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Article

Effect of Conversion to Organic Farming on Pest and Disease Control in French Vineyards

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Abstract: Since 2006, an increasing number of French vineyards have chosen to convert to organic farming. One major change in vineyard practices includes replacing chemical pesticides with copper and sulfur-based products in line with Council Regulation (EC) No. 834/2007. This change can make overall management and pest and disease control more difficult and potentially lead to yield losses. From 2013 to 2016, a network of 48 vineyard plots, in southern France, under conventional management and in conversion to organic farming were monitored throughout the three-year conversion phase to investigate the grapevine phytosanitary management of four major pests and diseases and variations in control efficiency. The severity of downy and powdery mildew, grape berry moths, and Botrytis bunch rot were assessed and linked to the protection strategy. The findings showed that pests and diseases were controlled in the third year of conversion at similar efficiency levels as in conventional farming. However, the first two years of conversion were a transitional and less successful period during which higher incidences of cryptogamic diseases were observed. This demonstrates a need for winegrowers to receive more in-depth technical advice and support, especially on pest and disease control, during this critical transition period.

Keywords: organic farming; conversion; pest management; grapevine; powdery mildew; assessment indicator of damage in bunches (AIDB); *Botrytis cinerea*; *Lobesia botrana*; *Erysiphe necator*; *Vitis vinifera*

1. Introduction

To ensure food security while reducing the negative impacts of agriculture, farming systems must be designed and managed in line with ecological principles [1]. However, this agroecological transition involves multiple and interdependent changes in agricultural and farm management practices in relation to the whole agroecosystem [2,3]. Duru et al. [4] proposed the following two pathways for the ecological transition: (i) efficiency-substitution agriculture by improving input use efficiency and limiting environmental impacts, and (ii) biodiversity-based agriculture implying a redesign approach associated with deeper changes [5].

Vineyard cropping systems are particularly affected by environmental and health challenges. In France, reducing pesticide use is a major issue for the viticulture sector, which is the second largest consumer of agrochemical plant protection products after the arable crop sector [6]. The average treatment frequency index (TFI), excluding biocontrol products, is 15.3, which corresponds to an average of 20.1 treatments per year [7]. Pesticide use in viticulture is characterized by two specific features which include the following: (i) high quantities applied on a small area, i.e., an average TFI of 15.3 full doses per hectare on 3% of the French agricultural area, and (ii) a predominance of fungicides (80% of treatments) to control mostly powdery mildew *Erysiphe necator* and downy mildew *Plasmopara viticola*

(Berk & Curt.). Thus, in the current context of production, organic farming (OF) is a viable alternative in vineyard systems.

In the field of crop protection, conversion to OF is an example of an agroecological transition characterized by the elimination of synthetic chemicals (in line with European Union Council Regulation (EC) No. 834/2007), namely those for pest and disease control, i.e., fungicides and insecticides [5]. Throughout this manuscript, "pests" refers to mite and insect pests, and "disease" refers mainly to annual fungal diseases. Weeds are excluded from this study, because the ways of managing weeds and soil covers totally differs from insect and fungi control methods. Conversion to OF in the European Union is a relatively short period of three years for orchards and vineyards that ends in certification. Conversion to OF generally involves a transitional management approach because farmers must adjust technical operations and align them with the certification requirements from the beginning of the first year of conversion [8,9]. They have to find the best way to manage their cropping system in accordance with these requirements, while achieving acceptable and sustainable performances [9]. During conversion, pest and disease management is often considered to be a key technical issue that can potentially lead to significant yield losses [10]. Decreased yields are a frequent concern among growers converting their vineyards to OF. In French commercial vineyards, yield losses have been shown to rise from 0% to 50% with an increase of up to 60% in the multi-pathogen "assessment indicator of damage in bunches" (AIDB) [10]. However, winegrowers did not experience any significant yield losses as long as they maintained the AIDB below a 10% threshold, whatever the pathogen, year, or French region (southeast/southwest) considered [10].

With regard to pest and disease management, the agroecological transition strategy is generally based on three major actions. First, the pesticide dose is reduced [11–13]; second, pesticides with synthetic active ingredients are replaced with nonchemically synthesized products (copper, sulfur, or biocontrol, as allowed in Council Regulation (EC) No. 834/2007); third, more prophylactic measures are implemented when possible (i.e., any action taken to reduce the pathogen inoculum amount or prevent disease spreading) or resistant cultivars are used [9,14]. This implies that the agroecological transition for vineyard pest and disease management requires winegrowers to have more information about the agrosystem functioning, as well as training and advice from extension services [15–17]. For example, copper and sulfur-based pesticides are less persistent and more leachable than that of adequately formulated synthetic chemicals, and so can be less efficient. Growers must also take into account practicalities such as weather forecasts when using these products. New decision rules, management indicators, and decision support systems (DSS) are necessary to improve pest and disease management strategies [11,13,18]. Prophylactic measures also require a deeper analysis of the cropping system, increased planning, and more knowledge of the multiple processes occurring in the biological and agricultural system and their interactions [16,19].

Transition periods are also intense learning periods for growers [15]. During the agroecological transition, growers test and implement transitional pest and disease management methods [20,21]. During this transitional management period, farmers must fill the gap between generic scientific knowledge and local personal knowledge [2,15]. Depending on how successfully they are in doing so, they may or may not be able to limit the conversion-induced uncertainties and variations in agricultural system performances.

Various scientific papers have addressed different questions regarding pests and diseases in organic vineyard systems, but there is a clear lack of knowledge about how multi-pest and pathogen pressure can change or be controlled during the specific three-year conversion period to OF. This also includes the transition process from pesticide-based agriculture (which uses highly efficient active ingredients for preventive and curative treatments) to a more strictly preventive agriculture using organic and biocontrol products, which are much more variable in terms of efficiency and bioavailability [22].

In this study, we followed the dynamics of several key variables characterizing the agronomical performances of vineyards during the three-year conversion phase, in order to gain insight into how growers approach the conversion process and undertake such a major agroecological transition.

Our case study looked at different vineyard management systems in southeastern France, which were monitored for pest and disease severity during every conversion year. Our main hypothesis was that the conversion phase and the changes involved resulted, to a certain extent, in less efficient pest and disease control by the grower. Therefore, the aim was to better understand, by the end of the conversion process, if the growers would be familiar enough with new organic-bound products and practices to obtain sufficient pest and disease control.

