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Abstract

Pesticides remain the most efficient way to control pest and disease pressure in vineyards and obtain satisfactory yields in terms of quality and quantity. However, because of the harmful effects of pesticides on human health and the environment, winegrowers have had to change their practices. To reduce pesticide use, winegrowers have a range of levers at their disposal that are implemented at different spatial and temporal scales and with different intensities of change. Beyond simply reducing pesticide use, these changes can also impact farms' economic and social performances notably because vine is a perennial crop with inertia in the impacts of changes operated. In this work, we assessed the covariation between various performances with time. We used the Agrosyst database, which compiles data on the performances of French vineyard cropping systems engaged in a pesticide reduction process for the past 10 years, implementing a reduction of 34%. Based on existing knowledge on transition processes and pesticide reduction in vineyards, we used partial least squares path modelling (PLS-PM) to assess the dynamic trade-offs between different performances during the pesticide use reduction process. We verified the model we built (GoF = 0.44) and found no significant correlation between pesticide reduction, economic performances (operating costs and fuel consumption), technical performance (mechanical work time) or productivity (yield). Interestingly, we did not observe any effect from reducing fungicides on yield. We only noticed a significant correlation between the initial weed control strategy and the change in weed control strategy ($\beta = 0.18$). Furthermore, stopping herbicide use did not affect mechanical work time or costs. Our results are encouraging in terms of maintaining both agronomic and economic performances when reducing pesticides in vineyards.

Keywords: Dynamic; Pesticide use reduction; TFI, Treatment frequency index; Trade-off; Vineyard; Yield

1. Introduction

The negative effects of pesticides on the environment and human health is a public concern (Aulagnier and Goulet, 2017). To make agriculture more sustainable, reducing pesticide use is therefore a major priority. The agricultural industry must transition to low-input systems. Debates on pesticide use are all the more true for the wine sector, given that it is one of the most input-intensive agricultural sectors (Urruty et al., 2016) since grapevine (*Vitis vinifera*) crops face significant pest and disease pressure. In 2019, for example, the average treatment frequency index (TFI, Pingault et al., 2008) for French vineyards was 12.4, with fungicide treatments accounting for 81% of this TFI (Simonovici and Caray, 2021). By way of comparison, the average TFI for wheat (a major annual crop in France) was 4.9 in 2017 (Agreste, 2020). To date, pesticides are still the most efficient solution to obtain satisfactory yields in terms of quality and quantity (Fermaud et al., 2016), but winegrowers must change their practices to become less dependent on these products and reduce their negative environmental impacts.

To reduce pesticide use, winegrowers can choose from among several technical levers that have variable impacts on the farming system organisation (e.g. increased working time, more complex work). Hill and MacRae (1996) classified the intensity of implemented changes through a framework known as ESR (efficiency, substitution and redesign). The first step in reducing pesticide use is to increase input efficiency (E), i.e. reducing the total pesticide dose while achieving the same level of production (Hill and MacRae 1996). This can be achieved by optimising the dose and frequency of treatments (Fouillet et al., 2022). The second step is substitution (S), where chemical products are replaced with non-chemical pest control solutions or chemical treatment with a lower environmental impact. The last step, redesign (R), corresponds to more complex changes at the farming system level. For each of these three steps, a range of levers exists but none of them alone suffices to sustainably reduce pesticide use. Thus, because each of these technical levers is only partially effective, they must be combined to achieve a meaningful reduction in pesticide use (Jeuffroy et al., 2022).

Since technical levers are implemented at different spatial scales and intensities, they have different impacts in terms of the environment, agronomy, farm organisation and working time. For example, on an operational level, doses can be adapted for each treatment intervention to consider vine sensitivity and fungicidal pressure. Farmers can also choose to use copper or sulfur-based products in place of synthetic products on a single plot, several plots or the whole farm. This is a tactical decision that can potentially impact vineyard performances. In fact, copper and sulfur-based products are more leachable than synthetic products. Their use implies more interventions per season and an increase in working time (Merot et al., 2019). From a more strategic angle, replacing herbicides with mechanical weeding requires financial and time investments. New equipment is needed for tilling, inter-weeding and mowing activities (Merot and Wery, 2017). The consequences of such changes are therefore technical but also organisational and economic.

To sustainably reduce their pesticide use, winegrowers need to change their practices while maintaining an economically viable agricultural production throughout the transition process. During the pesticide reduction process, winegrowers must revise their objectives, which can no longer be focused on yield maximisation (Jacquet et al., 2022). Multiple, conflicting environmental and economic objectives mean that compromises must be sought (Klapwijk et al., 2014). Indeed, competition between activities can occur at the farming system level (Delecourt et al., 2019). For example, increased working time and costs along with decreased productivity have been observed after winegrowers implemented mechanical weeding to replace chemical weeding (Jacquet et al., 2019).

To understand the pesticide reduction process and better support winegrowers during their transition, knowledge is needed on the covariations between the agronomic, economic, social and environmental performances. To acquire such knowledge, researchers often design and assess the performances of low-input cropping systems (Meynard et al., 2012), such as in the case of experimental plots designed with low pesticide use within the experimental DEPHY network (Métral et al., 2018; Thiollet-Scholtus et al., 2019). The performances of the newly designed systems are then assessed using tools and indicators (e.g. multi-criteria evaluation) and the impacts of the new technical strategies on environmental, economic, technical and agronomic performances are quantified (Métral et al., 2018; Thiollet-Scholtus et al., 2019). While the design and assessment of experimental trials with low pesticide inputs produce important results, real production situations must also be considered within a large set of production contexts, which can differ from experimental conditions (Jacquet et al., 2022).

Over the past two decades, numerous studies have proposed methods for multi-criteria evaluation of farming system sustainability (Soulé et al., 2021). Two main types of methods can be distinguished: conventional methods focusing on farming system assessment and production in the field (Repar et al., 2017), and life cycle assessments (LCAs), which focus on the products and cover activities both in and outside the field (such as input manufacturing and waste disposal). Both types of methods target high-yield farming systems to determine whether new technical strategies are efficient (Aouadi et al., 2019). Moreover, to our knowledge, these methods do not propose a dynamic view of farming systems during their transition towards systems using reduced amounts of pesticides nor do they consider the potential trade-offs between agronomic, socio-economic and environmental performances over time

(Dardonville et al., 2021; Hodbod et al., 2016; Soulé et al., 2021). Thus, several authors have pointed out the need to develop methods that integrate the dynamics of trade-offs.

To contribute to this issue, this paper aims to characterise the effect of the dynamics of pesticide reduction on productivity and socio-economic performances of farming systems over the long term (10 years). We used partial least squares path modelling that included dynamic indicators of these performances to explore the potential trade-offs between agronomical, sociotechnical and economic performances over time. We hypothesised that, during the transition process to reduce pesticide use, we would observe a decrease in yield and an increase in manual labour and mechanical working time. The work was performed at the production system scale to take into account the economic and labour evaluation.

