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1 Diversity of pesticide use trajectories during agroecological transitions in vineyards: The case of 2 the French DEPHY network

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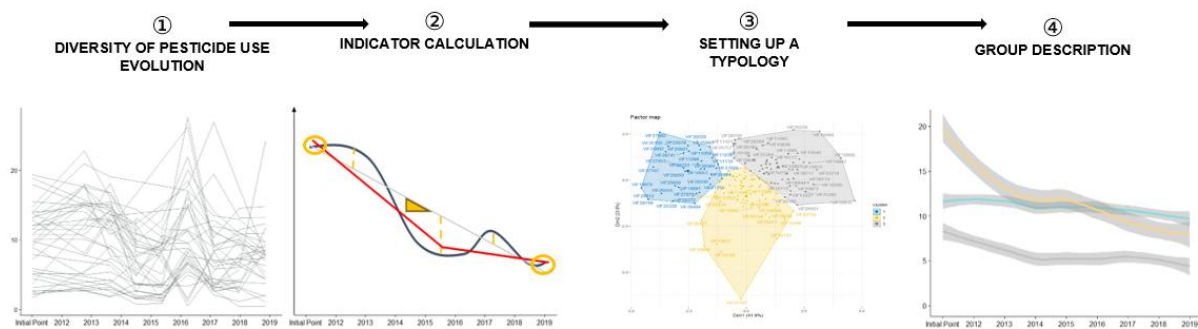
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8 **Keywords:** *typology, treatment frequency index, Efficiency, Substitution, Redesign, technical change*

9 Graphical abstract

10



11

12 Abstract

13 **CONTEXT:** Winegrowers apply large quantities of pesticides to their vineyards to reduce high cryptogamic
14 pressure. But these practices must change to lower pesticide use and improve viticulture sustainability. Different
15 options for curbing pesticide use exist, and they can be progressively implemented following a specific temporal
16 scheme in each production system. Some change trajectories can be more efficient than others in limiting
17 pesticide applications. Combining trajectory studies and typology may be helpful in characterizing how farmers
18 change their practices and in summarizing the various production system trajectories possible when transitioning
19 towards pesticide use reduction.

20

21 **OBJECTIVE:** The aims of this study were i) to identify different types of pesticide use trajectories, and ii) to
22 understand the options implemented by winegrowers to reduce their pesticide use.

23

24 **METHODS:** We analysed data from 161 farming systems in the DEPHY farm network in 12 French
25 winegrowing regions over a 10-year period. Pesticide use was assessed with the treatment frequency index (TFI).
26 We characterized the TFI trajectory of each farming system with six indicators and built a typology of TFI
27 trajectories. We then analysed several indicators such as the use of biocontrol products and the dose sprayed to
28 identify some of the management options chosen to achieve these pesticide use trajectories.

29

30 **RESULTS AND CONCLUSIONS:** Three clusters were identified and characterized in terms of pesticide use
31 strategy. The first cluster represented farms with an initial point close to the regional average and which did not
32 experience a significant TFI reduction (-13%). The second cluster comprised farms with a low TFI when
33 entering the network that were able to further reduce their TFI over time (-48%). The last cluster represented

34 farms with a high initial TFI and a high reduction (−63%). All clusters managed to reduce their pesticide use by
35 combining several technical levers at different intensities. Some differences in the levers between clusters were
36 observed. Cluster 2 farms are in the process of converting to organic farming and using the associated levers
37 such as biocontrol and mechanical weeding.

38

39 *SIGNIFICANCE:* The changes implemented by cluster indicate a varying degree of progress in the transition
40 towards pesticide use reduction. The initial point was identified as having a strong influence on the end result.
41 The more intensively the technical levers were combined, the more difficult it was to reduce pesticide use. The
42 DEPHY network supported winegrowers in their reduction of pesticides who managed to reduce their pesticide
43 use by 13% to 63%.

44 **1. Introduction**

45 The dominant agricultural model is being challenged by the rise of societal debates on the environmental and
46 health consequences of current intensive agricultural practices (Aubertot et al., 2005; Matson et al., 1997; Pretty
47 et al., 2018; Wilson and Tisdell, 2001). To support and stimulate the transition towards low pesticide inputs,
48 some countries have created public policies. In 2008 the French government launched its national ECOPHYTO
49 plan with the aim of cutting pesticide use in half and ending the use of glyphosate by 2025 (Barzman &
50 Dachbrodt-Saaydeh, 2011). Within the ECOPHYTO plan, a network of French demonstration farms, the
51 DEPHY farm network, was created to promote and assess practices implemented to reduce pesticide use.

52 In 2008, the French government started up the ECOPHYTO national plan with the aim of a 50% decrease of the
53 pesticide use and ending the use of glyphosate by 2018 (Barzman and Dachbrodt-Saaydeh, 2011). In 2015, the
54 ECOPHYTO II plan was launched with new goals, the aim of supporting farmers in the transition and find
55 solutions to reduce pesticide use while maintaining a high productivity. Within the ECOPHYTO plan, a network
56 of French demonstration farms, DEPHY-Farm network, was created to assess the implementation of practices to
57 reduce the pesticide use. Technical changes can be complex and challenging for winegrowers particularly (Merot
58 et al., 2019). The DEPHY-farm network is an interesting device to understand and characterize the way farmers
59 perform the transition towards low pesticide use systems.

60 Lamine & Bellon (2009) have identified two different transition processes used by farms shifting to organic
61 farming: i) an abrupt, direct and reversible transition or ii) a transition implemented through a progressive and
62 continuous process of adaptation. These two transitions differ in the speed of change and the degree of
63 modification to farm practices. Thus, the implementation of new practices is more or less gradual and can
64 involve profound technical changes (Chantre & Cardona, 2014; Lamine, 2011; Padel et al., 2020; Toffolini et al.,
65 2017).

66 During a transition towards pesticide use reduction, changes with various intensities can be implemented (Hill
67 and MacRae, 1996; Sutherland et al., 2012). Change intensity can be characterized with the Efficiency,
68 Substitution and Redesign framework (ESR) (Hill and MacRae, 1996). Thus, changes are associated to a gain of
69 Efficiency (*e.g.* dose reduction), Substitution (*e.g.* use of biocontrol product) or Redesign process (*e.g.*
70 conversion to organic farming). Changes linked to Efficiency or Substitution are associated with a progressive
71 transition while changes associated to redesign are linked to a more abrupt and direct transition (Hill and

72 MacRae, 1996; Lamine and Bellon, 2009; Merot et al., 2019). Wilson's transition theory (Wilson, 2008),
73 conceptualized the path during a transition as a succession of linear periods. The linear period determines the
74 possibility of a system to go in one direction but being interrupted by a nodal point.

