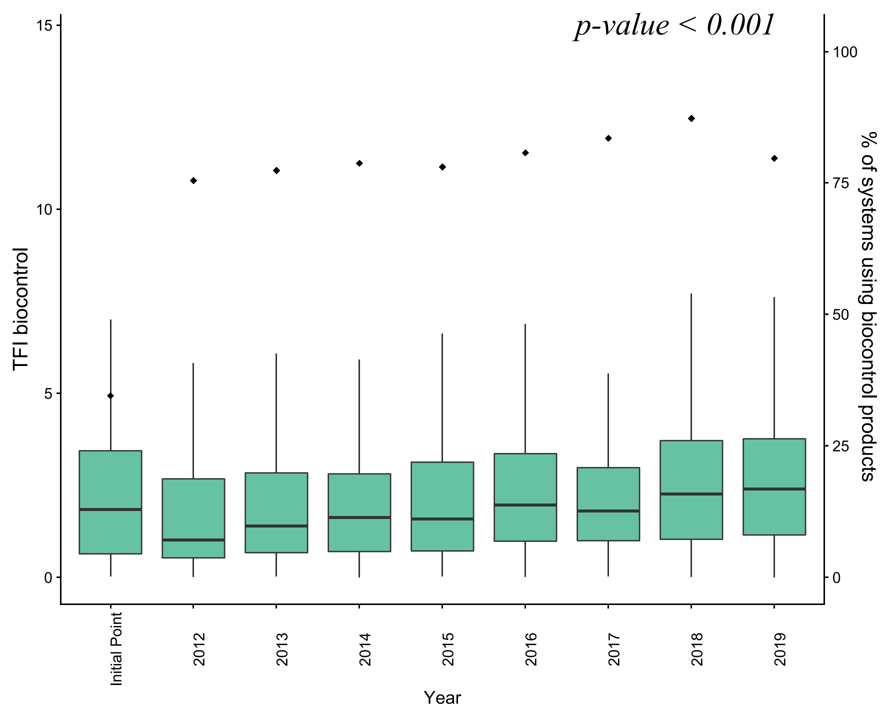

Fig. 5. Evolution of biocontrol use within the DEPHY network over the 10 years of the study. Box plot (left axis) representing the evolution of the biocontrol TFI and point plot (right axis) representing the percentage of systems using biocontrol products. Outliers are not represented. Whiskers display the 5th and 95th percentiles. Horizontal bars indicate the first, median and third quartiles. The p-value correspond to the results of the linear model (see Eq(2)).

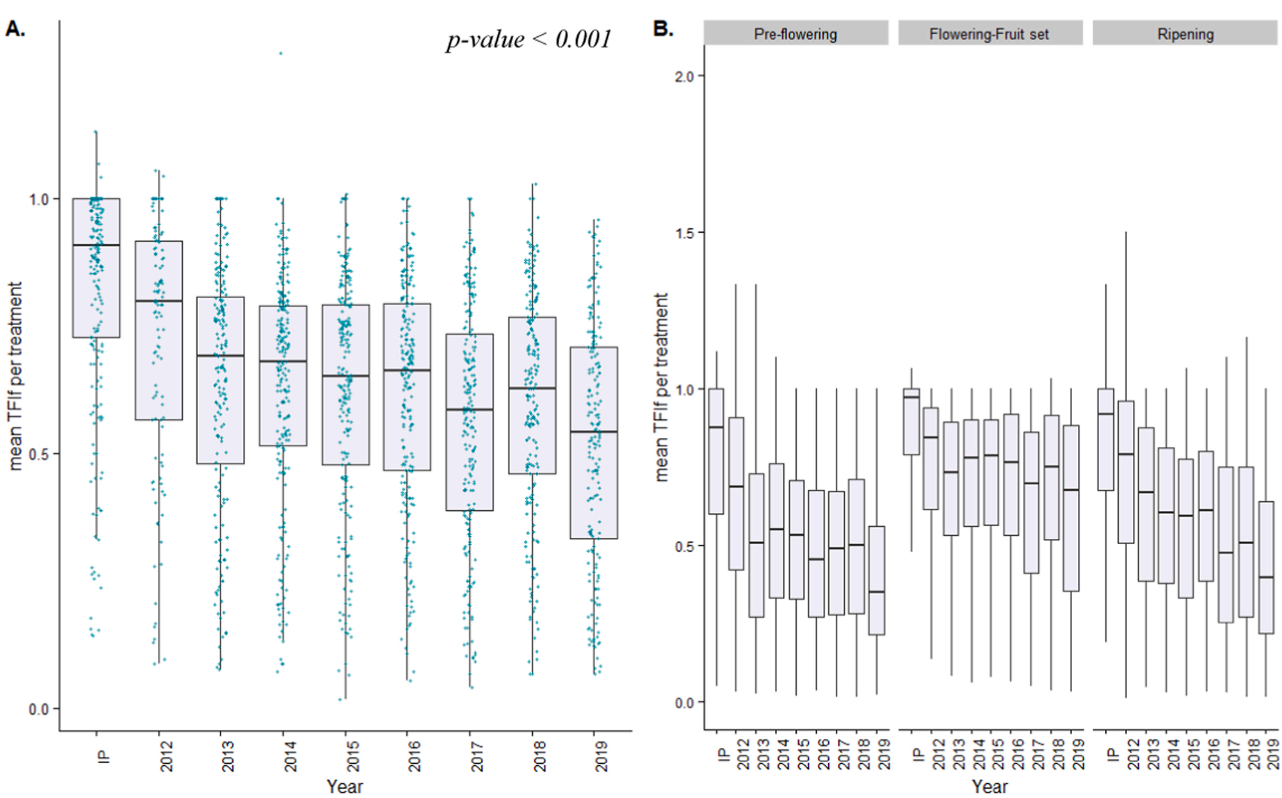

Fig. 6. Evolution of fungicide use over the 10 years of the study. (A) Box plot representing the TFI_f per treatment over the whole crop cycle. (B) Box plot of the TFI_f per treatment split into three distinct phenological periods: 1) Pre-flowering, 2) Around flowering and fruit set, and 3) Ripening. Outliers are not represented. Whiskers display the 5th and 95th percentiles and the horizontal bars indicate the first quartile, median and third quartiles. The p-value correspond to the results of the linear model (see Eq(2)).

systems using this herbicide ($p = 0.11$). But the number of cropping systems using glyphosate decreased: 68% of the cropping systems used products containing glyphosate at the Initial Point versus only 49% in Final Point.