2. Material and Methods

2.1. Grapevines (Vitis vinifera) Growing System

Grapevines are perennial plants with a lifespan of several decades. Each growing season, the individual yield per plant is the result of the number of bunches per plant, the number of berries per bunch, and the berry mass. The initiation of the blossoms that appear and grow in year n takes place in year n-1, around flowering time. This process is known to be highly dependent on environmental conditions at this stage, namely water and nutrient status [23]. The number of bunches is a major determinant of the final harvested yield, which is, therefore, highly dependent on the previous year's conditions around flowering time [23].

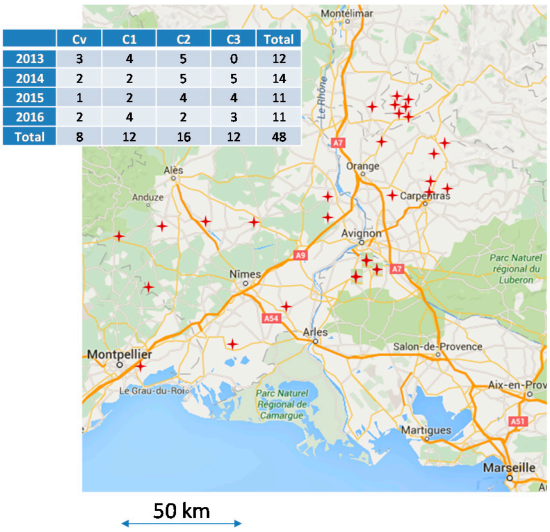
Annual diseases or pest outbreaks can affect the quantity and quality of the yield harvest in the same year. The quantity can be reduced due to the loss of partial or entire bunches, fewer berries on remaining bunches, or lower berry mass. The quality can be reduced, especially with regard to oenological characteristics of the must and wine produced. Major fungal pathogens, including downy mildew *Plasmopara viticola* (Berk & Curt.), powdery mildew *Erysiphe necator (Schwein.)*, and *Botrytis cinerea* (Pers.), are known to be quite harmful for many oenological characteristics [24–27]. Moreover, pests and diseases can affect the overall plant by limiting its capacity to create and stock biomass. Therefore, severe annual outbreaks can weaken the plant for one or more years [28,29].

2.2. Vineyard Network

A network of 25 vineyard plots was monitored across the Mediterranean Côtes du Rhône winegrowing regions in southeastern France (Figure 1). The network is comprised of conventionally grown vineyards (Cv) and vineyards in different stages of conversion as follows: first year of conversion (C1), second year of conversion (C2), or third year of conversion (C3). The vineyard plots were monitored from 2013 to 2016. Most were studied over two consecutive years, resulting in 48 plot * year situations at the end of the monitoring period (Figure 1). Each year, all four types of plots, i.e., Cv, C1, C2, and C3, were monitored (except for C3 in 2013), in order to be able to differentiate the year effect from the conversion effect.

The vineyards were all planted with the same cultivar (Grenache), which is typical of the French region studied. The year of planting ranged from 1980 to 2004. All plots were grown entirely for commercial production. The planting density was quite homogeneous across the network, varying between 3500 and 4500 vines per hectare. The trellising system varied among plots so as the rootstocks. In each plot, 30 vine stocks were monitored, which were distributed on three or five equidistant rows, and 10 or six regularly distributed vine stocks were selected in each row. Over the four years on the whole network, 1440 vine stocks were monitored.

Vine stocks showing clear symptoms of grapevine trunk disease (Esca *Stereum hirsutum* Per. Et *Phellinusigniarius* FR, and Eutypiose *Eutypa lata* mostly) were avoided because berries tend to dry on these vines, and this modifies annual diseases development. On each of the 30 sampled vine stocks, one reproductive organ, i.e., an inflorescence becoming a bunch, was monitored at three critical development phases, i.e., flowering, veraison, and harvest. By using the Eichhorn and Lorenz 1–47 scale, modified by Coombe [30], these main phenological stages corresponded to flowering ("full bloom," 50% caps off, code 23), veraison (berries begin to color and enlarge, code 35), and harvest (berries harvest-ripe, code 38).



	Cv	C1	C2	C3	Total
2013	3	4	5	0	12
2014	2	2	5	5	14
2015	1	2	4	4	11
2016	2	4	2	3	11
Total	8	12	16	12	48

Figure 1. Experimental network and number of plots in each stage of conversion monitored each year (Cv: conventional farming; C1 to C3: first to third year of conversion to OF). Red stars on the map indicate monitored vineyard plots. Some plots were followed two consecutive years. The network covers several geographical indications of the Mediterranean wine region (Rhône village wines, Ventoux wines, Chateauneuf du Pape wines, Costières de Nîmes and Languedoc wines, Southern Gard wines, and Southern Rhône wines).

The protection strategies were also monitored in each plot every year. Biocontrol interventions were counted in addition to synthetic-based interventions and non-synthetic-based interventions mostly copper and sulfur (Table 1). Plots in all stages of conversion were characterized by the absence of synthetic ingredients, as set out in the organic certification requirements. Copper based-products were used in conversion towards OF and biocontrol products were used for pest control (e.g., *Bacillus thuringiensis* and mating disruption) and powdery mildew control (sulfur-based products). The use of biocontrol increased from Cv to C1, C2, and C3. Conventional plots mainly used synthetic products, although sulfur and copper treatments were also used occasionally. Botrytis was not controlled during the conversion period and only at a very low level in conventional farming (average value 0.17 treatment/year).

Table 1. Protection strategies (number of treatments) adopted for the four types of plots Cv, C1, C2, and C3. Synthetic pesticides were separated from not-synthetic pesticides and biocontrol products to take into account different modes of action.

	Synthetic Pesticides		**Non Synthetic Pesticides Without Biocontrol Products**		**Biocontrol**	
	Fungicides (Powdery and Downy Mildew)	**Insecticides**	**Fungicides (Powdery and Downy Mildew)**	**Insecticides**	**Fungicides (Powdery and Downy Mildew)**	**Insecticides**
Cv	11	15	0	0	4.4	0
C1	0	0	5.2	0.2	4.8	0.1
C2	0	0	6.4	0.05	6.4	0.06
C3	0	0	5.6	1.1	6.7	0

Finally, each plot in conversion towards organic farming was characterized in terms of intensity of change. According to [31] (diversity of conversion strategy), four types of conversion towards organic farming (OF) were identified in Southeastern France: administrative conversion (A), precise conversion (B), innovative conversion (C), and abrupt conversion (D). The intensity of changes during conversion increased from type A to type D. We hypothesized that the less intense the conversion is, the better is the success of the protection strategy during the conversion.