75 Trajectory studies may help to characterize how farmers change as well as the factors and background of these
76 changes (Cerf et al., 2010). Trajectory studies are carried out at different levels (organizational, technical,
77 commercial, etc.) and can be linked to learning processes (Barbier and Lemery, 2000; Cerf et al., 2010).
78 According to Ross et al. (2008), the transition process can be described according to three elements. The first
79 element is the agent of change, i.e. what triggers change (public policies, psychosocial factors, etc.). The second
80 element corresponds to the effect of change, i.e. the difference between the initial state and the final state. The
81 last element is the mechanism of change, which corresponds to the path taken between states, i.e. the trajectory
82 from one state to another. Trajectory is here considered to be the path followed by a system during its transition
83 from an initial state to a final state through intermediate states (Merot et al., 2019). Thus, a transition can be
84 characterized by the initial point, the effect of the transition (direction and intensity), and the trajectory.

85 Studying a vineyard or a production system trajectory involves the use of indicators. The selected indicators
86 determine how the object of study is viewed. In the case of changes in practices, some studies have used the ESR
87 framework established by Hill & MacRae (1996) to characterize the change implemented (Chantre et al., 2015;
88 Merot et al., 2019) or calculated technical scores (Dupré et al., 2017). These indicators can be used to visualize
89 the trajectory sequentially.

90 Transitions towards pesticide use reduction are distinct from farm to farm. Different solutions exist to implement
91 change; for example, there are many levers to reduce pesticides in vineyards (use of biocontrol products, dose
92 reduction or soil tillage to replace chemical weeding, etc.) (Jeuffroy et al., 2022). The chosen solutions can
93 depend, for example, on the priority, the production mode and the specific farm context (Darnhofer et al., 2010).
94 The technical changes made by farmers when transitioning towards a low-input system differed from one farm to
95 another (Merot et al., 2019), even if different pathways can lead to the same final point (Deffontaines et al.,
96 2020).

97 To understand and summarize farm diversity, as observed in the DEPHY-farm network, during an
98 agroecological transition, the notion of farm typology is often used (Teixeira et al., 2018). Building a typology is
99 a way to simplify and group a variety of farm cases into fewer types to better understand this diversity (Alvarez
100 et al. 2018, Landais 1998). Typology can condense and summarize a large, heterogeneous dataset to identify
101 patterns and describe or even compare these patterns (Alvarez et al., 2018; Cortez-Arriola et al., 2015; Köbrich
102 et al., 2003). Typologies are a first step to understand the transition process because they are used to assess and
103 explain the differences between farming systems undergoing changes. In the literature, typologies built to
104 analyse trajectories of practices mainly focus on the difference between initial and final points, sometimes taking
105 an intermediate point and are based on qualitative data. Thus the trajectories, as a succession of phases building a
106 specific path between the initial and final point are scarcely taken into account in typologies. When taken into
107 account, trajectory studies are generally based on small samples of farms (ranging from a dozen to thirty farms)
108 and the building of the typology does not involve quantitative methods to analyse dynamics. Such methods
109 would become necessary when analysing large databases such as the DEPHY-Farm database.

110 We assumed that different strategies of pesticide use reduction exist but these strategies are difficult to identify
111 given the diversity of production contexts among the different winegrowing regions. A major obstacle to the
112 trajectories study is the need for a high amount of data over a long time. A method is needed to characterize the
113 long-term dynamic of pesticide use so as to go beyond regional effects. In fact, the method must overcome the
114 diversity of the production contexts by identifying indicators derived from the individual trajectory and which
115 are used to assess the dynamic. This paper aims to summarize and characterize the diversity of individual farms'
116 pesticide use trajectories within the DEPHY network at a national scale (France) in a way that reflects the long-
117 term dynamic of pesticide use reduction and goes beyond the regional effects.

118 To describe the diversity of transitions, we developed a typology to analyse pesticide use trajectory based on the
119 calculation of indicators linked to the change in TFI. We consider these trajectories as mathematical trajectories
120 (*i.e.* trajectory of quantitative data and numeric variables) to differentiate them from the mechanisms underlying
121 the transition process (*i.e.* trajectory built on qualitative data and variables). We also described the different
122 technical changes identified through performances evolution by Fouillet et al. (2022) with the Agrosyst database
123 for each type of pesticide use trajectory to identify which levers can be implemented to reduce pesticide use.

124 **2. Materials and Methods**

125 **2.1. Vineyard system**

126 Grapevine is a perennial plant, often planted in monoculture, which faces strong pest and disease pressures.
127 Several threats can cause major damage, thus impacting the qualitative and quantitative characteristics of
128 grapevine production (Fermaud et al., 2016). Pesticide applications remain the most effective way to control pest
129 and diseases. In 2019, the average TFI for French vineyards was 12.4, with an average of 18 treatments per year
130 (Simonovici and Caray, 2021), whereas the average TFI for wheat (a major annual crop in France) was 4.9 in
131 2017 (Agreste 2020). Among pesticides, fungicides represent around 80% of pesticide use in vineyards. Most of
132 these treatments aim to control downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*).
133 Insecticides account for less than 15% of pesticide treatments and are sprayed to control European grapevine
134 moth (*Lobesia botrana*) and the leafhopper vector of Flavescence dorée (*Scaphoideus titanus*). Depending on the
135 region and year, treatments to prevent Flavescence dorée can be compulsory by law. Herbicides represent the
136 remaining 5% of pesticide use (Mailly et al., 2017) but are still applied on 72% of vineyards (Simonovici and
137 Caray, 2021) on the inter-row or/and under the vine row. Pathogen development is highly correlated to the
138 climatic conditions of the vineyard (humidity, rainfall and wind) (Mailly et al., 2017). This relationship leads to
139 a range of practices between and within winegrowing regions.