The number of insecticide treatments was also stable, remaining at around 2.2 over the 10 years for the cropping systems using insecticides.

The evolution of the number of fungicide treatments showed no significant change over the 10 years ($p = 0.9$, see supplementary material 7). High inter- and intra-annual variability was observed (from 1 or 2 treatments to 29 treatments).

The evolution of the number of products containing CMR decreased over the 10 years ($p < 0.001$, see supplementary material 8). The mean number of CMR products used per farming system was 7.8 ± 4.8at the Initial Point and 1.3 ± 2.1at the Final Point.

3.3.2. Dose adjustments

The TFI_f per treatment decreased significantly between 2010 and 2019 ($p < 0.001$) (Fig. 6A). This decrease corresponded to a 39% reduction. An early change was observable between 2010 and 2012 with a 13% reduction.

Separating the TFI_f per treatment into phenological periods (Fig. 6B) showed that the average TFI_f per treatment decreased significantly for each period ($p< 0.001$). In 2010, the TFI_f per treatment was around 1 for the three periods analysed, meaning that winegrowers applied pesticides at the full recommended dose. After 2010, a decrease was observed for all three periods. A sharp, quick decrease in the TFI_f can be observed during pre-flowering (April-May) and ripening (August) of 50% and 47%, respectively. However, between flowering and fruit set, a highly sensitive period, the TFI_f per treatment showed a slighter decrease (−30%) and remained higher than in pre-flowering or ripening periods (around 0.75) from 2012 to 2019.

The average TFI_i per treatment decreased from 0.87 ± 0.25 at the Initial Point to 0.77 ± 0.29 in 2019 ($p < 0.001$, see supplementary material 9). The herbicide use per treatment decreased from 0.40 ± 0.27 mean in 2010–0.27 ± 0.25 in 2019 for the cropping systems using herbicides ($p < 0.001$, see supplementary material 10).

3.4. Yield evolution

A significant 19% yield reduction was observed over the 10 years at the overall DEPHY-network level ($p < 0.05$) (Fig. 7, supplementary material 2). The average yield in the network was 62.8 ± 22 $hL.ha^{-1}$ at the Initial Point and 51.2 ± 21 $hL.ha^{-1}$ in 2019.

A high diversity of trajectories was observed depending on the winegrowing region. In Bouches-du-Rhône, Bordeaux, Champagne, Côte-du-Rhône, Languedoc, Gaillac the linear model and the t-test showed no significant yield evolution. In Bouches-du-Rhône, for example, the mean yield stayed around 50 $hL.ha^{-1}$ over the 10 years. The difference between Initial Point and Final Point showed a significant difference in Gaillac.

In Bugey-Savoie, Burgundy, Provence and Loire Valley the linear model also showed a significant yield decrease.

The analysis of the differences between the Initial Point and the Final Point showed a significant yield decrease in Provence and Bugey-Savoie. In the regions of Provence, Bugey-Savoie, decreases in yields over the 10 years were 39.6%and 39.4%, respectively.

4. Discussion

In this study, we aimed to describe and analyse the trajectories of pesticide use in demonstration vineyards involved in pesticide reduction. We showed that the TFI decreased over the 10-year period within the DEPHY network, with a reduction rate of around 33%. The TFI decrease was driven by the fungicide reduction. The decrease was regular and progressive from the point when vineyards joined the network, although there was high inter- and intra-annual variability. This high variability is related to a large range of pesticide use trajectories, which can be explained partly by the inter-region diversity and year effects.

We observed TFI spikes in two specific years: 2016 and 2018. In 2016, climate conditions increased downy mildew pressure in Champagne and Alsace (north-eastern France) and in Provence (south-eastern France), leading to higher pesticide use (Simonovici, 2019). In 2018, a rainy spring leading to high downy mildew pressure was observed all