2.3. Pest and Disease Monitoring

The four prevalent cryptogamic diseases in the region are the following: (i) downy mildew due to *Plasmopara viticola* (Berk & Curt.), (ii) powdery mildew due to *Erysiphe necator* (Schwein.), (iii) Botrytis bunch rot (BBR) or gray mold due to *Botrytis cinerea* (Pers.), and (iv) black rot due to *Guignardia bidwellii* (Ellis, Viala & Ravaz 1892) (anamorph *Phyllosticta ampelicida*). All of these diseases were monitored on inflorescences or grape bunches (1440 observations) by visually estimating their severity at flowering, veraison, and harvest. Disease severity was estimated as a proportion (directly as a percentage) of the external surface area of the inflorescence or bunch showing typical symptoms of attacks by this pathogen (often sporulation signs) [10,32]. Observations were conducted by pairs of observers; one observer was present during the whole experiment, the second observer varied from one year to another but the bias potentially introduced was taken into account in the year effect (see paragraph 2.5). Black rot disease, which had previously been negligible, spread across the plot network in 2014, with very high severity in some places (up to 50%). Therefore, we decided to monitor this disease in 2015 and 2016, but these two years were not sufficient to perform a specific statistical analysis of the disease. The number of berry moth larvae of *Lobesia botrana* (Denis and Schiffermüller, 1775) and *Eupoecilia ambiguella* (Hübner, 1796) were estimated by counting the number of silky nests ("glomerules") per inflorescence at flowering (first generation assessment) [33].

One or two days before the general harvest of the vineyard by the grower, we collected the 30 bunches monitored in each plot. We used half of them (720 bunches) to measure a key yield component, i.e., the number of berries, in which we separated healthy berries from diseased berries. We used the remaining 15 bunches to estimate the number of berry moth larvae (third generation), which were assessed on a per bunch basis using the "brine method" (according to [10,34]). Each bunch was broken down into smaller pieces of a few berries and soaked in salt-saturated water. We used a batch of five bunches in 3 L of brine (NaCl, ~170 g/L of water) for 60 to 90 min in a bucket, and then counted the number of floating larvae at the brine surface.

The data presented hereafter relate only to pest and disease symptoms observed at harvest because their levels at intermediate phenological stages were too low to perform statistical analyses. On the basis of these observations, we characterized each plot, for each pest or disease, by the following: (1) The disease incidence, calculated as the frequency of infected plants among our 30-plant sample, and (2) the severity measured in infected plots.

We also measured and calculated the following two overall multi-pest indicators: (i) the AIDB indicator proposed by Fermaud et al. [10], and (ii) the percentage of healthy berries at harvest, i.e., without any visible pest or disease symptom or abiotic damage. The percentage of healthy berries at harvest was measured on the 15 separated bunches. This second indicator integrated black rot disease. The AIDB, an assessment indicator that includes four major pest and disease symptoms in reproductive organs, was calculated by combining the severity of downy mildew and gray mold at flowering, as well as the severity of powdery mildew, downy mildew, gray mold, and grape berry moth measured in bunches from veraison to harvest [10]. This indicator is a tool for characterizing the result of the pest and disease pressure and the grower's protection strategy over a growing season. Therefore, we considered that AIDB values over 10% indicated a problem in the grower's pest and disease control strategy [10]. We tracked the frequency of these unsuccessful situations in our plots.

2.4. Overall Climatic Conditions and Natural Pest and Disease Pressure at the Regional Scale

From 2013 to 2016, we analyzed the regional climatic conditions and natural pest and disease pressure in the grapevine growing area selected (Figure 1). The whole network area is characterized by a typical Mediterranean climate. The average annual climatic features, based on 1981–2010 data from Météo-France, the French national meteorological service, gathered at the "Carpentras-Serres" site, are the following: (i) minimum temperature, 8.1 °C; (ii) maximum temperature, 20.6 °C; (iii) rainfall, 648 mm; and (iv) number of rainy days, 65.7 days. Following the methodology proposed by Renaud-Gentie et al. [35], we performed a hierarchical classification on these climate data. We used the monthly rainfall amounts and monthly average minimum and maximum temperatures from April to September for the years 1993 to 2017. Three major Mediterranean annual climatic types were identified. They were observed during the four years of this study, as shown in Table 2a.

Table 2. Patterns of climatic conditions (a; W1 to W3) and pest and disease pressure (b; P1 to P3) identified in the Southeastern of France during the experiment, and years of occurrence.

	(a) Climatic Conditions	Year of Occurrence
Pattern W1	Temperature slightly below average and rain over average from January till September, fewer hot days (>30 °C) than average, sunny summer, very dry in June and August, "humid" in May and July	2013
Pattern W2	Slightly over average temperatures January–April, average temperatures in summer, more rain than average June–August	2014
Pattern W3	Less sunny than average July–September, less rainy than average, temperatures over average April–July	2015, 2016
	(b) Pests and Diseases Pressures	
Pattern P1	Very low downy mildew at harvest, grape moths at a very high level in first generation and high level in third generation	2015, 2016
Pattern P2	High number of moths at harvest, high severity of powdery mildew and low severity of downy mildew at harvest	2014
Pattern P3	At harvest, very high downy mildew and low powdery mildew pressure, very high number of second-generation grape moths	2013

In order to quantify pest and disease pressure at a regional scale, we used data collected from annual reports published by agricultural warning services. These reports rely on a large number of phytosanitary experts and numerous vineyard plots (including untreated plots) that are observed regularly in the region, and therefore offer a reliable characterization of the overall pest and disease pressure in vineyards. In these reports, three indicators of pest and disease pressure were extracted every year. The first was downy mildew pressure, indicated by the prevalence of healthy plots with very low levels of infestation, i.e., the percentage of plots in the network with, at most, five of the 50 monitored grape bunches presenting symptoms all season along. The second was for powdery mildew pressure, which was measured by the disease prevalence at bunch closure, i.e., the percentage of plots in the network with more than 10% of the monitored grape bunches expressing typical symptoms of the disease. The third was pressure from the main insect pest in the region, grape moth (mostly due to *Lobesia botrana*), which was indicated by the percentage of plots in the network with less than 10% of the monitored grape bunches showing typical second-generation larval symptoms.

We performed a hierarchical classification on these pest and disease data. We used the three indicators described above from years 2005 to 2017. Three biotic annual pattern types were identified (Table 2b) and represented during the four years of our study.