2. Materials and Methods

2.1. DEPHY network and Agrosyst database

In France, the DEPHY network (Demonstration, Experimentation and Production of references on low-pesticide-input systems) was created in 2010 to demonstrate the capacity of farmers to reduce their pesticide use within their cropping systems. Farmers voluntarily participated in the network. A total of 280 cropping systems (i.e. several plots that are grown with the same management strategy) were enlisted between 2010 and 2012 and another 270 vineyards joined in 2016. Vineyards were located across the 12 main French winegrowing regions (Alsace, Bordeaux, Bouches-du-Rhône, Bugey-Savoie, Burgundy, Champagne, Charente, Côtes-du-Rhône, Gaillac, Languedoc, Loire-Valley and Provence). Winegrowers were divided into groups managed by network advisors. These advisors guided farmers during their progress towards pesticide reduction. Data describing cropping system practices and performances, collected every year by the network advisors by survey, were gathered in the Agrosyst database. This database provides information on pesticide use and agronomic indicators such as yield at the field scale, with data available for each year starting from the year farmers joined the network. The Agrosyst team also calculated various performance indicators (e.g. equipment use time, operating costs). In total and considering missing data, we studied **161 cropping systems** for which we had at least 6 years of complete data for the studied variables.

2.2. Knowledge gained previously about the DEPHY network and potential covariations for performances

The 161 selected cropping systems were already studied in a previous study (Fouillet et al., 2023, 2022). Previous studies have shown an average pesticide reduction of 33% over 10 years within the DEPHY network based on TFI analysis (Fouillet et al., 2022). Various TFI trajectories were observed and classified into three types (Fouillet et al., 2023) which mainly differed by their TFI levels when farmers joined the DEPHY network (initial TFI). Analysis of the trajectories showed that the higher the initial TFI, the greater the TFI reduction between 2010 and 2019. The TFI reduction was mainly explained by reduced fungicide use and, to a lesser extent, reduced herbicide use during the 10-year study timeframe (Fouillet et al., 2022). Three key approaches to reducing fungicide use were identified: reducing doses, decreasing the number of treatments, and partially or totally substituting copper- and sulfur-based products and biocontrol for synthetic products. We assumed that reducing doses and the number of treatments would directly reduce production costs. Fewer treatments would also presumably impact the mechanical work and all related impacts (fuel consumption, mechanical costs, labour). Conversely, the use of biocontrol and copper-based products could require an increased number of treatments. Because copper and sulfur are more leachable and not systemic, their use requires more frequent interventions (every 8 days on average instead of every 14 days for synthetic products) and more frequent interventions before and after rain (Merot et al., 2019). If the treatments are not applied at the right time, berry damage and yield loss can occur (Merot et al., 2020). The herbicide TFI reduction was associated with the cessation of herbicide use on part or all of the vineyard (some inter-rows, all inter-rows, under the rows) (Fouillet et al., 2022). Chemical weeding could also be replaced by mechanical weeding or mowing. Substituting mechanical techniques for chemical weeding involved the acquisition of new equipment (e.g. undervine weeder, cover crop, mower) and more frequent interventions. As a result, this change could increase fuel consumption, production costs and labour. Furthermore, an unsuitable weed management strategy could lead to increased water and nitrogen competition and lower yields (Celette and Gary, 2013; Merot et al., 2022).

2.3. Individual performance analysis

2.3.1. Performance variables

Eight variables were selected to analyse farm performances to assess disease and weed control strategy, mechanical work intensity, costs and productivity. The Agrosyst team calculated them based on the Agrosyst database. These variables were used to characterise the changes in vineyards' disease and weed control strategy, productivity, labour and costs over the 10 years of the study.

- <u>*Disease and weed control strategy at field scale*</u>

Treatment frequency index: The level of pesticide use was estimated by calculating the TFI. The TFI is the main indicator used within the DEPHY network to assess changes in pesticide use. We calculated the TFI based on the recommended dose established for each product for any targeted pest or disease. The TFI was calculated with the applied dose expressed as a fraction of the dose recommended to control specific targeted pests or diseases and according to the proportion of sprayed area (**Eq(1)**, Fouillet et al., 2022; Pingault et al., 2008).

$$TFI = \sum_{P} \frac{\text{Dose\_sprayed}_p}{\text{Dose\_recommended}_p} \times \frac{\text{Area\_sprayed}_P}{\text{Area\_total}_P}$$

Eq(1): *Calculation of TFI* (Pingault et al., 2008) *for a given year at the cropping system scale. The TFI equals the sum of the TFIs per treatment, where one treatment equals 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 area of the field where the treatment was sprayed.*

We differentiated three partial TFIs: fungicide TFI (TFI_f), insecticide and acaricide TFI (TFI_i) and herbicide TFI (TFI_h).

- *Mechanical work intensity*

Mechanical working time (hour ha^{-1}): This indicator is calculated for each mechanical operation, taking into account the time spent using the equipment and the number of people required to carry out the operation.

Mechanical working time was calculated for the season (from the previous harvest to the harvest of the current season).

Fuel consumption (L ha^{-1}): Fuel consumption is the amount of fuel used for all the interventions using a combination of tools. It was calculated for each intervention based on references from the Bureau Commun du Machinisme Agricole (BCMA). This professional organisation creates decision support tools (mutual aid scale) and publishes documents to support agricultural equipment advisor networks, agricultural technicians and users. The calculated fuel consumption accounts for part of the tractor labour costs.

- *Costs*

Inputs costs (€ ha^{-1}): This indicator corresponds to the expenses related to the purchase of inputs such as seeds and plants, mineral and organic fertilisers, seed and plant treatments, irrigation and plant protection products, and biological control products. To calculate these operational expenses, we used the prices of the inputs as indicated by the users. When information on input prices was unavailable, the Agrosyst team used the default prices from an Agrosyst reference framework for the relevant cropping season.

Tractor labour costs (€ ha^{-1}): The tractor labour cost was calculated from the time of use of the equipment, based on a cost of 18 euro per one hour of work performed by a tractor operator (according to the Agroequipement Office from the national Chamber of Agriculture). This value was determined by the Agrosyst team and do not vary over time.

- *Productivity*

Yield (hL ha^{-1}): Reported yield was collected each year and expressed in hL of harvested grape juice per ha^{-1}. Yield values were declared by winegrowers at the field scale.

2.3.2. Statistical analysis

Statistical analyses were performed using R software v. 3.6.2 (R Core Team, 2019) with the lme4 package (Bates et al., 2015). The general change in each performance over time was assessed using linear mixed-effects models (**Eq(2)**). The winegrowing regions were integrated as a fixed effect to collect the slope and intercept coefficients, while the cropping systems followed over the studied period were integrated as a random effect.

mod1= lmer(X ~ Year * Winegrowing Region + (1+Year | cropping system))

Eq(2): *Linear models used to visualise the change in a variable* X *over the 10-year study timeframe, taking into account the winegrowing region effect, a categorical variable (*Winegrowing Region*). The cropping system effect over time was integrated as a random effect. The equation was formulated using the R software lme4 package language* (Bates et al., 2015).