140 **2.2. The DEPHY network and the AGROSYST database**

141 The DEPHY network was created in 2010 with the aim of demonstrating the capacity of farms voluntarily
142 enrolled in the network to reduce their pesticide use. The DEPHY network includes more than 4000 farms and
143 covers all French production sectors. The vineyard sector is represented by 280 farms that joined the network
144 between 2010 and 2012 and an additional 270 farms that joined in 2016. Farms entering the network in 2016 join
145 an existing group or form a new group depending on their location. The vineyards involved in the DEPHY
146 network are divided into 49 groups across the main French winegrowing regions. Each group is composed of
147 around a dozen winegrowers and is facilitated by a network engineer who supports the winegrowers in their

148 efforts to reduce pesticide use with individual assistance and collective projects. The role of network engineer is
149 essential in the motivation for change, in the choice of levers to implement and the dynamic of implementation.
150 Engineers promote generic and well-known levers of pesticide reduction (dose reduction, frequency of treatment,
151 choice of the products, equipment adjustments...), as well as tools to better schedule pesticide applications (*e.g.*
152 decision support system for dose and date choice). When entering the network, winegrowers engaged part of
153 their plots within the DEPHY-network named “cropping system” by the network.

154 The network engineer collects information on the phytosanitary strategy for each farm every year and enter the
155 data into a database (AGROSYST Information System). Each phytosanitary intervention is recorded in the
156 database with the dose and the name of the product.

157 To encourage data analysis and monitor pesticide use evolution, the AGROSYST database was created to
158 compile information about the farming systems: farm context (*e.g.* agricultural area, farm equipment),
159 phytosanitary strategy (all information on treatments: applied dose and product sprayed, etc.) and agronomic
160 indicators such as yield. Other performance indicators available in the database (*e.g.* number of carcinogenic,
161 mutagenic or toxic for reproduction (CMR) products used or the quantity of sulphur and copper applied) have
162 been calculated using the raw data. When a farm joins the network, a diagnostic is performed with the farmer to
163 collect information on its “initial point” based on the previous three years. Farming system details are then
164 collected every year.

165 Data available for 373 vineyards (*i.e.* 89% of the network) between 2017 and 2019 reported the different levers
166 mobilised in the DEPHY network. Among the levers most mobilized, the dose regulation (with or without DSS)
167 (80%), mechanical weeding to replace herbicide product (76%) and the use of biocontrol products (*e.g.* sulphur
168 products) (53%) were observed (internal communication). Few winegrowers mobilized levers based on
169 prophylactic measures (18%). Therefore, we expect to see a decrease of the use synthetic products (fungicide
170 and herbicide) linked to an increase and biocontrol products (Substitution strategy). Since most of the levers
171 focus on the phytosanitary strategy, we should be able to capture the differences in phytosanitary strategy
172 through the phytosanitary performances.

173 Only vineyards with more than 6 years of data were evaluated for this study. We selected a total of 161 farms
174 entered between 2010 and 2011 in the network. These farms were distributed across 11 major French
175 winegrowing regions: Alsace, Bordeaux, Bouches-du-Rhône, Bugey-Savoie, Champagne, Burgundy, Charente,
176 Côtes-du-Rhône, Gaillac, Provence and Loire Valley.

177 **2.3. TFI calculation**

178 We assessed pesticide use by using the treatment frequency index (TFI, Pingault et al. 2008). TFI is the main
179 indicator used within the DEPHY network to monitor pesticide use. TFI is the sum, for each pesticide product
180 applied during the crop season, of the ratio between the applied dose and the full registered and recommended
181 dose (Brunet et al., 2008; Fouillet et al., 2022). Different methods to calculate the TFI exist and differ regarding
182 the full registered dose, either established by product or by targeted pest or disease. The TFI used in our study
183 corresponds to the applied dose expressed as a fraction of the dose recommended to control specific targeted
184 pests or diseases and by the proportion of sprayed area (see [Equation 1](#)).

$$TFI = \sum_p \frac{Dose_sprayed_p}{Dose_recommended_p} \times \frac{Area_sprayed_p}{Area_total_p}$$

185 *Eq(1): Calculation of the TFI (Pingault et al., 2008) for a given year at the farming system scale. The dose*
 186 *sprayed per product corresponds to Dose_sprayed; the recommended dose for a product P for the target pest is*
 187 *Dose_recommended; Area_sprayed represents the surface area where the product was applied and Area_total is*
 188 *the total surface of the field where the treatment was sprayed (Pingault et al., 2008).*

189 The recommended doses per product and per targeted pest/disease were extracted from the e-phy database
 190 published by the French Ministry of Agriculture (Ministère de l’Agriculture et de l’Alimentation, 2021). The e-
 191 phy database for 2020 was used for all 10 years of the study in order not to take into account the variations of the
 192 dose regulations during this period. The variables dose_sprayed, area_sprayed, area_total and the product name
 193 were directly available from the AGROSYST database.

194 For 3% of the treatments, we were not able to identify the product in the official database. As proposed in
 195 Fouillet et al. (2022), for these treatments we assigned a TFI of 1, which stands for a full dose applied to a given
 196 area. The TFI for a growing season corresponds to the sum of the TFI per treatment for all interventions
 197 performed during that growing season (see [Equation 1](#)). We differentiated partial TFI depending on the target of
 198 the treatment: fungicide TFI (TFI_f), herbicide TFI (TFI_h) and insecticide/acaricide TFI (TFI_i). The TFI biocontrol
 199 was calculated separately following the principle of [Equation 1](#) for the interventions based on the list of
 200 biocontrol products (sulphur, macroorganisms, microorganisms, natural substances, pheromones, elicitors).

201

202 All the variables used to calculate the TFI are summarized in [Supplementary data 1](#).

203 2.4. Indicators used to build the typology

204 To characterize the type of pesticide use trajectories within the DEPHY network, six indicators were calculated
 205 using the TFI for each farm. These indicators can be used to describe the transition process. Some of the
 206 calculated indicators were adapted from the method of Martin et al. (2017) used by Bouttes et al. (2018) and
 207 Perrin et al. (2020). This method took into account the trends in farm performances: i) the slope of a linear model
 208 reveals the general trend (increase, decrease or stagnation), ii) the range of the residuals to evaluate the
 209 robustness and variability of the measurement and iii) the sum of squared deviations estimates the overall
 210 variability of the farming system. In total, the six indicators were calculated : the initial normalized TFI, the final
 211 TFI, the slope, the sum of square deviation, the maximum variation and the slope break.