2.5. Statistical Analysis

Different statistical analyses were performed to assess the effects of the conversion process, characterized by the years of conversion (C1, C2, and C3) as compared with the conventional system (Cv), on variables expressing the pest and disease levels. These analyses were carried out with R statistical software version 3.5.0 [36]. To be able to test different effects on the pest and disease variables, generalized linear mixed models (GLMMs) were used to have a broad range of models for the analysis of grouped data. Two statistical approaches are combined in GLMMs, therefore, we were able to (i) take into account random effects in linear mixed models, and (ii) deal with non-Gaussian data without using prior transformation [37,38].

We tested three candidate GLMMs for each variable (X) to analyze the process of conversion, and then selected the best model (see below for model selection). The type of plot (Cv, C1, C2, and C3), as an indicator of the process of conversion to organic farming, was taken into account in the model as a fixed effect (C).The "year" (Y) was introduced in two models as a random effect to take into account annual variations such as climatic conditions, and we also added in two models a "plot" (P) random effect to deal with plot individual particularities. The GLMMs were used with a binomial distribution on the "frequency of infested or diseased vine stocks per plot" and the "success of the protection strategy" by using the function glmer of R package lme4 [39]. To analyze "severity" variables, "AIDB" (%), and the percentage of healthy berries, we used mixed linear regression models with Gaussian distribution (function lme of R package nlme [39,40]).

C-YP: X ~ type of plot + year effect + plot effect + residuals

C-P: X ~ type of plot + plot effect + residuals

C-Y: X ~ type of plot + year effect + residuals

In order to deal with heteroscedasticity, we added a structure of variance (-V) to the mixed C-YP model. We chose a constant variance-covariance function structure allowing a different variance for each level of the conversion * year factor (interaction between stage of conversion and year) [38]:

C-YP-V: X ~ type of plot + year effect + plot effect + variance-covariance effect + residuals.

For each variable, we used the Akaike information criterion (AIC) to select the best model for our data [41,42]. The effect of the conversion process on each variable was tested by performing an ANOVA with the best GLMM. When significant differences were found, we performed a multiple comparison test among the different "types of plots" on the model outputs to analyze the effect of the conversion in greater detail (R package multcomp, [43]). In ANOVAs, as well as multiple comparison tests, we considered significance at the classical level of 0.05.

3. Results

3.1. Mixed Models Selection and Estimation

As explained in Section 2.5, the structure of the data led us to use different models for testing whether the stage of conversion influenced significantly, or not, the different variables monitored. For every variable, Table 3 shows the model selected, the significance of the conversion process, and the adjusted conversion stage. In most cases, the AIC criteria led to select the model including the stage of conversion, the year, and the plot effect (C-YP model) as compared with other models containing, only, either the stage of conversion and the year (C-Y) or the stage of conversion and the plot (C-P). Some of the studied variables, i.e., mostly severity variables, showed heterogeneity of variance. In order to take this heterogeneity into account, as mentioned in Section 2.5, we tested the mixed model with the variance-covariance structure containing the stage of conversion, the year, and the plot effect (C-YP-V). When tested, the model with variance structure (C-YP-V) was the best one following the AIC criterion, and fulfilled the conditions of normality and homogeneity of variances. Therefore, it was used to perform the statistical analyses (ANOVA and multiple comparisons). Thus, we found a significant effect of the conversion process on most of the incidence variables, but not on the severities monitored in the uninfected plots (Table 3). More detailed results are presented in the following paragraphs.

Table 3. Effect of the conversion process: model result, significance test, and adjusted means for each studied variable in the vineyard plot network. Model types are described in Section 2.5 (C, Y, and P represent conversion, year, and plot effects, respectively, and V is the variance effects), significance of conversion effect is indicated by the model *p*-value, and significantly different adjusted means at 5% threshold are followed by different letters.

Variable	**Model**		**Adjusted Means**			
	Model Type	***p*-Value**	**Cv**	**C1**	**C2**	**C3**
Per-pathogen results						
Downy mildew incidence	C-YP	0.01	0.27 ^{ab}	0.30 ^{ab}	0.40 ^{a}	0.27 ^{b}
Downy mildew severity in infected plots	C-YP-V	0.31	0.27	0.34	0.29	0.12
Powdery mildew incidence	C-P	0.0002	0.0049 ^{b}	0.068 ^{a}	0.044 ^{ab}	0.038 ^{b}
Powdery mildew severity in infected plots	C-YP-V	0.15	0.10	0.048	0.053	0.033
Botrytis incidence	C-YP	0.0001	0.36 ^{a}	0.26 ^{a}	0.18 ^{b}	0.23 ^{ab}
Botrytis severity in infected plots	C-YP-V	0.16	0.14	0.10	0.13	0.079
Grape moth incidence	C-YP	0.68	0.90	0.63	0.62	0.56
Grape moth severity in infected plots	C-YP-V	0.02	0.40 ^{a}	1.18 ^{a}	0.41 ^{a}	0.31 ^{a}
Synthetic indicators						
Frequency of plots with AIDB exceeding 10%	C-YP	0.002	31.6 ^{ab}	42.2 ^{a}	33.6 ^{a}	25.3 ^{b}
AIDB in infected plots	C-YP-V	0.37	41.1	44.1	43.5	25.5
% healthy berries	C-YP-V	0.29	81.4	65.1	65.5	74.7

AIDB–assessment indicator of damage in bunches

3.2. Per-Pathogen, Mono-Disease Analyses

3.2.1. Downy Mildew

The stage of conversion towards OF of the plot significantly influenced the incidence of downy mildew, measured at harvest by the frequency of infected plants per plot (p-value = 0.013) (Figure 2a). The significant influence of the process of conversion on downy mildew incidence was based on a relatively low disease incidence in conventional plots, with approximately one plant out of four infected by downy mildew (Cv, 0.26). From the conventional stage, the incidence of downy mildew increased slightly in the first year of conversion (C1, 0.29) and more deeply in the second year of conversion, reaching 0.40 in C2. In the third year of conversion, the incidence of downy mildew decreased back to a level close to that observed in conventional plots (C3, 0.27).

Among the plots affected by downy mildew at harvest, the severity decreased from the first year of conversion (C1) to the third year (C3) (Figure 2b). The average severity in infected plots reached 0.38 in C1, was intermediate in C2 (0.30) and decreased markedly down to 0.14 in C3.