A t-test was performed to determine whether there was a significant difference in the variables between the initial point (when the farm entered the DEPHY network) and the final point (2019).

2.4. Covariation analysis of the performance variables

2.4.1. Variables to describe the performance dynamics

To analyse the covariations between performances during the pesticide reduction process, we were not interested in the individual raw variables presented above but rather in their initial value upon entry to the network as well as their change in time. To assess the change in variables over time, we used dynamic indicators inspired by Martin et al. (2017) and Fouillet et al.(2023). We extracted the slope of the linear model of each raw variable as a function of time to reveal the overall change between the initial and final values (increase, decrease or stable) (see **Fig.1**.). The value at the initial point was extracted for a set of variables listed below in **Table 1**. The new variables corresponding to the slopes of linear regressions (figure 1, mod2) were named *Evo_<variable name>*. The new variables corresponding to the initial point values were named *Ini_<variable name>*. We calculated 9 variables in all to depict the performance dynamics (see **Table 1**).

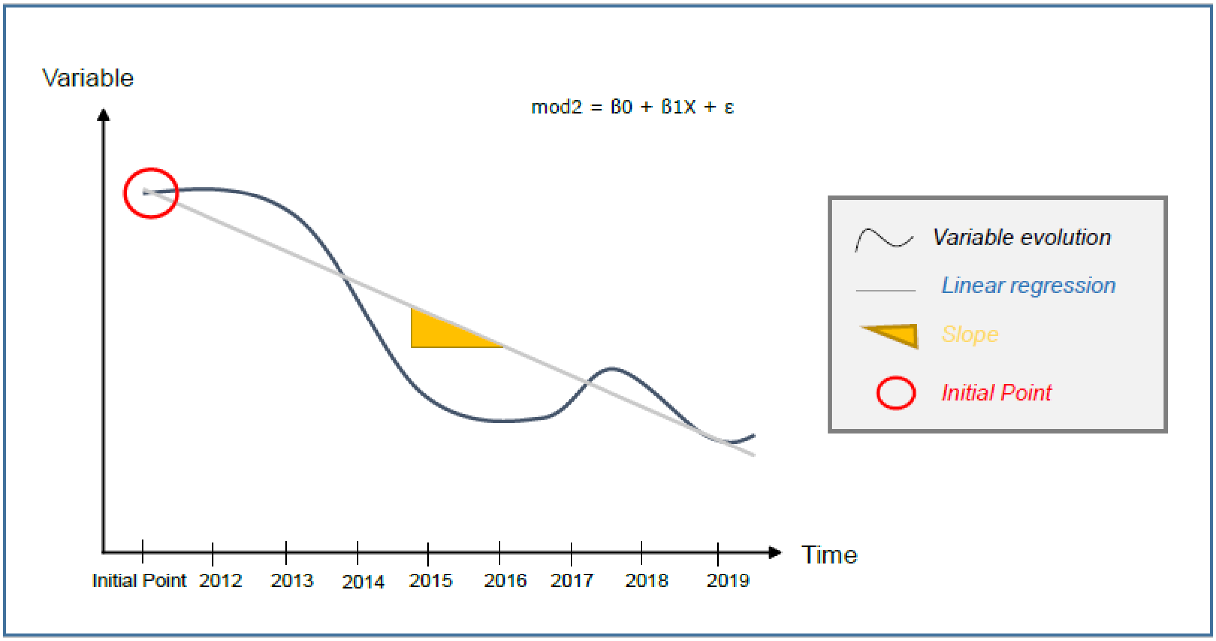

Fig. 1. Indicators used to characterise the dynamic of the selected performances. The model linear model used with X the studied variable, β1 the estimated slope, β0 the estimated intercept and ε the residual

2.4.2. *Covariation analysis: partial least squares path modelling (PLS-PM) method*

Method definition

Partial least squares path modelling (PLS-PM) is a method used to explore the multiple relationships between various variables and to quantify the respective weights associated with these relationships (Tenenhaus et al., 2005). To date, PLS-PM has been mainly applied in the fields of social sciences and ecology. More recently, this method was also applied to agronomic studies (Quinio et al., 2017). Path models are built using unobservable variables, called construct variables or latent variables (LVs), and observable variables, also known as manifest variables (MVs). An LV is described using one or more MVs. PLS-PM is comprised of two sub-models: an inner model and an outer model (Sanchez, 2013). The inner model is the structural model that takes into account the relationships between LVs. The outer model, which corresponds to the measurement model, describes the relationships between the LV and a set of MVs. The group of MVs associated with an LV is defined as a block.

MVs must be positively correlated to their LV (Vinzi et al., 2010). The correlation between LV and their MVs was estimated by using the loading (λ) (Sanchez, 2013). The strength and direction of the relationships between LVs and MVs was estimated with the path coefficient (β) obtained from regression. A negative β value indicated a negative correlation, whereas a positive β value indicated a positive correlation. β was only considered when λ indicated a significant correlation.

Model construction

We built our path model in a reflexive way, meaning we assumed that MVs were caused by their respective LVs (Baxter, 2009). Partial least squares path modelling (PLS-PM) was used to model the relationships between the 9 manifest variables presented above and depict the change in performance. These variables comprised the set of MVs in the model. The latent variables and the associated manifest variables are summarised in **Table 1**.

We used our path model to test the hypothesis that reducing pesticide use impacted the other studied performances of the farming system. The hypotheses used to construct the model were based on existing knowledge on pesticide reduction processes in vineyard systems (see **Table 2** for a detailed description of these hypotheses). The hypotheses used in the model also took into account existing knowledge on the transition pathway towards pesticide use reduction (Chantre and Cardona, 2014; Martin et al., 2017; Merot et al., 2019a).

We chose to focus on the change in fungicide and herbicide use within the DEPHY network as these are the two types of pesticides for which Fouillet et al. (2022) observed a significant decrease in use. Furthermore, insecticide products only represent a small part of the total TFI (14%, Simonovici and Caray, 2021) and most insecticide treatments are mandatory treatments against *Scaphoideus titanus*, the leafhopper vector of *Flavescence dorée*. Fouillet et al. (2022) showed no significant decrease in the use of insecticide products within the DEPHY network over 10 years.