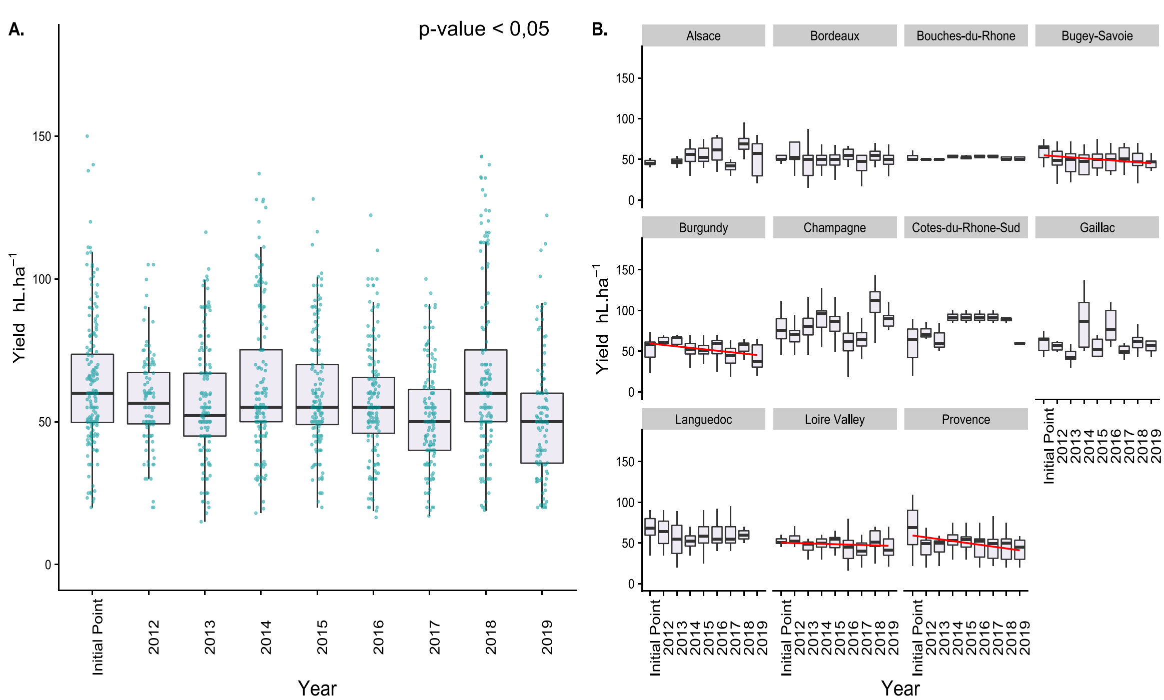

Fig. 7. (A) Evolution of the yield over the 10 years of the study. (B) Evolution of the yield over 10 years by winegrowing region. Outliers are not represented. Whiskers display the 5th and 95th percentiles and the horizontal bars indicate the first quartile, median and third quartiles. The p-value correspond to the results of the linear model (see Eq(2)).

across France, with the exception of Burgundy, Champagne and Alsace. The year effect had a huge impact on phytosanitary practices. Differing climate conditions from one winegrowing region to another lead to variability in practices implemented over time and space (Mailly et al., 2017).

At the winegrowing region level, a range of TFI trajectories among regions were also identified. Regions such as Charente, Bordeaux showed a high and progressive decrease in the TFI while Languedoc and Gaillac had relatively stable ones. Other regions showed a decrease in pesticide use, but the evolution was not regular. A rupture in the TFI evolution was observed when vineyards joined the network in Provence and Bouches-du-Rhone. This rupture appeared following analysis of the difference between the Initial Point and the Final Point. This rupture implies that winegrowers quickly implemented technical levers.

With regard to the rate of pesticide reduction, the highest TFI reduction rate could be noted for winegrowing regions joining the network where pesticide use is high, such as Charente and Bordeaux. Meanwhile, the TFI reduction was limited in Provence and Languedoc, regions that joined the DEPHY network with the lowest average TFI values.

Our results showed that the TFI reduction was driven by fungicide reduction. In this study, we identified significant but limited changes in the insecticide strategy. This limit is undoubtedly related to the government-mandated treatments to control the leafhopper vector of Flavescence Dorée. The number of mandatory treatments – from one to three – depends on the winegrowing region. Regions such as Gaillac, Languedoc and Charente must deal with high pest pressure that often requires three treatments (Simonovici, 2019). To control other pests like grape moths, the levers implemented are usually the use of biocontrol techniques such as mating disruption, microbial products, biological control with the release of natural enemies, etc. (Pertot et al., 2017). However, the TFI associated with grape moths is very low (less than one treatment on average), and is not a priority compared to fungicide reduction.

Fungicide reduction is an important issue because fungicides are the main pesticides used in terms of quantity and number of interventions in vineyards (accounting for over 80% of the TFI). A significant decrease in the TFI_f was observed for the cropping systems analysed for this study. This TFI_f decrease was due mainly to reduced doses, which improved efficiency according to the ESR framework (Hill and MacRae, 1996), whereas no change in the number of fungicide treatments was observed. Winegrowers adjusted their fungicide doses depending on the grapevine sensitivity. They tended to apply full doses during the sensitive phenological stages (e.g. flowering period) whereas they reduced the dose before and after the flowering period. A decision support system can further refine dosage choices: studies have quantified the potential pesticide reduction associated with their use and revealed a 50% reduction in fungicide (Delière et al., 2015). Decision support systems differ considerably with regard to the knowledge they provide and how easy they are to use. Deeper analysis is required to investigate the learning process associated with the implementation of dose reduction tools and whether some of them are more effective than others. It is commonly accepted that decision support systems and indicators more generally provide descriptive elements to support action, but a learning curve to understand indicator functions is reported by Toffolini et al. (2016). This learning curve is particularly important during a transition (Barbier and Lemery 2000; Deffontaines et al., 2020). Other elements of reasoning for fungicide treatments have been shown by Mailly et al. (2017) and Chen et al., (2019, 2020); furthermore, these studies highlighted that delaying the first application of fungicide was a major strategy to reduce TFI. However, dose reduction strategies are often preferred over delaying the first treatment when winegrowers use contact products such as copper or sulphur. These strategies are favoured by the development of organic farming, strategies that do not use CMR products or the progress of resistance problems with many synthetic products. This variable was not studied, but will need to be explored through further analysis. Other explanatory variables, relative to the context of the farming system and underlying pesticide use, could be used. For example, some variables such as grape varieties, targeted yield or planting density were not available in the database, but such information could significantly impact pesticide use. We were not able to investigate such questions.

The dose reduction can be combined with efficiency gains related to equipment choices (sprayer type and adjustments). In 2017, a survey among winegrowers involved in the DEPHY network showed that equipment choice, and especially sprayers, was an important lever for pesticide reduction (cited in 26% of surveys). In some cases, farmers must invest in new equipment, which represents a significant investment. It would have been interesting to study the implementation of such equipment, but the database did not allow for easy investigation of this aspect.

Substitutions, as defined by Hill and MacRae (1996), were also observed. Indeed, an increase in the TFI $_{\text{biocontrol}}$ was observed during the 10 years of the study and the rate of cropping systems using biocontrol products improved rapidly, from around 30% of the cropping systems at the Initial Point to almost 75% in 2012. Biocontrol strategies largely revolved around sulphur products.

The analysis of fungicide use dynamics showed that strategies of changes based on efficiency gains were quick to be implemented (from 2010 and 2012) with substantial results. Biocontrol was introduced more gradually, unlike the TFI per treatment, which began to fall immediately after vineyards joined the network. However, it should be noted that biocontrol methods are less effective than synthetic pesticides (Laurent et al., 2021). Sulphur products, which account for the majority of biocontrol products, are more leachable and less effective. Hill and MacRae (1996) showed that efficiency and substitution, like sulphur introduction, are the first steps of change towards an agroecological transition. Thus, it would be interesting to look at the trajectories followed by the cropping systems that specifically converted to organic farming over the 10 years analysed in this study. The decrease in the use of CMR products confirms the substitution of products that are harmful for human health and environment for more environmental friendly products.