212 In our case study, we first characterized for each vineyard the initial and “final” state of the transition and
 213 extracted the two following indicators to characterize changes:

- 214 - the **initial normalized TFI** (*normalized_TFI*) corresponds to the ratio between the initial TFI in a
 215 vineyard and the regional TFI provided by the French Ministerial Statistical Service for Agriculture
 216 data. The normalization let to eliminate the winegrowing region effect. In fact, the indicator *initial*
 217 *normalized_TFI* reflects the intensity of pesticide reduction compared to other vineyards in the same
 218 winegrowing region. The database from the French Ministerial Statistical Service for Agriculture is

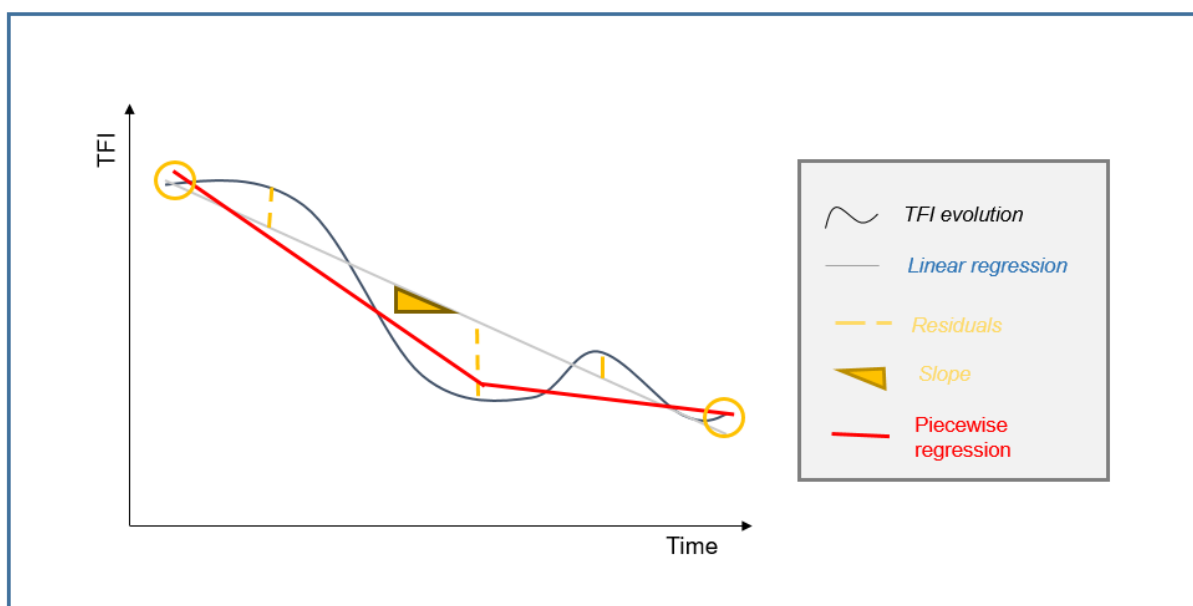
219 representative of the cropping practices in the different French winegrowing regions. The surveys are
220 conducted every three years at the field scale on a representative sample of 4000 farms. For farms
221 which entered the DEPHY network in 2010, the initial TFI was calculated using the data from 2008,
222 2009 and 2010. For the farms which entered in 2011, the calculation was made using the 2009, 2010
223 and 2011 data. The normalization was performed with the 2010 regional TFI. A normalized TFI under
224 1 indicates that the winegrower is using less pesticide than the regional average.
225 - the **final TFI** (*final_TFI*) corresponds to the mean TFI for the last three years (2017, 2018, 2019) to be
226 consistent with the initial point calculation and to limit the year effect. The final TFI is an un-
227 normalized value.

228 These first two indicators were completed by indicators of the trajectory. We used a linear model to characterize
229 the pesticide use trajectory based on TFI evolution (data not normalized) over the 10-year period. For each
230 production system, several indicators were extracted:

- 231 - the **slope** (*slope*) was used to characterize the path taken from the initial TFI to TFI in 2019;
- 232 - the **sum of squared deviations** (*SSD*) was calculated to characterize the variability around the slope
- 233 - the **maximum variation** (*max_variability*) corresponds to the maximum residuals having the largest
234 absolute value were extracted to indicate the variability of the TFI over the 10-year study period.

235 Trajectories are not necessarily linear and regular, and ruptures can occur (Wilson, 2007).

- 236 - the **slope break** (*slope_break*) was used to characterize ruptures during the trajectory. In order to
237 qualify these ruptures, two-piecewise continuous linear regressions were conducted for each farm. Two-
238 piecewise linear models are a common nonlinear model which assume the existence of a breakpoint at
239 the junction of two-line segments. The location of the breakpoint was considered as a model parameter
240 and the most relevant value was found by maximum likelihood. The slopes of the lines before and after
241 the “best” hypothetical breakpoint were compared. The slope change is used to evaluate if the farming
242 system was experiencing a break during the pesticide reduction process. We hypothesized that only one
243 main rupture happened during the transition. We also hypothesized that a rupture could happen during
244 the re-engagement of farms in 2016.



245
 246 *Fig. 1. Overview of the indicators calculated to set up the pesticide use trajectory typology inspired by the*
 247 *methodology from Martin et al. (2017). The slope was obtained with the linear regression over time based on the*
 248 *raw measurement, and the maximal residual of the regression was extracted. The piecewise regression was used*
 249 *to identify the existence of a transitional rupture. The initial TFI and final TFI were also extracted.*

250 **2.5. Indicators describing the phytosanitary strategies and used to explain the types of TFI**
 251 **trajectories**

252 To identify changes in the phytosanitary strategy that were implemented to reduce pesticide use, we looked at
 253 the management practices used by the DEPHY farmers highlighted in the study by (Fouillet et al., 2022). The list
 254 of the data we used for the study are summarized in the [Supplementary data 2](#). All the indicators used to
 255 characterize changes in the phytosanitary practices are available in the AGROSYST database. The different
 256 management practices studied were : the type of product used, the applied dose per treatment, the use of
 257 chemical herbicide and the production mode.