3.2.2. Powdery Mildew

The levels of powdery mildew incidence remained low among the plot * year situations during the whole experiment, mostly not exceeding one-tenth of infected plants (Figure 2c). However, clear variations were noticeable in symptom expression between the different plot types considered. In most of the conventional plots, we did not observe any powdery mildew symptom at all, corresponding to an average incidence of 0.005. While remaining rather low during the whole conversion process, the powdery mildew incidence was significantly influenced by the type of plot (p-value < 0.001). The average disease incidence was 0.067 in C1 plots, 0.047 in C2 plots, and decreased to 0.039 in plots undergoing third year of conversion. Within diseased plots only, the mean severity at harvest did not differ significantly between the three years of conversion and conventional situations (Figure 2d, p-value = 0.396).

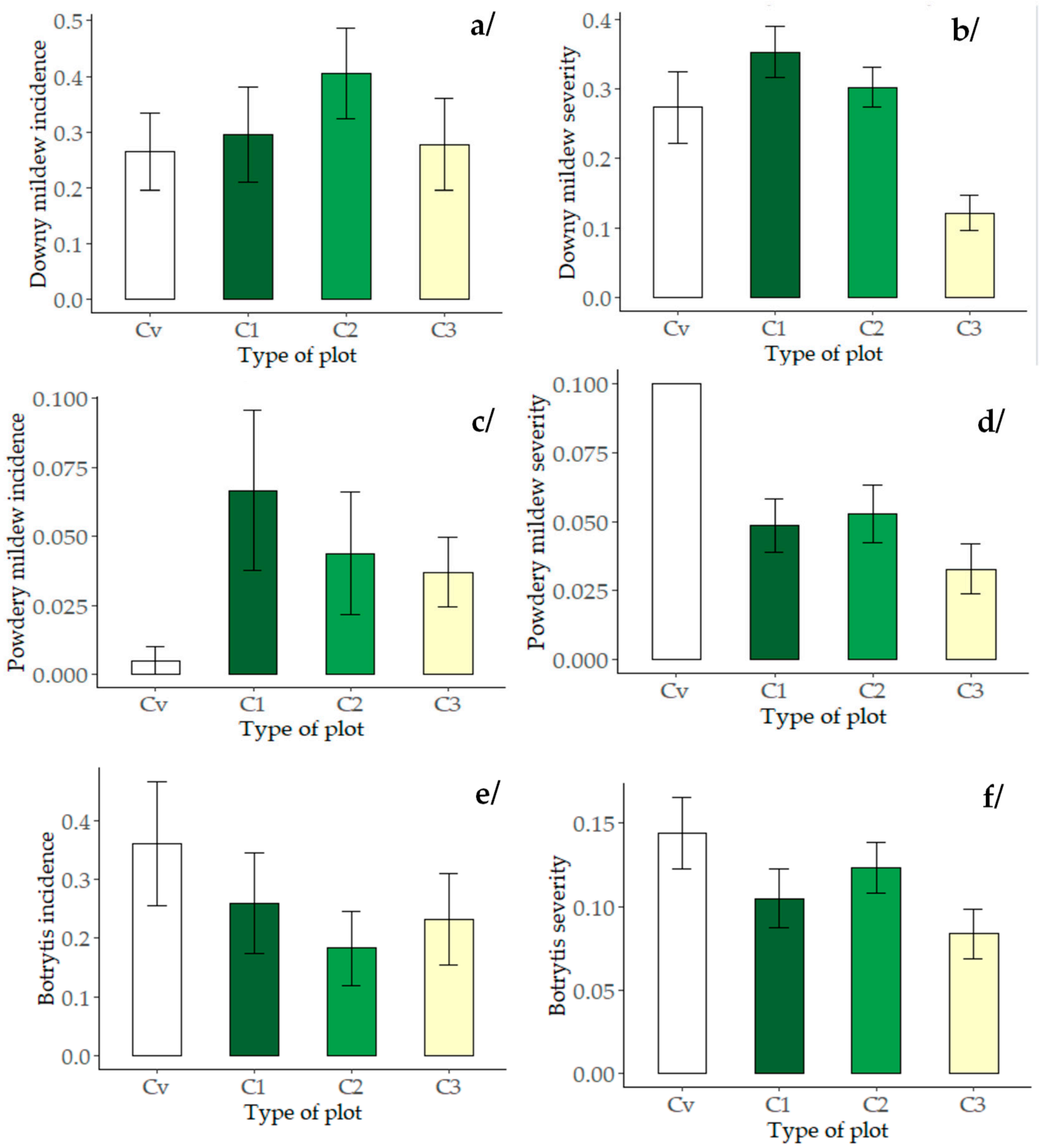


Figure 2. Pathogen incidences and severities in infected plots (downy mildew, powdery mildew, and Botrytis) monitored on the vineyard network depending on the type of plot. (**a**,**c**,**e**): frequency of infected plants per plot (incidence); (**b**,**d**,**f**): severity of each pathogen as measured in infected plots where incidence >0. Error bars represent standard errors.

3.2.3. *Botrytis*

The severity levels of Botrytis bunch rot (BBR) in the plot network were low during the four-year experiment (less than 6% in average). However, as for powdery mildew, clear variations in symptom expression were noticeable between the different plot types. A significant effect of the conversion process was shown on the incidence of BBR (p-value < 0.001, Figure 2e). The BBR incidence was significantly lower in the second year of the conversion towards OF (average incidence = 0.18) than in conventional plots (0.36), or in C1 (0.25). The BBR incidence was intermediate during the third year of conversion to OF with an average of 0.23 (Figure 2f). The average disease severity in the BBR-affected plots was 0.14 in conventional plots, 0.10 in C1 plots, 0.12 in C2 plots, and 0.08 in C3 plots. Although there were significant differences in disease incidence, we did not find any significant effect of the conversion stage on Botrytis severity in our trial.

3.2.4. Grape Moth

Considering grape moth incidence, we did not find any significant difference between the different plots undergoing different stages of conversion towards OF (Figure 3a). The grape moth frequency was lower in the in-conversion plots (C1, 0.60; C2, 0.60; and C3, 0.55) than in conventional farming (av. incidence = 0.86). In infested plots, we found significant differences in grape moth severity at harvest between the four types of fields (p-value = 0.02, Figure 3b). The average number of larvae per bunch was 0.40 in conventional plots, 2.1 larvae in C1 plots, 0.41 larvae in C2 plots, and 0.63 larvae in C3 plots.