Other indicators can be used to qualify pesticide use, such as the number of unit doses (NUD) or the quantity of active ingredient (QAI). The QAI corresponds to the sum of the weight of active substances contained in the applied products according to the dose (Ecophyto, 2019). The NUD is obtained by calculating the ratio between the QAI and the recommended dose. The biocontrol NUD cannot be calculated and there are no NUD references by region (Ecophyto, 2019). The NUD indicator is less known and thus less accessible to farmers. Looking at the evolution of the QAI shows bias because the new registered substances have a lower weight than the old substances. The QAI can vary greatly because it combines very different active substances in terms of application doses (Sanson and Joulin, 2018). This indicator does not take into account the properties, nor the toxicity of the active substances The QAI does not really reflect the farmer's practices (Guichard, 2010). These two indicators are mainly interesting on a sector-wide scale (Guichard, 2010). We based our study on the TFI because it is the official indicator used by the DEPHY network and the farmers. TFI is an indicator that drives change within the DEPHY network.

Herbicide reduction was the second way to reduce the TFI. The TFI_h decreased over the 10 years of the study, especially between the Initial Point and 2012. Reduced herbicide use seems to be one of the first levers activated to reduce pesticide inputs. For weed control, the existing levers are based on efficiency gains or redesign. In fact, chemical weeding can be maintained or stopped. When stopped it must be replaced by manual or mechanical methods. A reduction of the TFI_h per treatment was observed: modularity in herbicide reduction efforts can be achieved using differentiated treatments i) between row and inter-row compartments and ii) between inter-rows. Thus, herbicide reduction is only possible in some areas of the plot. In the DEPHY network, numerous winegrowers stopped herbicide use entirely on the entire area involved in the network. Jacquet et al. (2019) found that such a change lead to an increase in workload, from 1 to 2 field interventions with herbicides to 4–6 field interventions for manual and mechanical weeding. This increase implies a heavier workload during a critical period, e.g. spring (Merot and Wery, 2017) that could be a source of lock-in for pesticide use. Mechanical weeding also implies purchasing new equipment and learning how to use it. Herbicide reduction suggested that changes implemented in the DEPHY network involved deeper changes to practices than those required for fungicide reduction. It is highly probable that repercussions on other performances could be observed. Jacquet et al. (2019) showed that mechanical weeding could cause a 5–20% yield loss and increase work time from 8 h/ha to 11 h/ha. These changes imply economic impacts (equipment investment and labour costs). Further study on trade-offs between performances is needed. It would be interesting to verify if cropping systems that continued to use herbicides could absorb these repercussions or if they are locked in.

One important aspect of performance to assess in the case of technical change is yield. A significant decrease in yield was observed (−19%). This decrease seems highly dependent on the winegrowing region and the specific production context. Yield can be impacted by many factors. Climate events (frost, hail, etc.) can cause major damage in vineyards. More recently, studies highlighted the fact that grapevine trunk diseases could cause vine dieback (Gramaje et al., 2018; Mondello et al., 2018). A longitudinal study of yields from 1900 to 2016 showed that most French departments experienced yield stagnation, and perhaps even a decline, across 79% of all viticulture cropping areas (Schauberger et al., 2018). Thus, in this study, it is difficult to attribute the decrease in yield performance observed in the network to changes in practices related to the decrease in pesticide use. Studies have shown that the transition of cropping systems to organic agriculture leads to significant yield reductions (Merot and Smits, 2020). The yield decrease can be explained by new processes that are undertaken, but not mastered, such as mechanical weeding below the row, which can reach the stock stumps and thus impact productivity (Jacquet et al., 2019) or the introduction of sulphur- and copper-based treatments (Merot et al., 2020). Further analysis is needed to answer this question.

Besides the analysis of TFI absolute values, we showed that the TFI of the cropping systems engaged in the network differed from the national trends (Simonovici, 2019). In fact, the DEPHY network went further in its approach to pesticide reduction. The evolution of the normalised TFI from the DEPHY network showed a potential progress margin for the French vineyard system of 30% in 2016. This reduction is worthwhile as long as yield is not impacted. However, it is difficult to imagine that all French winegrowers would be ready to change their practices and to the same degree. Innovative practice implementation is highly correlated with financial investment, complexity of implementation, workload and availability of technical resources such as equipment (Deffontaines et al., 2020). Moreover, there are many psychological and social factors underlying farmers' intentions to adopt practices, which results in huge differences in implementation (Bonke et al., 2021).

In this study, we showed that the DEPHY network provided good support to farmers that are willing to reduce pesticide use. Thus, the DEPHY network was an effective driving force for the implementation of new levers. Advisors play a key role in supporting changes. Like farmers, they must also change their practices (Cerf et al., 2010). The DEPHY network also helps advisors stay abreast of changes in their field to support farmers in the agroecological transition. With this study, we were able to verify the effectiveness of some of the technical levers mobilised, even if some of them cannot be fully traced. A more detailed study on the crop management system must be carried out to explore change mechanisms and trade-offs made between performance factors. Some performance considerations such as profit are not available in the AGROSYST database. It is important to point out that changes to practices and system redesign require taking a financial risk (Boulanger-Fassier, 2008) and that one possible lever is to adjust selling prices. Individual and collective support could be one way to encourage the implementation of practices to achieve a sustainable reduction of the TFI through knowledge acquisition. DEPHY is an opportunity to learn and enrich both knowledge and knowledge indicators (Toffolini et al., 2016).

5. Conclusion

We showed that the TFI decreased over 10 years within the DEPHY network, with an overall reduction rate of around 33%. The first levers identified are mostly based on efficiency and substitution. Such results could be used to improve farm stakeholders' support towards agroecological transition. However, it is essential to assess changes from a social point of view and to take into account socio-economic indicators such as labour intensiveness and health risks.