258 We described changes in the type of product used, the applied dose per treatment, use of chemical herbicide and
 259 production mode by us the Efficiency, Substitution, Redesign (ESR) framework (Hill & MacRae, 1996; Pretty,
 260 2018). The ESR framework distinguishes three different changes: the first type of changes (E, efficiency) mainly
 261 seeks to resources optimisation, the second type of changes (S, substitution) is mostly based on the substitution
 262 of one or more elements (*i.e.* products, equipment...) and the third changes (R, redesign) generally focused on
 263 reorganizing the production system. The redesign strategy is associated with both technical levers and the
 264 production mode (organic farming).

265 **Type of product used**

266 First, we focused on the use of biocontrol products. The list of biocontrol products authorized by the Ministry of
 267 Agriculture includes 4 categories: macroorganisms (insects, mites, etc.), microorganisms (bacteria, viruses),
 268 chemical mediators (pheromones and elicitors) and natural substances (biocontrol products are composed of
 269 substances present in the natural environment and can be of plant, animal or mineral origin). These new
 270 compounds in the products are more leachable and the frequency of application is more dependent on rainfalls.

271 (Rouault et al., 2016). A change of product was characterized as a substitution. The substitution of chemical
272 products with biocontrol involves a different reasoning of the treatments (increase of the number of treatments).
273 To characterize the use of biocontrol products, we used several indicators:

- 274 • Whether or not a biocontrol product was used
- 275 • The biocontrol share ($TFI_{\text{biocontrol}}$ over total TFI)
- 276 • The sulphur quantity applied. Sulphur products are considered by French regulations as biocontrol
277 products. In organic vineyards, sulphur is mostly used to control powdery mildew.
- 278 • The use of mating disruption (biocontrol product) against the leafhopper vector of *Flavescence dorée*.

279 Then, we focused on the use of copper products. Copper products are not considered to be a biocontrol product
280 but are authorized and mostly used in organic farming against downy mildew. Similar as the sulphur product,
281 copper products are more leachable. Indicators used to characterize copper products used were:

- 282 • Whether or not a copper product was used
- 283 • The quantity of copper sprayed

284 The number of carcinogenic, mutagenic or toxic for reproduction (CMR) products sprayed was also
285 characterized.

286 **Applied dose per treatment** (fungicides, herbicides, insecticides). The dose sprayed indicates if a dose was
287 adapted to the current situation with a more or less complex decision-making process (for fungicide and
288 insecticides products). Decision Support System or dose adaptation depending on climate and phenological stage
289 are tools highly implemented by the winegrowers in the DEPHY-Network (internal communication). In 2019,
290 80% of the farms were using these levers to reduce their pesticide use. The DSS are nowadays well known
291 (DECIttrait or Optidose) and are often proposed to the winegrowers when they are joining the DEPHY network.
292 Pesticide use can be reduced by 30-50% in vineyard systems by using decision support system (Thiollet-
293 Scholtus et al., 2019).

294 An herbicide dose reduction indicates a change in the weeded strip under the row or the stopping of the weeding
295 in the inter-row. Dose reduction was qualified as gain of efficiency.

296 **Use of chemical herbicides.** Even if herbicide represents a small part of the TFI, stopping the use of herbicide
297 product implies organisational change (e.g. increase in work time, increase of the cost (Jacquet et al., 2019). If
298 the TFI_h was zero, we considered that the winegrowers were implementing mechanical weeding under the row
299 (Fouillet et al., 2022). Replacing the use of herbicide product by mechanical weeding was qualified as redesign
300 (Merot et al., 2019).

301 **The production mode** (conventional farming, organic farming or farming system in conversion) was also
302 available in the database. The conversion to organic farming implies the implementation of several levers (the
303 stopping of systemic product and herbicide product) (Merot et al., 2019). Hill and MacRae (1996) qualified the
304 conversion toward organic farming as redesign.

305 Data on behavioural levers (e.g. use of decision support systems) are not available in the database; the indicators
306 used are mainly quantitative indicators linked to the use of phytosanitary treatments.

307 2.6. Statistical analysis and data processing

308 The data were processed with R software v. 3.6.2 (R Core Team, 2019) and Rstudio v. 1.3.1093 (RStudio Team,
309 2020) with the Tidyverse package (Wickham et al., 2019) and the broom package (Robinson and Hayes, 2020).
310 The graphics were made using the ggplot2 package (Wickham, 2016).

311 2.6.1. Statistical method used to build the typology

312 The typology was based on the indicators presented in section 2.4. A principal component analysis (PCA)
313 followed by a hierarchical cluster analysis (HCA) were performed using FactoMineR (Lê et al. 2008).

314 We performed the PCA with the six indicators to identify the relationships between the variables. The missing
315 values represented only 0.6% of the data, which is why the missing values were replaced by the mean of the
316 variable.

317 The farm trajectory typology was then produced using an HCA on the coordinates on the PCA axes with an
318 eigenvalue greater than 1 (Kaiser criterion). We used the Euclidean distance computed on the factorial
319 coordinate of the individuals. We identified the optimum number of clusters based on the largest relative loss of
320 inertia using Ward's method.

321 2.6.2. Characterization of the different clusters of pesticide use trajectory

322 In order to compare the indicators used to set up the typology between clusters, we used a one-way ANOVA and
323 Tukey test for numeric and continuous indicators with normal distribution of the errors. A non-parametric test
324 (Kruskall-Wallis) and Wilcoxon test were used for non-normal distribution.

325 We assessed changes in the phytosanitary strategy indicators by comparing the initial point (un-normalized) and
326 final points between and within clusters. For indicators computed as proportions, we used a **Pearson's chi-**
327 **squared test** to test the change in indicators between the initial and final point between and within clusters. To
328 test the evolution of numeric indicators between the initial and final points, we used a **t-test**. P-values are
329 mentioned throughout the results section.