We began building the model by setting up two latent variables representing the initial state of disease control (cryptogamic diseases) and the initial state of weed control. This is because, during a pesticide reduction process, the initial states of control indicate the potential for improvement that winegrowers may reach in terms of pesticide use reduction (Fouillet et al., 2023; Merot et al., 2019b; Ross et al., 2008). Since regional effects have a strong influence on pest and disease pressure (Fouillet et al., 2022; Mailly et al., 2017; Simonovici, 2019), we normalised the TFI_f by using data provided by the French Ministry of Agriculture (Simonovici and Caray, 2021). TFI_h was not normalised as it represents a small part of the TFI (4.8% in 2019, Fouillet et al., (2022) and consequently even if there is a regional effect, it is limited on the TFI variation. (Mailly et al., 2017).

Model quality assessment

We assessed the quality of the constructed path model using a two-step process (Sanchez, 2013). First, we verified the homogeneity and unidimensionality of the blocks and then the cross-loadings. The unidimensionality of each block was verified since all MVs were positively correlated with their respective LVs (Sanchez, 2013). Blocks were homogenous, meaning that we would be measuring the same unique underlying concept in each block (Vinzi et al., 2010).

Table 1. Description of the latent variables and the associated manifest variables used in the PLS-PM model

Latent variable	Manifest variable	Manifest variable calculation	Unit of the converted variable
Initial disease control strategy	Ini_TFI_f	Normalised TFI_f at the initial point	Ø
Initial weed control strategy	Ini_TFI_h	TFI_H at the initial point of the TFI_h	Ø
Change in disease control strategy	Evo_TFI_h	Extracted slope of the TFI_f from Initial Point to 2019.	Ø
Change in weed control strategy	Evo_TFI_h	Extracted slope of the TFI_h from Initial Point to 2019.	Ø
Change in productivity	Evo_Yield	Extracted slope of the yield from Initial Point to 2019.	hL ha^{-1}
Change in mechanical work intensity	Evo_FuelConsumption	Extracted slope of the change in fuel consumption from Initial Point to 2019.	L ha^{-1}
	Evo_MechanicalWork	Extracted slope of the change in mechanical work from Initial Point to 2019.	hour ha^{-1}
Change in costs	Evo_TractorCost	Extracted slope of the change in tractor labour cost from Initial Point to 2019.	€ ha^{-1}
	Evo_OperatingCost	Extracted slope of the change in operating cost from Initial Point to 2019.	€ ha^{-1}

Table 2. Hypotheses used to construct the PLS-PM model based on the existing knowledge on pesticide reduction processes in vineyard systems

Hypothesis number	Relationships between latent variables (LVs)	Hypothesis	References
(1)	Initial disease control strategy → Change in disease control strategy	The initial disease control strategy is related to the potential pesticide reduction. It is easier to significantly decrease pesticide use when the initial disease control strategy mainly relies on the use of systemic products rather than other products (copper/sulfur or biocontrol)	Fouillet et al. (2022)
(2)	Initial disease control strategy → Change in productivity	Productivity is highly dependent on disease control. Powdery and downy mildew can cause considerable yield losses in the absence of pesticide use or a suitable plant protection strategy. Depending on the initial disease control strategy, the change in productivity when pesticide use is reduced will vary: - With high disease pressure and a strong initial disease control strategy, productivity is expected to decline; - With high disease pressure and a minimal initial disease control strategy, productivity is expected to remain stable; - With low disease pressure and regardless of the initial disease control strategy, productivity is expected to remain stable.	Fermaud et al. (2016) ; Merot and Smits (2020); Leroy et al. (2013)
(3)	Change in disease control strategy → Change in productivity	A better disease control strategy limits damages and substantial yield losses. When changing a disease control strategy, yields have been observed to fall after a decrease in pesticide use before returning to the initial level.	Merot and Smits (2020)
(4)	Change in disease control strategy → Change in mechanical work intensity	Disease control strategies depend on the type of products used, the dose per treatment and the frequency of applications. - If the dose per treatment is decreased without changes in the type of product used, no impact on mechanical work intensity is expected; - If the frequency of applications decreases without changes in the type of product used, the number of interventions is reduced and less mechanical work is expected; - A change in the type of products used has implications on the number of interventions and consequently on the mechanical work intensity. In particular, replacing synthetic pesticides with more leachable copper-based, sulfur-based or biocontrol products increases the frequency of treatments needed, especially in oceanic and northern winegrowing regions.	Merot et al. (2019b); Rouault et al. (2016)
(5)	Change in disease control strategy → Change in costs	A change in disease control strategy can impact costs. - If the dose per treatment is decreased, costs are expected to fall; - If the frequency of applications decreases without changes in the type of product used, the number of interventions is reduced and costs are expected to fall; - A change in the type of products used has implications for the number of interventions and consequently for costs. As noted in hypothesis 4, replacing synthetic products with copper, sulfur or biocontrol products whose frequency of application is more dependent on rainfall can lead to an increase in the number of treatments, especially in oceanic and northern winegrowing	Leroy et al. (2013); Merot et al. (2019b)

		regions. An increase in the number of treatments increases costs (fuel consumption, mechanical costs). Biocontrol products are also more expensive than synthetic products.	
(6)	Initial weed control strategy → Change in weed control strategy	The initial weed control strategy is related to the potential of herbicide use reduction. It is easier to significantly decrease herbicide use when the initial weed control strategy is highly dependent on the use of systemic products. In fact, the available levers to reduce herbicide use are limited to three options: - Replacing synthetic herbicides with biocontrol herbicides; - Replacing herbicides with mechanical weeding; - Replacing herbicides with cover crops mown. The implemented strategy can combine these options for the entire the plot or in the inter-rows.	Delpuech and Metay, (2018); Fouillet et al., (2022)
(7)	Initial weed control strategy → Change in productivity	The initial weed control strategy can impact the change in productivity. In fact, considering the major changes required to reduce herbicide use – namely changes in knowledge, equipment, and management and decision rules – there is a significant risk associated with leaving weeds to grow in spring after the changes are implemented. If vineyards are farmed without water and nitrogen restrictions, yields may fall before returning to their initial levels.	Jacquet et al. (2019) Merot and Smits (2020) Ripoche et al. (2011)
(8)	Change in weed control strategy → Change in productivity	Weed control strategies limit competition and substantial yield losses. As mentioned in hypothesis 7, when implementing levers to reduce herbicide use, allowing weeds to grow in spring, a critical stage for grapevine, comes with a significant risk. Competition for nitrogen and water from weeds can cause yields to decline before they return to initial levels.	Jacquet et al. (2019); Merot et al. (2022) Delpuech & Metay (2018), Celette & Gary (2013)
(9)	Change in weed control strategy → Change in mechanical work intensity	The change in weed control strategy related to the reduction of herbicides is expected to lead to an increase in mechanical work intensity because mechanical tillage is the most common alternative for herbicide reduction.	Jacquet et al. (2019) Merot et al. (2019)
(10)	Change in weed control strategy → Change in costs	The three potential options to reduce herbicide use cited in hypothesis 7 are all more expensive to implement than relying solely on synthetic herbicides. For example, an increase in the number of interventions will be more costly than herbicide interventions since the time required for mechanical weeding is higher than applying herbicides. Reducing expenses related to synthetic herbicides does not offset the increase in costs related to mechanical work intensity.	Jacquet et al. (2019) Merot et al. (2019)
(11)	Change in mechanical work intensity → Change in costs	An increase in mechanical workload can lead to the hiring of new employees and therefore to an increase in costs.	Merot et al. (2019)

We checked the loadings, i.e. the correlation between a latent variable and its manifest variables (Vinzi et al., 2010). We verified that the shared variance between an MV and its LVs was larger than with other blocks using cross loadings. Finally, the cross loadings were checked to ensure that the loadings (λ) between the MVs and their respective LVs were higher than their loadings with the other LVs implemented in the model.