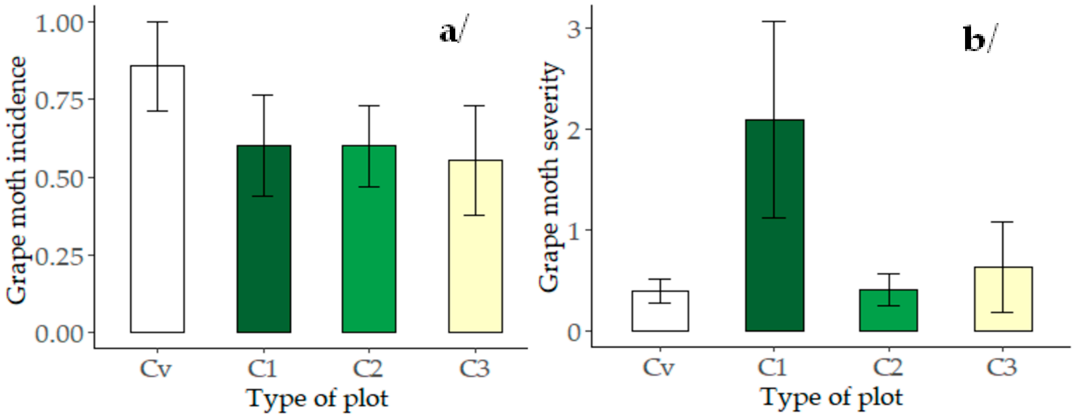


Figure 3. Mean grape moth incidence (frequency of infested plants (**a**), and severity in infected plots (number of larvae per bunch (**b**), in the plots, depending on their stage of conversion (Cv, conventional production; C1, C2, and C3 represent first, second, and third year of conversion, respectively). Error bars represent standard errors.

3.3. Integrated Multi-Pathogen Approaches

3.3.1. Assessment Indicator of Damage in Berries (AIDB)

The frequency of plants showing unsuccessful protection (AIDB higher than 10%) in each plot * year situation depended significantly on the type of plot (Figure 4a, p-value = 0.0023).

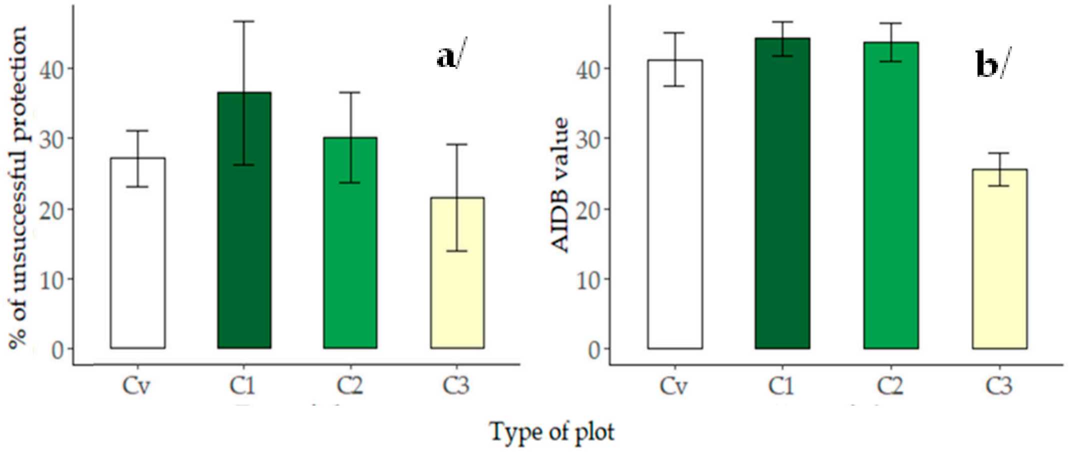


Figure 4. Multi-pathogen indicators observed in conventional and in-conversion plots. (**a**) Percentage of plants per plot showing unsuccessful protection strategies (assessment indicator of damage in bunches (AIDB) > 10%); (**b**) AIDB mean values in plots showing unsuccessful protection.

Marked and significant differences were noticeable between conventional farming and plots undergoing conversion towards OF in the percentage of unsuccessful strategies against the four main pest and diseases considered (*p*-value = 0.0023). In conventional farming, the protection failed (AIDB > 10%) in one-third (32%) of the studied plots x year combinations. The protection strategies were less efficient in plots undergoing first and second years of conversion (C1 47% and C2 37%), with a higher variability of the results during these two stages of conversion. In the third conversion year C3, the percentage of failure situations was at the minimum, i.e., 23%, meaning that less than a quarter of the studied cases showed a multipest damage indicator (AIDB) exceeding 10%. We observed a significant difference between the third year (C3) and the first two ones (C1 and C2) (Table 3).

In order to further understand the previous results, we focused on AIDB values when the plot protection was unsuccessful (AIDB > 10%). There was no significant difference in the mean AIDB values between the different stages of conversion (Figure 4b). The mean AIDB values were as follows: 39% in conventional plots, 47% in C1, and 40% in C2 plots. Interestingly, although not significant, the multipest damage indicator was the lowest during the third year of conversion, C3 (28%), when focusing on the situations with AIDB > 10%. This third year of conversion C3 was also associated with a lower variability, suggesting an overall better control of pest and diseases, in keeping with the previous results of percentage of unsuccessful control strategies.

3.3.2. Healthy Berries Percentage

The percentage of healthy berries at harvest was analyzed as a proxy of yield losses at harvest. This integrated variable may take into account all pests and annual diseases, in particular some more sporadic pathogens (not included in the published AIDB equation in [10]). In these experiments, Black rot, notably in 2015 and 2016, and to a lesser extent, sour rot in 2016, affected grapevine berries and were not included in the previous AIDB calculations (see Figure 5).