330 3. Results

331 3.1 Typology of pesticide use trajectory

332 3.1.1 Classification quality

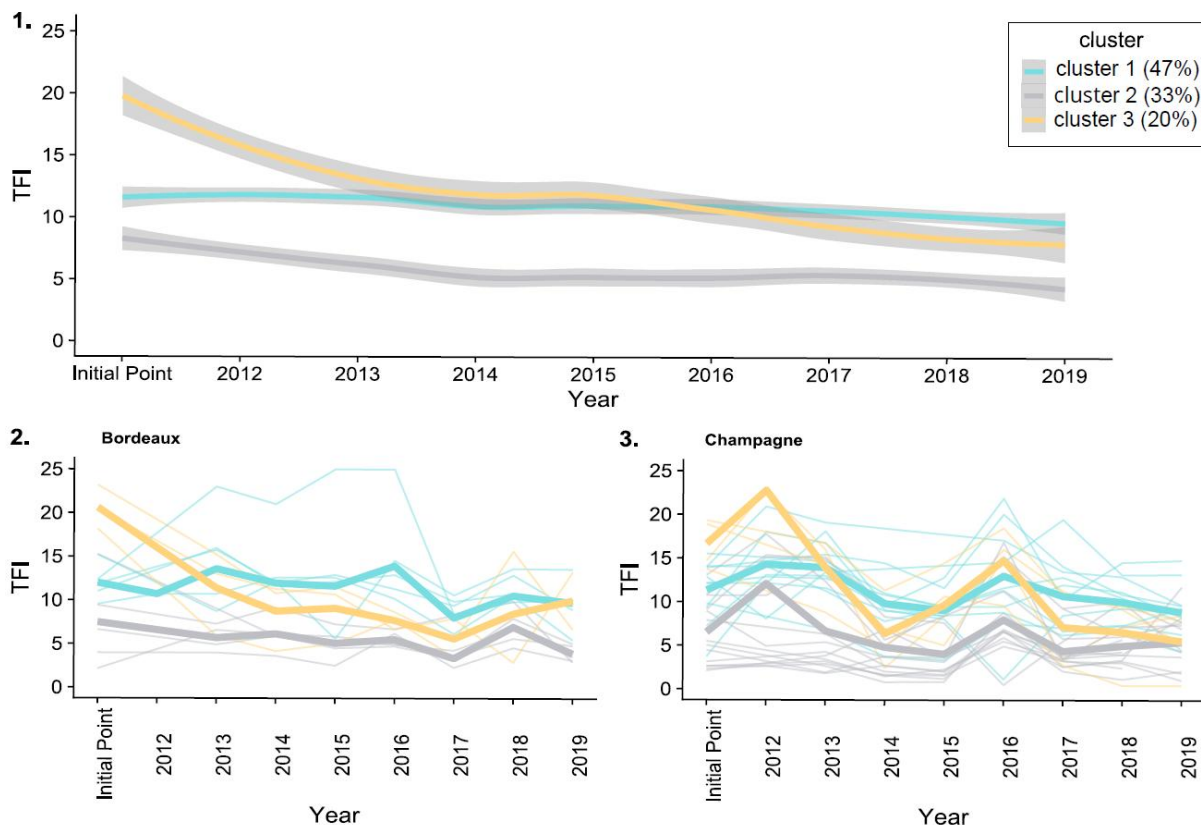
333 The dataset used for the classification contained 161 farms. The first two components of the PCA combined
334 67.9% of the variance. The first PCA component, which accounts for 40.8% of the total variance, expresses the
335 strong positive correlation between the normalized TFI upon entry in the network and the SSD. The variable
336 slope and the slope change are also associated with this component. The second component, which explains
337 27.1% of the variance, is associated with three variables: *final_TFI*, *max_variability* and *slope change*. The HCA
338 was based on the first 2 components of the PCA.

339 3.1.2 Typology

340 Three clusters of 75, 53 and 33 farms were identified. All indicators were significantly related to each cluster
341 (Supplementary data 3). The three types are present in almost every winegrowing region and every group (see

342 [Supplementary data 4 and 5](#)) but in different proportions. Farms belonging to cluster 2 were dominant in the
 343 Bouches-du-Rhône, Provence and Alsace. In Charente and Côtes-du-Rhône, there were no farms in cluster 3.
 344 Farms belonging to cluster 1 were mainly in the Loire Valley, Charente and Côtes-du-Rhône.

345



346

347 *Fig. 2. Change in the TFI per cluster (1.) Mean pesticide use trajectory per cluster. (2.) Change in the TFI per*
 348 *cluster in Bordeaux. The bold lines correspond to the average trajectories by type. The thin lines correspond to*
 349 *the individual trajectories. (3.) Change in the TFI per cluster in Champagne. The bold lines correspond to the*
 350 *average trajectories by type. The thin lines correspond to the individual trajectories. The changes in the TFI for*
 351 *the other winegrowing regions are available in [Supplementary data 6](#). Cluster 1 is represented by the blue line,*
 352 *cluster 2 by the grey line and cluster 3 by the yellow line.*

353 The three different types of pesticide use trajectories are differentiated (Fig. 2.1). The first type, cluster 1,
 354 corresponds to farms with lower pesticide use than cluster 3 when entering the DEPHY network and which did
 355 not decrease their TFI. The second type, cluster 2, also corresponds to farms with lower initial pesticide use upon
 356 entering the network than cluster 3 and which decreased their TFI over the 10-year period. The last type, cluster
 357 3, corresponds to farms with the highest level of pesticide use at the initial point among the three clusters and
 358 which achieved a substantial pesticide reduction over the 10-year period.

359 When looking at TFI changes according to winegrowing regions, the same trends were observed visually even in
 360 different regions (see supplementary 6). For example, for Bordeaux and Champagne (Fig. 2.2 and 2.3), the mean
 361 trajectories show similar trends but some differences are still observed. More inter-annual variability is observed
 362 for each cluster in Champagne (e.g. TFI pikes in 2012).

363 *Characteristics of the six TFI trajectory indicators for the three clusters*