Model validation

The model robustness was validated using the goodness of fit (GoF) index and a bootstrapping procedure (1000 times). A GoF threshold value of 0.4 was considered acceptable to verify the model (see Grace et al., 2016; Puech et al., 2015; Quinio et al., 2017). The PLS-PM was performed with R software v. 3.6.2 (R Core Team, 2019) using the *plspm* package (Sanchez et al., 2015).

3. Results

3.1. Change in environmental, economic and technical performances over the 10-year study timeframe

Both fungicide and herbicide uses were significantly reduced over the 10-year study period according to the linear model ($p<0.05$, **Fig. 2, supplementary data 1**). Concerning fungicide use, the TFI_f decreased from 10.6±4.9 to 7±5.4 between the initial year and 2019, corresponding to a 34% mean reduction with a high inter- and intra-annual variability As for herbicide use, the TFI_h decreased from 1.2±1.5 to 0.5±0.9 between the initial year and 2019, corresponding to a 58% mean reduction. In all, 27% of the cropping systems used herbicides in 2019, compared to 43% at the initial point.

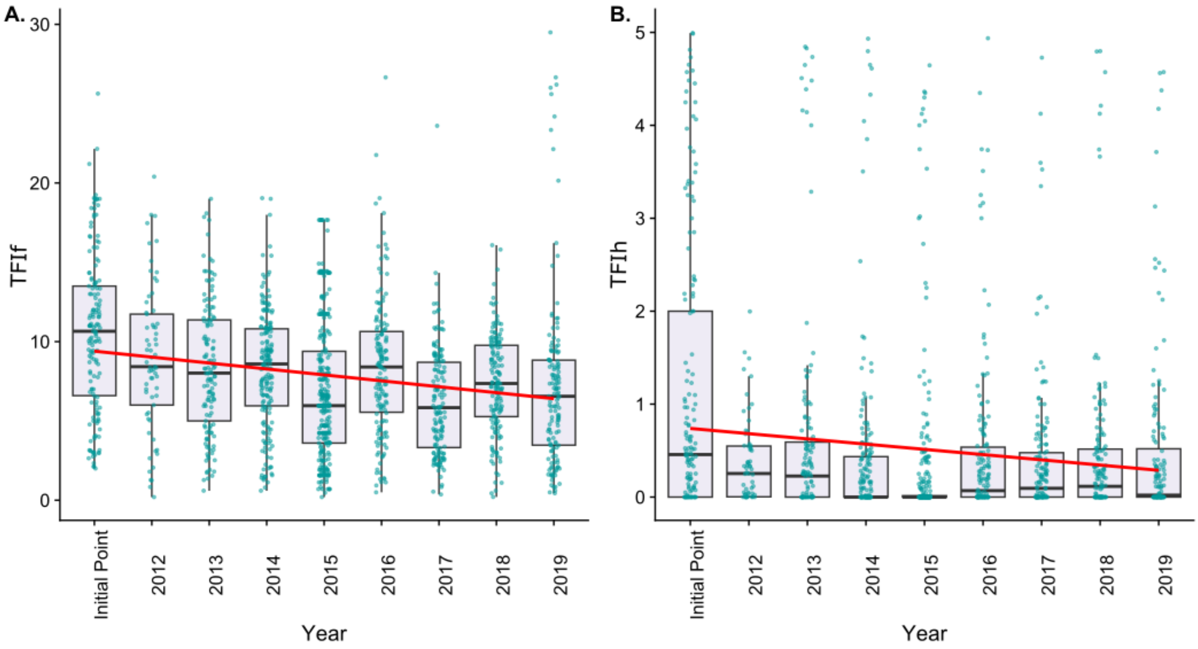

Fig. 2. Change in pesticide use over the 10 years of the study. (A.) Change in TFI_f. and (B.) change in TFI_h.. Outliers are not represented. Whiskers display the 5th and 95th percentiles. Horizontal bars indicate the first quartile, median and third quartile.

The linear model showed a significant decrease in operational costs (p value<0.01, Fig. 3D). The operational costs decreased from 648.2±402.7 € ha^{-1} to 349.9±707 € ha^{-1} between the initial year and 2019, corresponding to a 46% mean reduction.

No significant change in the mechanical working time, fuel consumption or tractor labour costs was observed over the study period. The mechanical working time ranged between 26.6±17.3 and 21.6±28 hour ha^{-1} between the initial point and 2019 (Fig. 3A). The fuel consumption varied between 247±132 L ha^{-1} and 286±288 L ha^{-1} between the initial point and 2019 (Fig. 3B). The tractor labour cost varied between 427.2±311.8 € ha^{-1} and 347.3±445.8 € ha^{-1} between the initial point and 2019 (Fig. 3C). The yield varied from 63.4±22.3 hL ha^{-1} and 65.7±23.9 hL ha^{-1} (Fig. 4).