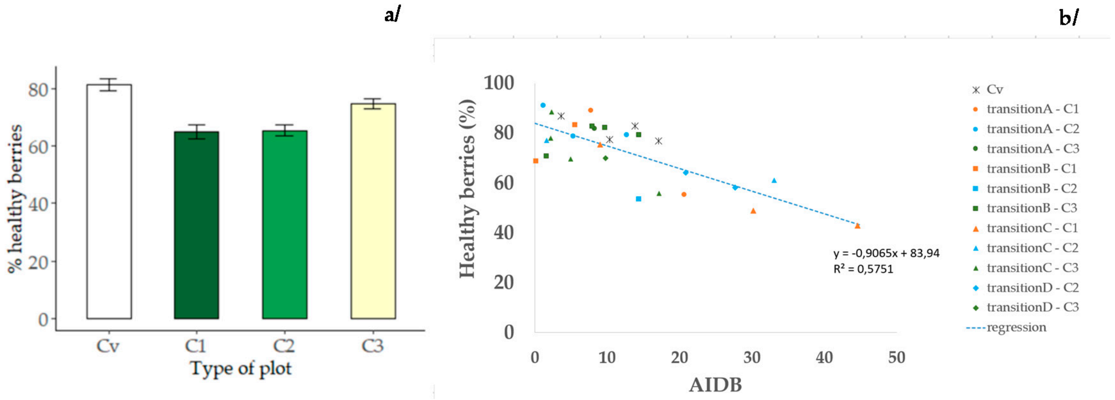


Figure 5. Percentage of healthy berries at harvest measured on conventional and in-conversion plots. (**a**) Dynamics of healthy berries percentage during conversion (error bars represent the standard errors); (**b**) Relationship among healthy berries percentages and AIDB (linear regression), the symbol shape indicates the intensity of the conversion process from A to D, the color shape indicates the stage of conversion (C1 to C3). We excluded two outliers from the analysis of this relationship which consisted of two plot * year situations with low percentages of healthy berries (21 and 37%) but null or quasi-null AIDB values. We identified them as 2015 occurrences of high severities of Black rot, not taken into account by AIDB.

The percentage of healthy berries measured at plot scale ranged from 43% to 91%, indicating a potential significant yield loss in some plot * year situations. The overall dynamics of healthy berries percentage appear to be similar to those observed for the frequency of unsuccessful protection. However, there were no significant differences (*p*-value = 0.29) among the four types of plots in conventional farming or in conversion (Figure 5a). The average percentage in conventional plots was 81%. Lower percentages of healthy berries at harvest (respectively 66% and 65%) were assessed in C1 and C2. In the third year of conversion C3, the percentage of healthy berries almost reached the level observed in conventional plots (75%).

The relationship between AIDB and the percentage of healthy berries at harvest was significant (p-value < 0.01 on 29 situations) (Figure 5b). As expected, when AIDB increased, the percentage of healthy berries decreased linearly. For example, an AIDB value of 30% corresponded approximatively to 55% of healthy berries. An AIDB value of 0 indicated no damage in bunches by any pest or disease, corresponding to a successful protection strategy. This was associated with an average percentage of healthy berries of 83.9%. The 16% gap can be accounted for by some yield loss factors not taken into account in the AIDB calculation (e.g., abiotic or biotic factors such as Black rot, Sour rot, berry shriveling, etc).

4. Discussion

The main objective of this study was to show an effect of the process of conversion towards organic farming on levels of major pest and diseases in vineyards. We monitored the levels of three major vineyard diseases and one key pest targeted mostly by pesticides in viticulture worldwide (downy mildew, powdery mildew, Botrytis, and grape berry moth). We measured the success of the protection strategy by using the multi-pathogen AIDB indicator and the percentage of healthy berries at harvest, and we compared the values in plots managed in conventional system or undergoing the three-year process of conversion to OF. Our key conclusion is that pests and diseases are controlled at a similar level in conventional farming as compared with the third year of conversion. However, higher pest and disease incidences and severities were detected in the first two years of conversion to OF. This pattern was observed for each of the different diseases considered except for botrytis and was also indicated by using the multi-pathogen AIDB indicator [10].

During the transitional period of the first two years of conversion to OF, the rate of unsuccessfully controlled plots (AIDB > 10%) was higher than in the conventionally managed plots (Cv). This was especially noticeable in the first year of conversion, C1, with a mean value of 42% unsuccessfully controlled plots vs. 35% in Cv plots, showing a 20% relative increase when starting the conversion process. This indicated a general lack of control of the four major pests and diseases (Figure 5), because the protection strategies implemented according to organic certification rules, especially in C1, tended to be less efficient than in the Cv plots. The effects of the management system on multi-disease control efficiency and yields have also been observed in previous studies. In German vineyards, yields resulting from organic and biodynamic plant protection strategies decreased partially, due to higher disease incidence as compared with an integrated treatment strategy [44]. Similarly, significant differences in downy mildew incidence have occurred among integrated, organic, and biodynamic Austrian vineyards [45]. This confirms our main hypothesis that the process of conversion to OF is associated with significant variations in pest and disease control efficacy for winegrowers. As in the above-mentioned German and Austrian studies, which highlighted downy mildew as the main disease that winegrowers had to contend with, we found fungal diseases to be the major issues for winegrowers, primarily downy mildew. Downy mildew has been commonly described as the most serious grapevine disease in relatively warm and humid summer conditions, with the potential for complete defoliation and crop destruction. It can also lead to lower grapevine vigor the following year after an epidemic [28,29,32,46]. Accordingly, in the present study, the high levels of downy mildew severity were unacceptable leading to high levels of AIDB. The negative relationship between AIDB levels and the percentage of healthy berries showed that the high levels of downy mildew severity negatively impacted the percentage of healthy berries at harvest (analyzed as a proxy of yield losses at harvest).

In this context, BBR can also be considered to be a key disease, given that in the German study [44], BBR severity was higher in the biological management systems studied, for example, significant in the biodynamic system. Although we studied a susceptible cultivar [47], the disease severity was mostly low to moderate. Overall, the final severity of the disease was lower than or close to 5% at harvest, which can be considered to be both a quantitative and qualitative threshold [26]. Nevertheless, we detected a significant decrease in BBR incidence in the second year of conversion as compared with the conventional plots. This key result, which is contrary to that obtained in the German study [44], is very likely explained by differences in BBR control. Synthetic botryticides were used in the conventional system in Germany, but no treatments were applied in the conventional conditions in this present study (as mentioned in Table 2). Since they are targeted specifically against the fungal pathogen, synthetic botryticides are indeed extremely effective against *B. cinerea* except when resistant strains of the pathogen develop. As expected, they have a very significant effect on the results of such studies. The absence or low use of synthetic botryticides in vineyards in Southeastern France [6] is often due to economic reasons such as the high cost of these specific chemical fungicides as compared with the relatively low overall BBR climatic risk in the region. Finally, powdery mildew epidemics are capable of partially or totally wiping out yields [24,25] and the control of the pathogen was also affected during the conversion process. However, powdery mildew infections remained quite low throughout the study. The overall disease severity can be considered to be at an acceptable level in every study year. The incidence was mostly lower than 5% (Figure 2c), which can be considered to be very low in terms of potential yield loss [25]. Furthermore, from a qualitative or oenological point of view, the acceptable threshold corresponds to 20% of diseased berries in a harvested production [24,46]. Thus, based on all these multi-pathogen results, we can hypothesize that a significant part of the yield losses reported during conversion, particularly during the first two years, can be explained by a lack of control of the major fungal diseases, and chiefly downy mildew. In addition, in other perennial cropping systems such as orchards, it has been reported that the difference between conventional and organic farming did not show a clear dichotomy between the two modes of production [48]. This confirms our results in C3 as compared with the conventional plots.