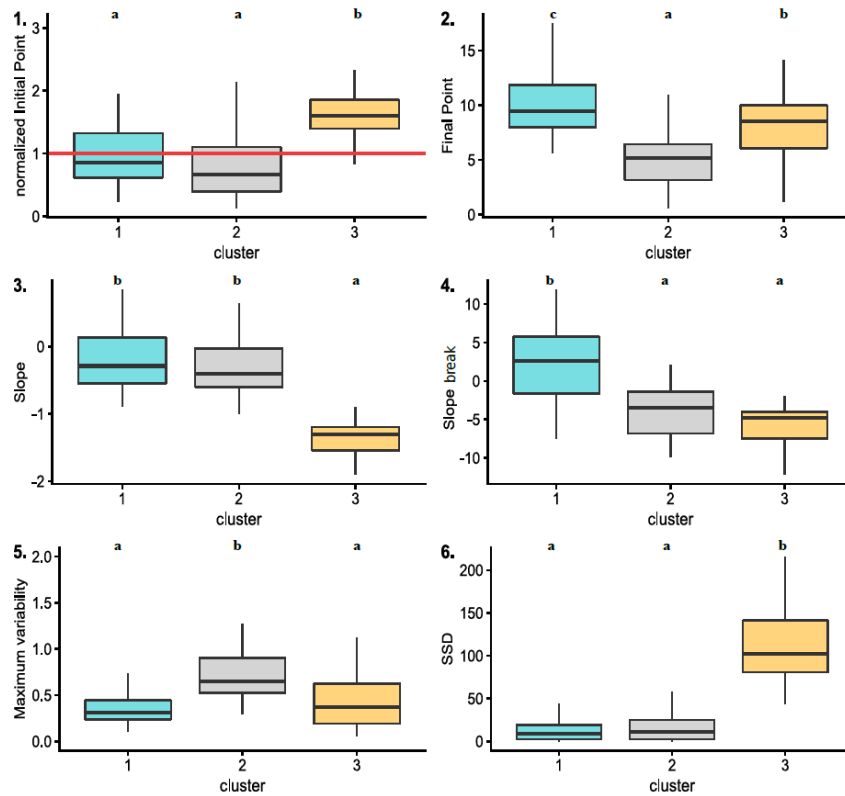
364 Cluster 1 farms presented a mean normalized TFI that was similar to the national standards (0.89). The mean TFI
365 at the initial point was 11.6 and the mean final TFI was 9.7, which corresponds to a decrease of 1.9 TFI points.
366 Farms in this cluster had the smallest TFI reduction (-16.4%). The mean slope is -0.23 TFI points per year. The
367 farming systems in cluster 1 had the smallest maximum variability (0.37) and a mean SSD of 14.47. A total of
368 30.6% of farms in this cluster experienced a break in their trajectories. The median year of TFI slope change for
369 these farms was 2015, with a positive mean increase of 0.68. This increase indicates a slowdown in the TFI
370 decrease process.

371 Cluster 2 farms were characterized by the smallest normalized initial TFI (0.52), meaning that before entering in
372 the network, these farms were already applying around half the quantity of pesticides than other farms in the
373 region. In the network, these farms still reduced their TFI by 48.7% with an initial TFI of 8.2 and a final TFI of
374 4.2, which corresponds to a decrease of 4 TFI points. The mean slope is -0.32. The cluster 2 farms also had the
375 highest variability (0.86) but a low SSD (17.8). A total of 24% of these farms experienced a break in their
376 trajectories during the 10-year period. The mean slope change was -1, indicating an acceleration in the process
377 of pesticide use reduction. The median year of TFI slope change was 2013.

378 Cluster 3 farms had the highest initial TFI, higher than the national trends (1.53). The mean TFI at the initial
379 point was 20.8 and the mean final TFI was 7.7, which corresponds to a decrease of 13.1 TFI points. The farms in
380 this cluster had the highest TFI reduction rate (-63%) and the highest slope (-1.38). A large variability was
381 observed: the SSD was highest for cluster 3 with a mean of 113 and the mean maximum of variability was 0.42.
382 A total of 30% of the farms in cluster 3 experienced a break in their trajectories. A mean slope change of -1.7
383 was observed, indicating an acceleration in the process of pesticide use reduction. The median year of the slope
384 change was 2014.

385 The initial normalized TFI, slope change and SSD were not significantly different for clusters 1 and 2 (Fig. 3).
386 No significant difference was identified for the slope break for clusters 2 and 3 (p-value > 0.05).

387 No significant difference was identified for the maximum variability for clusters 1 and 3. The final point
388 distribution was significantly different among the three clusters.



389

390 *Fig. 3 Distribution of the calculated indicators per cluster. (1.) Initial point normalized the red line represent the*
 391 *mean level of pesticide use at the national scale (2.) Final point, (3.) Slope, (4.) Slope break, (5.) Maximum*
 392 *variability, (6.) Sum square deviation (SSD).*

393 *The horizontal black lines across the boxes represent the median. The end of the boxes represents the first and*
 394 *third quartiles; the whiskers indicate the minimum and maximum values. For a given indicator, distributions per*
 395 *cluster are significantly different if associated with a different letter (Wilcoxon test, $p < 0.05$ or Tukey test, p -*
 396 *value < 0.05).*

397

3.2 Levers implemented within clusters identified with pesticide use evolution

398

3.2.1 Disease control

399

400 The t-test showed a significant difference between the TFI at the initial and final points for the three clusters (t-
 401 test, $p < 0.001$, [Table 2](#)). The percentage of decrease, calculated between the initial point and the final point, was
 402 -16.4% for cluster 1, -49.7% for cluster 2 and -63% for cluster 3. The same trends are observed for the TFI_f as
 403 all clusters significantly reduced their fungicide use from the initial to the final point (t-test, $p < 0.05$, [Table 2](#)).
 404 The reduction of the fungicide dose applied per treatment was significantly different between the initial and final
 405 points within the 3 clusters (t-test, $p < 0.001$, [Fig. 5B](#)). A significant fungicide dose reduction from 11.6% from
 406 the initial point to 2019 was observed within cluster 1, -42.8% for cluster 2 and -43.6% for cluster 3.

407 At the initial point, the proportion of farms using biocontrol products was significantly different among the
 408 clusters (Pearson's chi-squared test, $p < 0.05$, [Table 1](#)). Cluster 2 had the highest proportion of farming systems
 409 using biocontrol products at the initial point (79.3%). An average 80% of the farms in the three clusters used
 410 biocontrol products at the final point ([Fig. 5A](#)). The TFI_{biocontrol} product increased significantly for cluster 2 over
 411 the 10-year period (t-test, $p < 0.01$). The percentage of farms using biocontrol increased over the 10-year period
 412 for clusters 1 and 3 (Pearson's chi-squared test, $p < 0.05$). The biocontrol rate increased significantly over the 10-

413 year period (t-test, $p < 0.05$): +74.5% in cluster 2 and +115% for cluster 3. The change in cluster 1 (+32.3%) was
414 not significant.

415 The proportion of farms using copper and sulphur products was not significantly different between clusters at the
416 initial point or at the final point (Pearson's chi-squared test, $p > 0.05$). Additionally, the change in the number of
417 farms using copper and sulphur was similar between the initial and final points for the three clusters (Pearson's
418 chi-squared test, $p > 0.05$). The quantity of copper products was stable over the 10 years for the 3 clusters (t-test,
419 $p > 0.05$). The quantity of sulphur applied increased for cluster 2 between initial and final point (t-test, $p < 0.01$,
420 Fig. 5F).