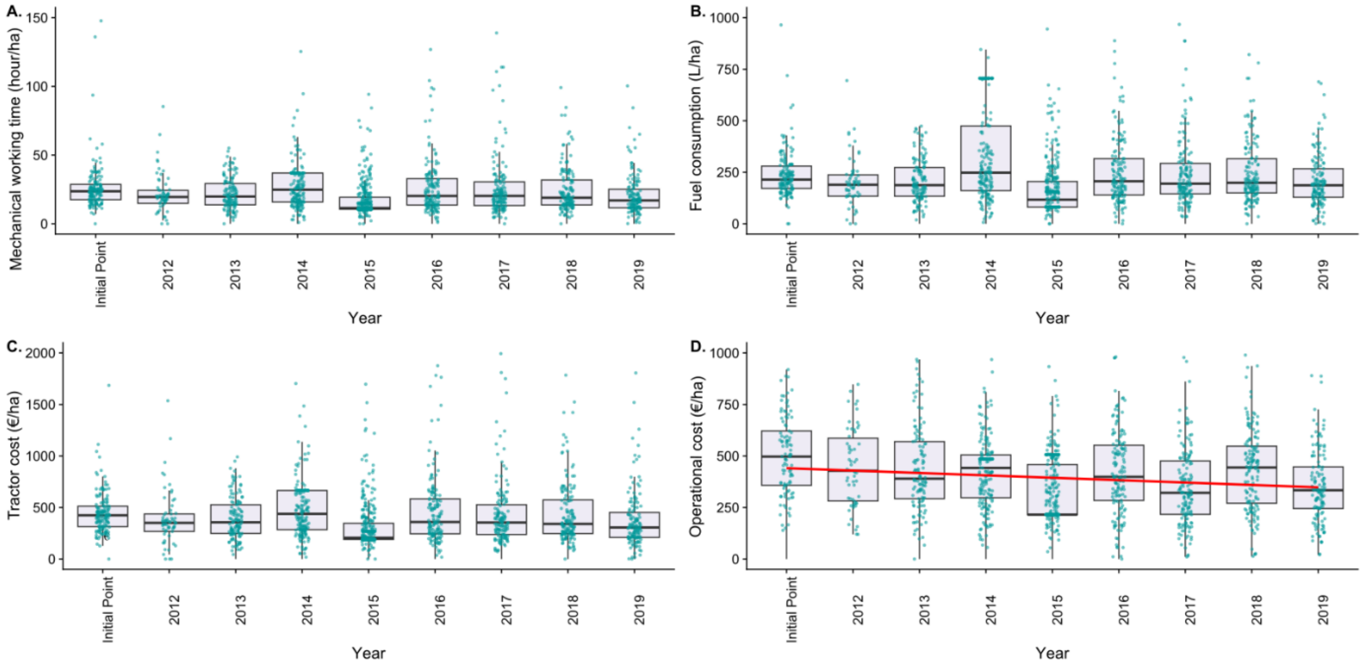

Fig. 3. Change in the economic and working time performances over the 10 years of the study. (A.) Change in mechanical working time (hour ha^{-1}). (B.) Change in the fuel consumption (L ha^{-1}). (C.) Change in the tractor labour cost (€ ha^{-1}). (D.) Change in the operational cost (€ ha^{-1}).

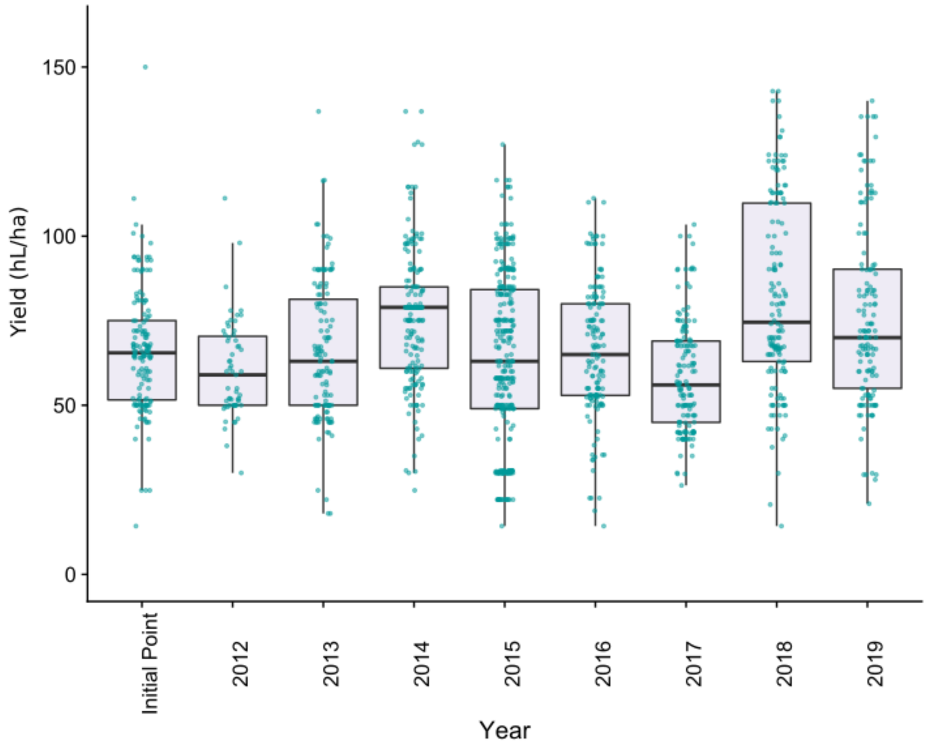

Fig. 4. Change in the yield (hL/ha) from the initial point to 2019.

3.2. Path model: covariation of environmental, economic and technical performances over the 10-year study period

The path model (Fig. 5) was verified since blocks were unidimensional and by cross-loading validation (see supplementary data2). Furthermore, the goodness of fit was acceptable (GoF = 0.44). The bootstrap procedure indicated that only 2 of the 11 path coefficients (β) were significant (Fig. 5): i) the link between initial herbicide use and the change in herbicide use and ii) the link between the change in work intensity and the change in costs.

Among the variables describing plant health control strategies, we only observed a low positive effect of the initial weed control strategy on the change in weed control ($\beta = 0.18$, pvalue = 0.025). The impact of the initial disease control strategy on the change in disease strategy was negative but non-significant ($\beta = -0.52$, pvalue>0.05). No significant impact of the weed control strategy or disease control strategy was observed on productivity. The initial weed control strategy and the change in weed control strategy had a non-significant negative impact on productivity ($\beta = -0.06$ and $\beta = -0.07$, pvalue<0.01). Our hypothesis of a yield reduction due to a decrease in or cessation of herbicide use was not validated. The same finding was observed for the initial disease control strategy and the change in disease control strategy, as the impacts of both on productivity was non-significant. Therefore, our hypothesis of a yield decrease due to a fungicide reduction was not verified.

A strong and positive relationship between the change in work intensity and the change in the costs was observed ($\beta = 0.94$, p value<0.05). Our hypothesis of a mechanical work increase due to a change in weed control strategy was not validated since the correlation, although positive, was found to be non-significant ($\beta = 0.14$, p value>0.05). The same finding was observed for the change in disease control strategy with regard to the change in mechanical work intensity. There were non-significant correlations between the change in costs and changes in the disease control strategy ($\beta = 0.04$, p value>0.05) and in the weed control strategy ($\beta = -0.03$, p value>0.05).