One major issue encountered when studying the conversion of perennial-based cropping systems was data collection. The processes we studied, namely disease and pest epidemiological development, were highly dependent on annual climate. Therefore, multiyear trials are undeniably needed that include the different stages of conversion in every studied growing season. In order to limit other sources of variability, we had to restrain the monitored geographical area and limit to one grape cultivar only. Despite these restrictions, the plot network still showed a considerable range of different practices, soil types, microclimates, and types of wine produced. This diversity resulted in very high variability in the dataset. Thus, to be able to detect and show significant effects of conversion on pest and disease control, it was crucial to use statistical models with a "plot" and a "year" effect and a specific component for taking variability into account [38]. When selecting the model, the "year" effect was significant for all variables studied, except for grape berry moth. Furthermore, the highest incidences and severities of fungal diseases that we measured at harvest corresponded exactly to the years also reported as severe at the regional scale [48,49]. The year effect is a crucial one to be taken into account statistically in such relatively short studies (three years), because natural disease pressure can be quite low or null in a few study seasons. For example, Doring et al. [44] clearly showed the occurrence of a significant interaction between the management-system effect and the year effect. They experienced one season (2011), out of three, without any significant downy mildew damage, but another season (2010) in which approximately 10% of yield loss was due to the disease. Similarly, such key interactions were also noticeable in previous French viticultural studies including marked interseasonal effect, i.e., 2011, characterized by a very low downy mildew pressure [10]. Among the four years in the present study, the highest downy mildew severity was noticeable in 2013, and lower pressure of the disease occurred in 2015 and 2016. Despite all these differences, the network and the time span of the experiment were effective in analyzing and demonstrating some of the main effects of conversion to OF in real production situations.

The differences we observed between conventional farming, the first two years of conversion to OF, and the third year of conversion were in keeping with the observation made by Merot et al. [9] on the progress of the winegrowers' ability to manage grape protection against the major pests and diseases. There was no significant effect of the conversion stage on grape berry moth infestation (either incidence or severity). To control this pest, shifting from conventional to conversion to OF often came down to just substituting one or more products, with similar mode(s) of action or similar logical ground(s) for decision making [9]. For the major cryptogamic diseases, the shift to organic production can be based on additional changes in phytosanitary product choice. In the Mediterranean context, a detailed analysis of the changes in downy and powdery mildew management during the conversion to OF showed that synthetic active materials were first replaced in C1 by copper/sulfur-based products [9]. This can, at first, be considered to be a direct substitution for downy and powdery mildew control. However, then, growers, in C2 and C3, introduced adjustments in the doses and frequency of application. In practice, the properties of formulated copper/sulfur-based products are different from synthetic products. They are leachable and may also be less effective and exhibit a higher efficiency variability [50,51]. The direct consequence is the need for an increased number of treatments and a higher dependency on rainfall events following every spraying. Our results on fungal disease control showed that there was a learning process for winegrowers associated with changes in their practices [15,17,52]. The changes led to a higher level of fungal symptoms and multi-disease severity in C1 and C2 plots. However, the variability in disease severity in C1 and C2 indicates that the learning process can be faster for some winegrowers than for others. Further investigations would be of interest for a more detailed analysis of the treatment schedules to better understand why some growers were much more successful than others. The disparity can also be, partly, due to differences in the vineyard starting point before conversion, such as the following key growers' features, but also the intrinsic plot susceptibility [9]. Some winegrowers, beforehand, had implemented certain organic practices before the conversion towards OF and had the knowledge necessary to speed up the conversion process [9,53]. This was the case for growers in "type A" conversion [31], whose situations in conventional farming in terms of grape protection did not differentiate from growers in organic management. For other intense conversions "types C" and mostly "D", the conversion process to OF was an important change observed in the first year of the conversion [9,31], with the stoppage of synthetic-based interventions which were replaced by non-synthetic-based interventions with mostly copper and sulfur. Additional changes in practices, even in C3, were also required [9,53]. This undoubtedly contributed to account for the variability of disease severities we observed in C1 and C2. Furthermore, even if the average disease severity in C3 was comparable to that in conventional plots in our study, Doring et al. [44] reported a slight decrease of yields in organic vineyards due to higher downy mildew incidence. Thus, even if we have shown that growers were able to achieve quite efficient disease control at the end of the conversion, the mode of action of copper and sulfur-based treatments, which are more leachable than synthetic based-treatments [50], increased the risk of an unsuccessful protection strategy.

The present study also suggests that the conversion to OF must be supported by advisors to limit the increase in multi-pathogen incidence or severity during the first and second year of the conversion. Beyond knowledge of rules, regulations, and the administrative conversion process, farmers need to better understand and monitor the key epidemiological features of major pests and diseases. Similarly, they need to improve their expertise on the mode(s) of action of available products and have better access to practical advice for optimizing use of the control products (e.g., specific decision support system when available). They need to precisely identify pests and diseases and increase the use of decision support tools to make every management decision. Some of these tools could be specific to the transition process to help in implementing changes, such as those during the conversion to OF to adjust doses and treatment frequencies [54]. Toffolini [17] suggested that indicators are mostly designed to impact assessment while they should be designed also to efficiently "serve farmer's action and learning during the transitions of their cropping system" taking into account the function that "indicators fulfill in the course of a farmer's action".

Finally, the present study provided insight into some of the difficulties during the conversion period to OF. As mentioned above, supporting farmers converting to OF could limit epidemiological risks, but our results showed that beyond the need for the growers to increase their expertise for a successful transition, conversion could lead to yield losses. This is a critical issue, from our point of view, and financially, subsidies for OF conversion would be necessary in many situations. Thus, the analysis of the yield dynamics and the yield components affected during conversion should be further investigated to more precisely identify potential loss and economic impacts of major pests and diseases. This should help to anticipate and better understand possible losses in both grape and must production throughout the conversion process. There were some constraints in this study, such as the restricted geographical area that was monitored, as well the network based on a single cultivar, which limited our conclusion genericity. Thus, it would be interesting to conduct and further analyze similar experiments in other viticultural regions or countries and with other key grape varieties worldwide.

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