CRediT authorship contribution statement

Esther Fouillet: Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Laurent Delière:** Formal analysis, Methodology, Writing – review & editing. **Nicolas Chartier:** Formal analysis, Methodology, Resources, Writing – review & editing. **Nicolas Munier-Jolain**: Writing – review & editing. **Sébastien Cortel:** Resources, Methodology, Writing – review & editing. **Bruno Rapidel:** Writing – review & editing. **Anne Merot:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgements

We would like to thank the winegrowers and farm advisors from the DEPHY network. This research is part of a PhD project funded by the Région Occitanie (France) and ECOPHYTO Plan (ARPHY - OFB N° 4147). The authors also thank Teri Jones-Villeneuve for the English language review and Lucas Etienne for the help in creating the map.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126503.

References

Agreste. (2016) GRAPH'AGRI. Chapter 9: Agriculture Biologique; Service de la Statistique et de la Prospective: Paris, France, pp.106–107.

Agreste, 2020. Pratiques culturales en grandes cultures 2017. IFT Et. Nr. De. Traite.

Aubertot, J.N., Barbier, J.M., Carpentier, A., Gril, J.J., Guichard, L., Lucas, P., Savary, S., Savini, I., Voltz, M., 2005. Pesticides, agriculture et environnement: réduire l'utilisation des pesticides et en limiter les impacts environnementaux. Synthèse du Rapp. De. l'expertise 65.

Aveline, N., Samuel, R., & Fau, J.-B. (2009). Produits alternatifs et SDN pour protéger la vigne. 164. ⟨https://www.vinopole.com/fileadmin/user_upload/fichiers_vinopole/Protection_du_vignoble/SDN/PA_et_SDN_pour_proteger_la_vigne_2009⟩_Aveline.pdf.

Baldi, I., Filleul, L., Mohammed-Brahim, B., Fabrigoule, C., Dartigues, J.F., Schwall, S., Drevet, J.P., Salamon, R., Brochard, P., 2001. Neuropsychologic effects of long-term exposure to pesticides: results from the French Phytoner study. Environ. Health Perspect. 109 (8), 839–844. https://doi.org/10.1289/ehp.01109839.

Baldi, I., Lebailly, P., Rondeau, V., Bouchart, V., Blanc-Lapierre, A., Bouvier, G., Canal-Raffin, M., Garrigou, A., 2012. Levels and determinants of pesticide exposure in operators involved in treatment of vineyards: results of the PESTEXPO study. J. Expo. Sci. Environ. Epidemiol. 22 (6), 593–600. https://doi.org/10.1038/jes.2012.82.

Barbier, M., & Lemery, B. (2000). "Learning" through Processes of Change in Agriculture: A methodological Framework. In Knowing and Learning for Change in Agriculture: Case Studies from Industrialised Countries (M. Cerf, D. Gibbon, B. Hubert, R. Ison, J. Jiggins, M. Paine, J. Proost, N. Röling, p. 381–393).

Barzman, M., Dachbrodt-Saaydeh, S., 2011. Comparative analysis of pesticide action plans in five European countries. Pest Manag. Sci. 6. https://doi.org/10.1002/ps.2283.

Bleyer, G., Kassemeyer, H.H., Breuer, M., Krause, R., Viret, O., Dubuis, P.H., Frabre, A.L., Bloesch, B., Siegfried, W., Naef, A., Huber, M., 2011. "VitiMeteo" a future oriented forecasting system for viticulture. Bull. IOBC/WPRS 67, 69–77.

Bonke, V., Michels, M., Musshoff, O., 2021. Will farmers accept lower gross margins for the sustainable cultivation method of mixed cropping? First insights from Germany. Sustainability 13 (4), 1631. https://doi.org/10.3390/su13041631.

Bony, S., Gillet, C., Bouchez, A., Margoum, C., Devaux, A., 2008. Genotoxic pressure of vineyard pesticides in fish: field and mesocosm surveys. Aquat. Toxicol. 89 (3), 197–203. https://doi.org/10.1016/j.aquatox.2008.06.017.

Boulanger-Fassier, S., 2008. La viticulture durable, une démarche en faveur de la pérennisation des territoires viticoles français ? Géocarrefour 2008 (83), 181–190. https://doi.org/10.4000/geocarrefour.6856.

Caffi, T., Legler, S.E., Rossi, V., Bugiani, R., 2012. Evaluation of a warning system for early-season control of grapevine powdery mildew. Plant Dis. 96 (1), 104–110. https://doi.org/10.1094/PDIS-06-11-0484.

Carisse, O., Bacon, R., Lefebvre, A., Lessard, K., 2009. A degree-day model to initiate fungicide spray programs for management of grape powdery mildew [Erysiphe necator]. Can. J. Plant Pathol. 10. https://doi.org/10.1080/07060660909507592.

Celette, F., Findeling, A., Gary, C., 2009. Competition for nitrogen in an unfertilized intercropping system: the case of an association of grapevine and grass cover in a Mediterranean climate. Eur. J. Agron. 30 (1), 41–51. https://doi.org/10.1016/j.eja.2008.07.003.

Celette, F., Gary, C., 2013. Dynamics of water and nitrogen stress along the grapevine cycle as affected by cover cropping. Eur. J. Agron. 45, 142–152. https://doi.org/10.1016/j.eja.2012.10.001.

Cerdà, A., Daliakopoulos, I.N., Terol, E., Novara, A., Fatahi, Y., Moradi, E., Salvati, L., Pulido, M., 2021. Long-term monitoring of soil bulk density and erosion rates in two Prunus persica (L) plantations under flood irrigation and glyphosate herbicide treatment in La Ribera district, Spain. J. Environ. Manag. 282, 111965 https://doi.org/10.1016/j.jenvman.2021.111965.

Cerf, M., Omon, B., Chantre, E., Guillot, M., Bail, M.L., Lamine, C., Olry, P., 2010. Vers des systèmes économes en intrants: quelles trajectoires et quel accompagnement pour les producteurs en grandes cultures. Innov. Agron. 8, 105–119.

Chen, M., Brun, F., Raynal, M., Makowski, D., 2019. Timing of grape downy mildew onset in bordeaux vineyards. Phytopathology® 109 (5), 787–795. https://doi.org/10.1094/PHYTO-12-17-0412-R.