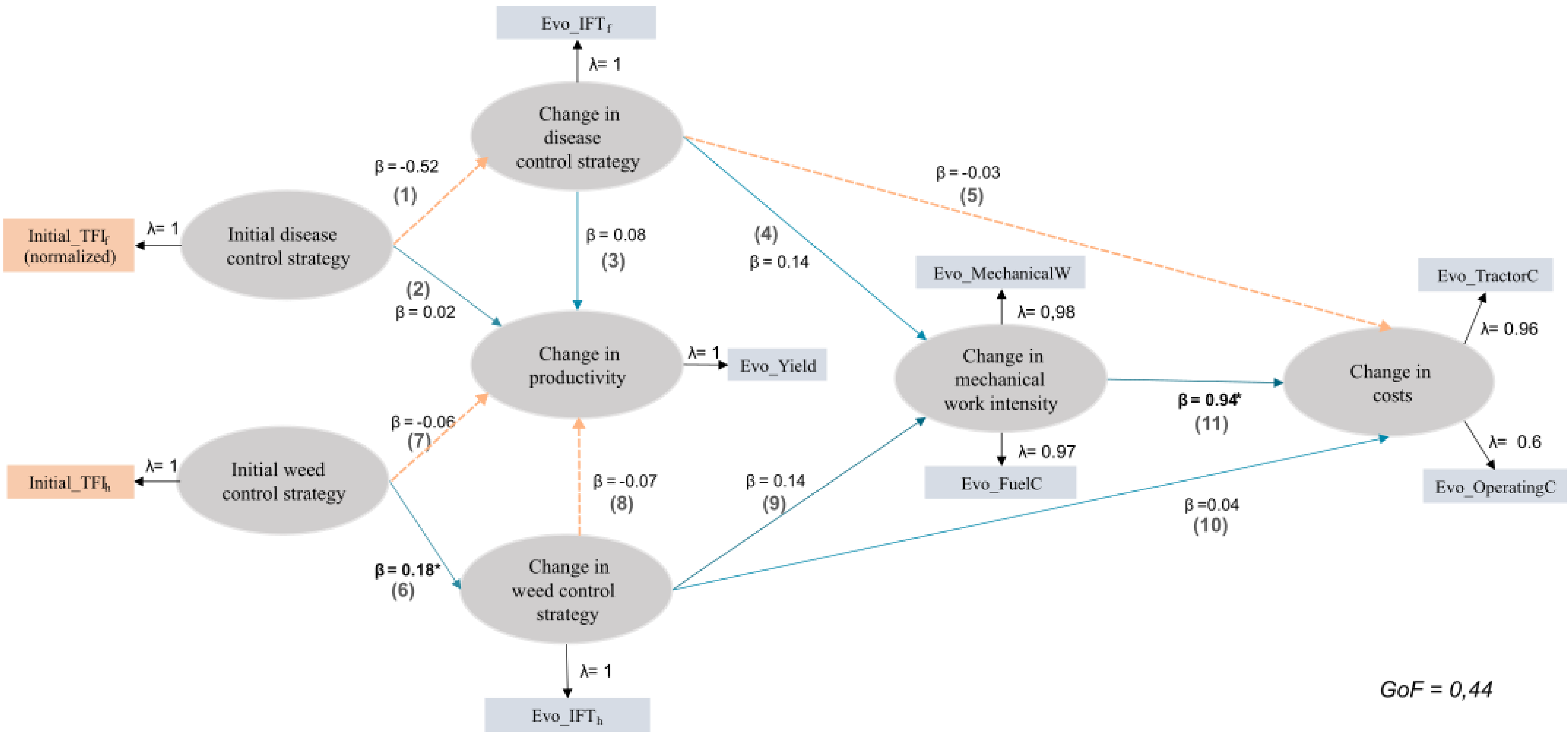

Fig. 5. The complete path model with latent variables (LVs, grey ovals) and manifest variables (MVs, blue rectangles). Path coefficients (β) were computed from regressions; they represent the strength and direction (orange arrow, dotted line = negative; blue arrow, full line = positive) of relationships between the LVs. Loading (λ) represents the correlation between an MV and its respective LV. Asterisks indicate that the path coefficients (β) were significantly different from 0 based on 95% percentile confidence intervals calculated using 1000 bootstrap samples. Meanings of the variables are detailed in Table 1 and the numbers in parentheses correspond to the model construction hypotheses described in Table 2.

4. Discussion

4.1. This article aimed to characterise the covariations between the performances of different vineyard cropping systems as winegrowers were transitioning to lower pesticide use.

We used the French national Agrosyst database, which provides comprehensive information over a long time period (10 years). We built and verified a statistical method (PLS-PM), considering the dynamic of the pesticide reduction process, and showed that pesticide use reduction was not significantly related to the evolution of productivity (yield), economic (operating costs and fuel consumption) and technical performances, technical performance (mechanical work time). **Change in performances over time**

Analysis of the individual performances indicated that nearly all of them remained stable over the 10-year study timeframe, despite a 34% decrease in TFI_f and 58% decrease in TFI_h, with only the input costs experiencing a 46% decrease. All the other performances – mechanical work time, tractor labour costs, fuel consumption and yield – showed no significant change over time.

Performances result from multiple processes. Thus, the lack of change observed here can be partly explained by the context and characteristics of grapevine production systems. First, the vineyard crop management sequence requires numerous manual and mechanical interventions that must be carried out every year, regardless of the pesticide use strategy (e.g. pruning, harvesting). This elucidates why there is minimal variation in the proportion of work time (both manual and mechanical) and operational costs across different years for each vineyard recorded in the database.Even if pesticide use was reduced, harvest costs or winter pruning costs do not vary every year. This regular share of performances can make it difficult to identify an impact due to pesticide reduction for each individual vineyard. Second, regarding changes in yield, in most vineyards, yield is regulated by protected designation of origin (PDO) and protected geographical indication (PDI) schemes (Stranieri and Tedeschi, 2019). Winegrowers voluntarily control the productive potential in their vineyards during winter pruning to meet PDO and PDI requirements. Lastly, a high variability between individual vineyards in the database was observed for each performance each year. Part of this variability can be traced back to the regional effect and its impact on pest and disease pressure, as well as to the specific features of each winegrowing region (in particular yield objectives) (Fouillet et al., 2022; Mailly et al., 2017). For example, some practices, such as the type of pruning or the width between the rows – just like the yield restrictions mentioned above – are imposed by the specifications of the geographical indication schemes.

4.2. Lowering TFI is not related to reductions in yield, costs or mechanical work

4.2.1. Changes in yield and pesticide reduction

We observed that the 34% mean pesticide reduction was not related to an evolution in productivity. In particular, we did not observe any impact of the fungicide reduction on yield, regardless of the initial yield when entering the network. We can therefore assume that fungal diseases have been sufficiently controlled despite lower fungicide use regardless of the level of initial fungicide use. This finding is a validation of a winegrower's choice to undertake the transition to reduce pesticide use. Data analysis was performed at the national scale (see **supplementary data 3**). To investigate further, it could be interesting to consider local yield objectives because yields in vineyard systems are highly variable at inter- and intra-region scales (Fouillet et al., 2022; Mailly et al., 2017; Merot et al., 2022). With the yield objective, another indicator such as the yield achievement ratio (ratio between the reported yield and the target yield, which was unavailable in the Agrosyst database; Merot et al. (2022)) could have been used to explicitly integrate the production target and avoid the strong winegrowing region effect.