Chen, M., Brun, F., Raynal, M., Makowski, D., 2020. Delaying the first grapevine fungicide application reduces exposure on operators by half. Nat. Res. 13. https://doi.org/10.1038/s41598-020-62954-4.

Coll, P., Le Cadre, E., Blanchart, E., Hinsinger, P., Villenave, C., 2011. Organic viticulture and soil quality: a long-term study in Southern France. Appl. Soil Ecol. 8. https://doi.org/10.1016/j.apsoil.2011.07.013.

Cordeau, S., Triolet, M., Wayman, S., Steinberg, C., Guillemin, J.-P., 2016. Bioherbicides: dead in the water? A review of the existing products for integrated weed management. Crop Prot. 87, 44–49. https://doi.org/10.1016/j.cropro.2016.04.016.

Davy, A., Raynal, M., Vergnes, M., Debord, C., Codis, S., Naud, O., Deliere, L., Davidou, L., Fermaud, M., Roudet, J., Metral, R., Bouisson, Y., Guilbault, P., Dupin, S., Genevet, B., Mahieux, V., Baron, M., Perot, S., 2020. Decitrait®: Un OAD pour la protection de la vigne. Innov. Agron. 89–99. https://doi.org/10.15454/7fk8-gt23.

Deffontaines, L., Mottes, C., Della Rossa, P., Lesueur-Jannoyer, M., Cattan, P., Le Bail, M., 2020. How farmers learn to change their weed management practices: simple changes lead to system redesign in the French West Indies. Agric. Syst. 179, 102769 https://doi.org/10.1016/j.agsy.2019.102769.

Deliere, L., Cartolaro, P., Goutouly, J.-P., Barbier, J.M., Bonicel, L., Forget, D., Leroy, P., Naud, O., Ugaglia, A., Del'Homme, C., Davy, A.L., Davidou, L., Guilbault, P., Guisset, M., Guillois, F., 2013. Conception et transfert de systèmes décisionnels pour la réduction des traitements en viticulture: le projet SyDéRéT. Innov. Agron. 28, 155–168.

Delière, L., Cartolaro, P., Léger, B., Naud, O., 2015. Field evaluation of an expertise-based formal decision system for fungicide management of grapevine downy and powdery mildews: decision system for management of grapevine mildews. Pest Manag. Sci. 71 (9), 1247–1257. https://doi.org/10.1002/ps.3917.

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. Innov. Agron. 70, 37–54. https://doi.org/10.15454/3WLRXP.

Deliere, L., Rougier, M., Emonet, E., Pillet, E., Burgun, X., Lafond, D., Mahé, H., Metral, R., Serrano, E., & Thiollet-Scholtus, M. (2016). Réseau DEPHY EXPE: Synthèse des résultats à mi-parcours à l'échelle nationale—Filière Viticulture. 71.

Delpuech, X., Carra, M., 2016. Adapter le parc matériel pour traiter plus précisement. PHYTOMA 698, 24–27.

Ecophyto. (2019). Méthodologie de calcul du NODU (Nombre de doses unités). ⟨https://agriculture.gouv.fr/quest-ce-que-le-nodu⟩.

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. Aust. J. Grape Wine Res. 22 (3), 450–461. https://doi.org/10.1111/ajgw.12238.

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. Agric., Ecosyst. Environ. 251, 158–170. https://doi.org/10.1016/j.agee.2017.09.030.

Gil, E., Llorens, J., Landers, A., Llop, J., Giralt, L., 2011. Field validation of dosaviña, a decision support system to determine the optimal volume rate for pesticide application in vineyards. Eur. J. Agron. 35 (1), 33–46. https://doi.org/10.1016/j.eja.2011.03.005.

Gramaje, D., Úrbez-Torres, J.R., Sosnowski, M.R., 2018. Managing grapevine trunk diseases with respect to etiology and epidemiology: current strategies and future prospects. Plant Dis. 102 (1), 12–39. https://doi.org/10.1094/PDIS-04-17-0512-FE.

Guichard, L. (2010). Caractérisation des pratiques de protection des cultures et de leur évolution: Méthodologie de diagnostic et propositions visant à améliorer l'impact environnemental des systèmes de culture et d'élevage. (p. 14). Rapport d'étude, INRA/AgroParisTech.

Hill, S.B., MacRae, R.J., 1996. Conceptual framework for the transition from conventional to sustainable agriculture. J. Sustain. Agric. 7 (1), 81–87. https://doi.org/10.1300/J064v07n01_07.

Jacquet, F., Delame, N., Vita, J.L., Reboud, X., Huyghe, C., 2019. Alternatives au glyphosate en viticulture. Eval. économique Des. Prat. De. désherbage 28.

Jermini, M., Blaise, P., Gessler, C., 2010. Quantitative effect of leaf damage caused by downy mildew (Plasmopara viticola) on growth and yield quality of grapevine " Merlot " (Vitis vinifera). J. Grapevine Res. 10. https://doi.org/10.5073/vitis.2010.49.77-85.

Keesstra, S.D., Rodrigo-Comino, J., Novara, A., Giménez-Morera, A., Pulido, M., Di Prima, S., Cerdà, A., 2019. Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments. CATENA 174, 95–103. https://doi.org/10.1016/j.catena.2018.11.007.

Kuflik, T., Prodorutti, D., Frizzi, A., Gafni, Y., Simon, S., Pertot, I., 2009. Optimization of copper treatments in organic viticulture by using a web-based decision support system. Comput. Electron. Agric. 68 (1), 36–43. https://doi.org/10.1016/j.compag.2009.04.008.

Lamichhane, J.R., Bischoff-Schaefer, M., Bluemel, S., Dachbrodt-Saaydeh, S., Dreux, L., Jansen, J.-P., Kiss, J., Köhl, J., Kudsk, P., Malausa, T., Messéan, A., Nicot, P.C., Ricci, P., Thibierge, J., Villeneuve, F., 2017. Identifying obstacles and ranking common biological control research priorities for Europe to manage most economically important pests in arable, vegetable and perennial crops: pest management in arable, vegetable and perennial crops in Europe. Pest Manag. Sci. 73 (1), 14–21. https://doi.org/10.1002/ps.4423.

Laurent, A., Makowski, D., Aveline, N., Dupin, S., Miguez, F.E., 2021. On-farm trials reveal significant but uncertain control of botrytis cinerea by aureobasidium pullulans and potassium bicarbonate in organic grapevines. Front. Plant Sci. 12, 620786 https://doi.org/10.3389/fpls.2021.620786.

Louchart, X., Voltz, M., Andrieux, P., Moussa, R., 2001. Herbicide transport to surface waters at field and watershed scales in a mediterranean vineyard area. J. Environ. Qual. 30 (3), 982–991. https://doi.org/10.2134/jeq2001.303982x.

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. Eur. J. Agron. 84, 23–34. https://doi.org/10.1016/j.eja.2016.12.005.

Merot, A., Alonso Ugaglia, A., Barbier, J.-M., Del'homme, B., 2019. Diversity of conversion strategies for organic vineyards. Agron. Sustain. Dev. 39 (2), 16. https://doi.org/10.1007/s13593-019-0560-8.

Merot, A., Belhouchette, H., Saj, S., Wery, J., 2020. Implementing organic farming in vineyards. Agroecol. Sustain. Food Syst. 44 (2), 164–187. https://doi.org/10.1080/21683565.2019.1631934.

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., Wery, J., 2017. Converting to organic viticulture increases cropping system structure and management complexity. Agron. Sustain. Dev. 37 (3), 19. https://doi.org/10.1007/s13593-017-0427-9.

Métral, R., Chevrier, C., Bals, N., Bouisson, Y., Didier, V., Enard, C., Fremond, N., Garin, P., Gauthier, T., Genevet, B., Goma-Fortin, N., Guillios, F., Ohl, B., Thierry, J., 2018. DEPHY EXPE EcoViti Arc Méditerranéen: Synthèse des résultats 2012-2017. Innov. Agron. 70, 3–20.

Ministère de l'Agriculture et de l'Alimentation. (2021). Doses de références des produits phytosanitaires. ⟨https://alim.agriculture.gouv.fr/ift/fichiers-csv⟩.

Mondello, V., Songy, A., Battiston, E., Pinto, C., Coppin, C., Trotel-Aziz, P., Clément, C., Mugnai, L., Fontaine, F., 2018. Grapevine trunk diseases: a review of fifteen years of trials for their control with chemicals and biocontrol agents. Plant Dis. 102 (7), 1189–1217. https://doi.org/10.1094/PDIS-08-17-1181-FE.

Naud, O., Davy, A., Codis, S., 2018. Traiter avec précision – concepts en jeu dans le contexte de la gestion du mildiou et de l'oïdium de la vigne. Innov. Agron. 67, 17–22. https://doi.org/10.15454/F5MZZT.

Niles, M.T., Garrett, R.D., Walsh, D., 2018. Ecological and economic benefits of integrating sheep into viticulture production. Agron. Sustain. Dev. 38 (1), 1. https://doi.org/10.1007/s13593-017-0478-y.

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M.S., Gary, C., Lafond, D., Duso, C., Thiery, D., Mazzoni, V., Anfora, G., 2017. A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. Crop Prot. 97, 70–84. https://doi.org/10.1016/j.cropro.2016.11.025.

Petit, A.-N., Fontaine, F., Clément, C., Vaillant-Gaveau, N., 2008. Photosynthesis limitations of grapevine after treatment with the fungicide fludioxonil. J. Agric. Food Chem. 56 (15), 6761–6767. https://doi.org/10.1021/jf800919u.

Pingault, N., Pleyber, É., Champeaux, C., Guichard, L., Omon, B., 2008. Produits phytosanitaires et protection intégrée des cultures: L'indicateur de fréquence de traitement (IFT). Notes Et. études Socio-économiques 61–94.

Polge de Combret, -, Champart, L., Guilpart, N., Mérot, A., Capillon, A., Gary, C., 2013. Determinants of the degradation of soil structure in vineyards with a view to conversion to organic farming. Soil Use Manag. 29 (4), 557–566. https://doi.org/10.1111/sum.12071.

Pons, A., Mouakka, N., Deliere, L., Crachereau, J.C., Davidou, L., Sauris, P., Guilbault, P., Darriet, P., 2018. Impact of Plasmopara viticola infection of Merlot and Cabernet Sauvignon grapes on wine composition and flavor. Food Chem. 239, 102–110. https://doi.org/10.1016/j.foodchem.2017.06.087.

Raherison, C., Baldi, I., Pouquet, M., Berteaud, E., Moesch, C., Bouvier, G., Canal-Raffin, M., 2019. Pesticides exposure by air in vineyard rural area and respiratory health in children: a pilot study. Environ. Res. 169, 189–195. https://doi.org/10.1016/j.envres.2018.11.002.

Raynal, M., Debord, C., Vergnes, M., & Coulon, T. (2010). Epicure, a geographic information system applied on downy and powdery mildew risks of epidemics on the Bordeaux vineyard. Proceedings of the 6th International Workshop on Grapevine Downy and Powdery Mildew. Bordeaux, 4–9 July, 2010., 144–146.

Rodrigo Comino, J., Keesstra, S.D., Cerdà, A., 2018. Connectivity assessment in Mediterranean vineyards using improved stock unearthing method, LiDAR and soil erosion field surveys: connectivity assessment in Mediterranean vineyards. Earth Surf. Process. Landf. 43 (10), 2193–2206. https://doi.org/10.1002/esp.4385.

Sanson, S., & Joulin, A. (2018). État des lieux de l′usage des produits phytopharmaceutiques en Grand Est. Direction Régionale de l′Alimentation, de l′Agriculture et de la Forêt (DRAAF). 〈https://draaf.grand-est.agriculture.gouv.fr/IMG/pdf/EDL2015_PPP_Grand_Est_vfinal_cle838e9c〉.pdf.