4.2.2. Costs, change in work time and pesticide reduction

Interestingly, no impact of the pesticide reduction was observed on economic (costs) or sociotechnical (work time) performances. This result invalidates our hypothesis of an increase in costs due to substituting mechanical weeding for herbicide inputs, such as what was observed by Jacquet et al. (2021) in vineyards. Similarly, Lechenet et al. (2014, 2017), using the Agrosyst database on arable crops, showed that farmers could reduce their pesticide use by an average of 42% without negatively impacting their profitability or productivity (Lechenet et al., 2017, 2014). The 2017 study by Lechenet et al. was based on a single datapoint per farm (when farmers entered the network) and used a regression model to assess the effect of TFI on productivity and profitability. In our study, which was based on a longer time scale (10 years), we integrated the slope as an evolution of indicators. Indeed, since pesticide use is mainly reduced due to gains in efficiency (e.g. dose reduction) and substitution (e.g. use of biocontrol products) (Aulagnier and Goulet, 2017; Fouillet et al., 2022), it does not involve any change in equipment or number of operations (Román et al., 2022). Studies showed that only a few farmers redesigned their farming systems within the DEPHY network (Aulagnier and Goulet, 2017), therefore avoiding levers such as preventive treatments, or even the more involved process of converting to organic farming, both of which are known to significantly impact the way the vineyard is managed (increase in work time and changes in equipment, etc.).

Moreover, some technical operations that are expensive in terms of costs and work time, such as pruning or harvesting, are not affected by reduced pesticide use and can mask the impact of other changes in practices (e.g. change from herbicide use to mechanical weeding) (Strub et al., 2021). In their study on the impact of conversion to organic farming in terms of the technical and economic performances of vineyard systems, Merot et al. (2019) separated grape-growing and harvesting costs because switching from mechanical to manual harvesting (or vice versa) significantly impacts production costs. Analysing grape-growing and harvesting costs separately would make it possible to better identify the impact of technical changes when reducing pesticide use.

The economic performance was assessed using production cost while most studies assess economic performance through net or gross margins (Delord et al., 2015). Net margin is calculated as total fixed revenue minus input costs, mechanisation costs and labour costs (Aouadi et al., 2019). In the Agrosyst database, economic data such as gross and net margins were not available for vineyard systems. . We used other economic indicators and integrated more social indicators by considering the work involved (mechanical and manual work time) (Sgroi and Sciancalepore, 2022). Furthermore, total revenues in viticulture systems are highly variable due to the diversity of marketing strategies and the high yield variability on a spatial and temporal scale (Aouadi et al., 2019)..

4.3. Methodology used to study the covariation between performances

4.3.1. Characterising temporal variations of practices and performances

The Agrosyst database provided a large quantity of information on vineyards and their economic, sociotechnical and economic performances over 10 years at the French national scale. Change can be seen as a multistep process that includes periods of learning and experimentation (Catalogna, 2018; Chantre and Cardona, 2014), and studying the dynamics of these changes is necessary to take into account the fact that farmers implement and adapt their practices over a long time. Yet, there are still methodological issues to address when assessing these cropping system performances to integrate their dynamics. In this study, we adapted the PLS-PM method by integrating dynamic indicators to characterise the change in performances. The dynamic was considered by extracting slopes from linear models. The small number of methods integrating dynamics with mathematical indicators raises the question of how to consider temporal evolutions. We chose to describe the evolution by integrating the slope and the initial point in the PLS-PM model. Dardonville et al. (2022) describe the dynamics of agricultural performances with four different criteria over 8 years: the level of performance calculated with the mean, the stability or variability calculated with the standard deviation or the coefficient of variation, the trend calculated with the slope coefficient of a mixed linear regression; and finally, the resistance calculated by subtracting the average performance before and after the break (high and rapid evolution).

4.3.2. Possible sensitivity indicator to pesticide reduction

In our model, the environmental impact of pesticide use was assessed using the TFI, which is the main indicator used within the French ECOPHYTO plan to assess pesticide use in farming systems (Guichard et al., 2017). Pesticide use can also be assessed with other indicators such as the number of unit doses (NUD) or the quantity of active ingredients (QAI). More recent indicators include the toxicity risk indicator (IRT, Mghirbi et al., 2015) or the pesticide load (Kudsk et al., 2018), which both take into account the ecotoxicity of the sprayed products. All of the above indicators, including TFI, can highlight changes in plant protection strategies. However, none of these indicators can assess the changes in practices that lead to this reduction, such as prophylactic measures or cover crops (Jacquet et al., 2022) or change in spraying equipment (Michael et al., 2021).

We assumed that a model that takes into account finer variables (e.g. risk to the operator depending on product toxicity, working conditions and safety issues) could identify potential trade-offs, especially in terms of health, labour and costs. Delecourt et al. (2019) and Duval et al. (2021) highlighted a change in work organization during agroecological transitions, in terms of working time and human resources (workforce and skills), work organisation (competition between activities at the farming system scale) and work safety. Overall, indicators of working conditions, such as greater meaningfulness of the work performed (Duval et al., 2021) or the satisfaction of livestock farmers (Perrin and Martin, 2021), improved when farms were converting to organic farming.These findings on work-related variables highlight the need to better account for socio-economic indicators such as net margin or number of workers. Yet, such socio-economic data are difficult to obtain from existing databases, and acquiring it requires in-depth surveys

Furthermore, the implementation of new practices depends on the farmer’s attitude towards and perception of risk (e.g. yield loss acceptability). Bonke et al. (2021) showed that some farmers were willing to accept potential yield losses and forego profits by diversifying their crops depending on the farm’s economic strategy. One of the limitations of big data analysis is gaining access to these more specific variables as used in multi-criteria evaluation that are not avalaible in the AGROSYST database. For example, DEPXiPM-grapevine (Gary et al., 2015) is a multi-criteria model for assessing the sustainability of vineyard systems. The description of environmental durability is exhaustive and the socio-economic evaluation is based on expert knowledge.

Conclusion

This study aimed to characterise the covariation between the different performances of vineyard cropping systems, involved in a pesticide reduction process over 10 years. The study focused on vineyard, a perennial crop with a high change inertia. First, the evolution of pesticides use (fungicide and herbicide), economic and technical performances were characterized. Over the ten years, a reduction of pesticide (fungicide and herbicide) and operational cost was observed while the other performances remained stable. e built and verified a model to study the correlations between performances and changes in practices, which is necessary when studying change processes. We did not identify any relation between initial pesticide use (fungicide and herbicide) on agronomic and sociotechnical performances.

The DEPHY network seems to offer relevant support to help winegrowers reduce their pesticide use given that no covariation between performances was observed during the pesticide reduction process. The observed reduction in TFI had no impact on changes in yield nor work intensity or costs. We suggest that a similar model should be adapted for the vineyard cropping system with indicators to give greater weight to socio-economic indicators, such as work organisation or farmers' objectives and satisfaction during the pesticide reduction process, all of these being key elements of a successful transition to low-input systems.

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