Schauberger, B., Ben-Ari, T., Makowski, D., Kato, T., Kato, H., Ciais, P., 2018. Yield trends, variability and stagnation analysis of major crops in France over more than a century. Sci. Rep. 8 (1), 16865. https://doi.org/10.1038/s41598-018-35351-1.

Schreck, E., Foucault, Y., Sarret, G., Sobanska, S., Cécillon, L., Castrec-Rouelle, M., Uzu, G., Dumat, C., 2012. Metal and metalloid foliar uptake by various plant species exposed to atmospheric industrial fallout: mechanisms involved for lead. Sci. Total Environ. 427–428, 253–262. https://doi.org/10.1016/j.scitotenv.2012.03.051.

Siegfried, W., Viret, O., Huber, B., Wohlhauser, R., 2007. Dosage of plant protection products adapted to leaf area index in viticulture. Crop Prot. 26 (2), 73–82. https://doi.org/10.1016/j.cropro.2006.04.002.

Simonovici, M., 2019. Enquête Pratiques phytosanitaires en viticulture en 2016. Nr. De. Traite Et. Indic. De. fréquence De. Traite 50.

Sinfort, C., Vallet, A., 2003. Modélisation de la dispersion des pesticides pendant les applications. Ingénieries eau-Agric. -Territ. 85–94.

Thierry, D., Yengue, J.-L., 2018. Vigne et ville. Le paradoxe de l′urbanisme. Rev. Des. Oenogues 169, 60–61.

Thiollet-Scholtus, M., Muller, A., Abidon, C., Audema, P., Bailly, C., Chaumonnot, S., Grignion, J., Keichinger, O., Klein, C., 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). Innov. Agron. 76 (1), 219–236.

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. Eur. J. Agron. 123, 126210 https://doi.org/10.1016/j.eja.2020.126210.

Toffolini, Q., Jeuffroy, M.-H., Prost, L., 2016. Indicators used by farmers to design agricultural systems: a survey. Agron. Sustain. Dev. 36 (1), 5. https://doi.org/10.1007/s13593-015-0340-z.

Tsakirakis, A.N., Kasiotis, K.M., Charistou, A.N., Arapaki, N., Tsatsakis, A., Tsakalof, A., Machera, K., 2014. Dermal & inhalation exposure of operators during fungicide application in vineyards. Evaluation of coverall performance. Sci. Total Environ. 470–471, 282–289. https://doi.org/10.1016/j.scitotenv.2013.09.021.

Urruty, N., Deveaud, T., Guyomard, H., Boiffin, J., 2016. Impacts of agricultural land use changes on pesticide use in French agriculture. Eur. J. Agron. 80, 113–123. https://doi.org/10.1016/j.eja.2016.07.004.

Valdés-Gómez, H., Fermaud, M., Roudet, J., Calonnec, A., Gary, C., 2008. Grey mould incidence is reduced on grapevines with lower vegetative and reproductive growth. Crop Prot. 27 (8), 1174–1186. https://doi.org/10.1016/j.cropro.2008.02.003.

Verret, V., Pelzer, E., Bedoussac, L., Jeuffroy, M.-H., 2020. Tracking on-farm innovative practices to support crop mixture design: the case of annual mixtures including a legume crop. Eur. J. Agron. 115, 126018 https://doi.org/10.1016/j.eja.2020.126018.

Viret, O., Dubuis, P.H., Frabre, A.L., Bloesch, B., Siegfried, W., Naef, A., Huber, M., Bleyer, G., Kassemeyer, H.H., Breuer, M., Krause, R., 2011. Www.agrometeo.ch an interactive platform for a better management for grapevine diseases and pests. Bull. IOBC/wprs 67, 85–91.

Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. Agron. Sustain. Dev. 34 (1), 22. https://doi.org/10.1007/s13593-013-0180-7.

Wilson, C., Tisdell, C., 2001. Why farmers continue to use pesticides despite environmental, health and sustainability costs. Ecol. Econ. 39 (3), 449–462. https://doi.org/10.1016/S0921-8009(01)00238-5.

Zhu, X., Liu, W., Chen, J., Bruijnzeel, L.A., Mao, Z., Yang, X., Cardinael, R., Meng, F.-R., Sidle, R.C., Seitz, S., Nair, V.D., Nanko, K., Zou, X., Chen, C., Jiang, X.J., 2020. Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: a review of evidence and processes. Plant Soil 453 (1–2), 45–86. https://doi.org/10.1007/s11104-019-04377-3.

Zuur, A.F., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R. Springer, New York. https://doi.org/10.1007/978-0-387-87458-6.

Momas, I., Caillard, J.-F., Lesaffre, B., 2004. Rapport de la Commission d'orientation du Plan national santé-environnement. Environ. Risques Sante. 3 (3), 141–144.

Brunet, N., Guichard, L., Omon, B., Pingault, N., Pley-Ber, E., et al., 2008. L'indicateur de fréquence de traitements (IFT): un indicateur pour une utilisation durable des pesticides. Le Courrier de l'environnement de l'INRA, 56. Institut national de la recherche agronomique Délégation permanente à l'environnement, Paris, pp. 131–141.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemund, G., Hayes, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S. M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., Yutani, H., 2019. Welcome to the tidyverse. J. Open Source Softw. 4 (43), 1686. https://doi.org/10.21105/joss.01686.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Softw. 67 (1), 1–48. https://doi.org/10.18637/jss.v067.i01.

D. Robinson, A. Hayes, S. Couch (2022). broom: Convert Statistical Objects into Tidy Tibbles. R package version 0.7.12. https://CRAN.R-project.org/package=broom.

Wickham, H. (2009) Ggplot2: Elegant Graphics for Data Analysis. 2nd Edition, Springer, New York. https://doi.org/10.1007/978-0-387-98141-3.

Pebesma, E., 2018. Simple Features for R: Standardized Support for Spatial Vector Data. The R Journal 10 (1), 439–446. https://doi.org/10.32614/RJ-2018-009.

Giraud, T., Lambert, N., 2018. Cartography: Create and Integrate Maps in your R Workflow. JOSS 1 (4). https://doi.org/10.21105/joss.00054.