421 The proportion of farms using CMR products was significantly different among clusters both at the initial point
422 and when tested at the final point (Pearson's chi-squared test, $p < 0.01$ for the initial and final points, Table 2).
423 Regarding the change between the initial and final points, the highest rate of decrease of CMR product use was
424 for the cluster 2 farms: at the final point, only 13% of the farms were using CMR products (Fig. 5E). Cluster 3
425 had the highest proportion of farms using CMR products at the initial and final points. The mean number of
426 CMR products used decreased significantly over the 10-year period for all 3 clusters (t-test, $p < 0.001$). Cluster 3
427 farms had the highest number of CMR products used at the initial point (10.4). At the final point, cluster 3 farms
428 had the highest number of CMR products used (3.1), similar to cluster 1 (2.9).

429

430 Table 1. Change in the technical levers between initial and final points. Pearson's chi-squared test was conducted
431 between the initial and final points within and between clusters.
432 NS: $p > 0.05$; *: $p < 0.1$; **: $p < 0.01$; ***: $p < 0.001$.

433

434

<Table 1 HERE>

435

436

3.2.2 Weed control

437 The change in the TFI_h between the initial and final points was significantly different for clusters 2 and 3,
438 indicating a significant reduction in the use of herbicidal products (t-test, $p < 0.05$, Table 2). The change between
439 the initial and final points in the proportion of farms using herbicides was significantly different within the three
440 clusters (Pearson's chi-squared test, $p < 0.05$, Table 1, Fig. 5C). The proportion of farms among clusters using
441 herbicides was similar at the initial point (Pearson's chi-squared test, p -value = 0.12) but significantly different
442 at the final point (Pearson's chi-squared test, p -value < 0.001). A significant decrease in the applied dose was
443 observed for the three clusters between the initial and final points (t-test, $p < 0.01$, Table 2). Farms from cluster 1
444 managed to reduce their dose applications by 70%, from a mean dose of 0.61 to a mean dose of 0.19.

445

3.2.3 Pest control

446 Regarding the change in insecticidal management, a non-significant decrease in the TFI_i was observed in all
447 clusters (t-test, $p > 0.05$, Table 2). However, a significant decrease in the TFI_i per treatment was observed for
448 cluster 1 and cluster 3 (t-test, $p < 0.05$). The proportion of farms using insecticidal products was significantly
449 different among clusters at both the initial and final points (Pearson's chi-squared test, $p < 0.05$, Table 1, Fig.
450 5D). The proportion of farms from clusters 1 and 2 using insecticidal products decreased by 19% and 46.8%,
451 respectively. The proportion of farms using mating disruption significantly increased over the 10-year period in
452 all three clusters (Pearson's chi-squared test, $p < 0.001$). In 2010, the proportion of farms using mating disruption

453 was similar among clusters (Pearson's chi-squared test, $p = 0.12$) but was significantly different at the final point
454 (Pearson's chi-squared test, $p < 0.001$).

455

456 Table 2. Change in the technical levers over time. T-tests were conducted to assess whether the reduction was
457 significant.

458 *NS*: $p > 0.05$; *: $p < 0.1$; **: $p < 0.01$; ***: $p < 0.001$.

459

460

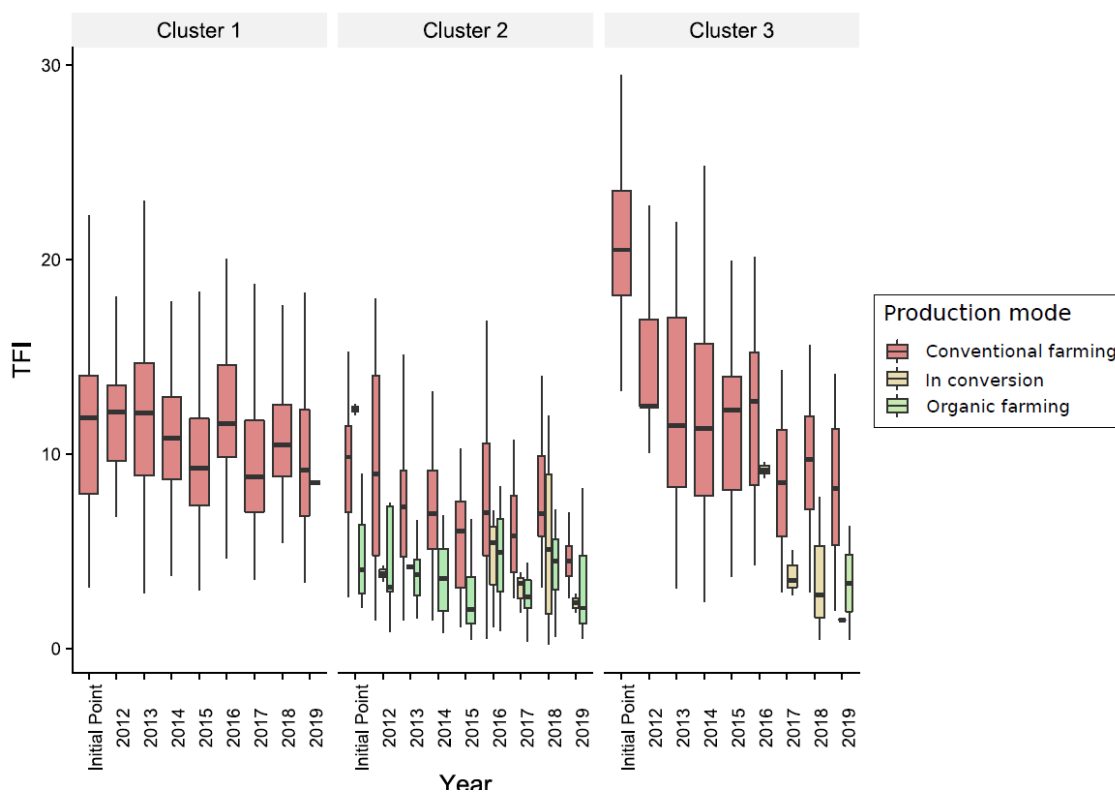
461

<Table 2 HERE>

462

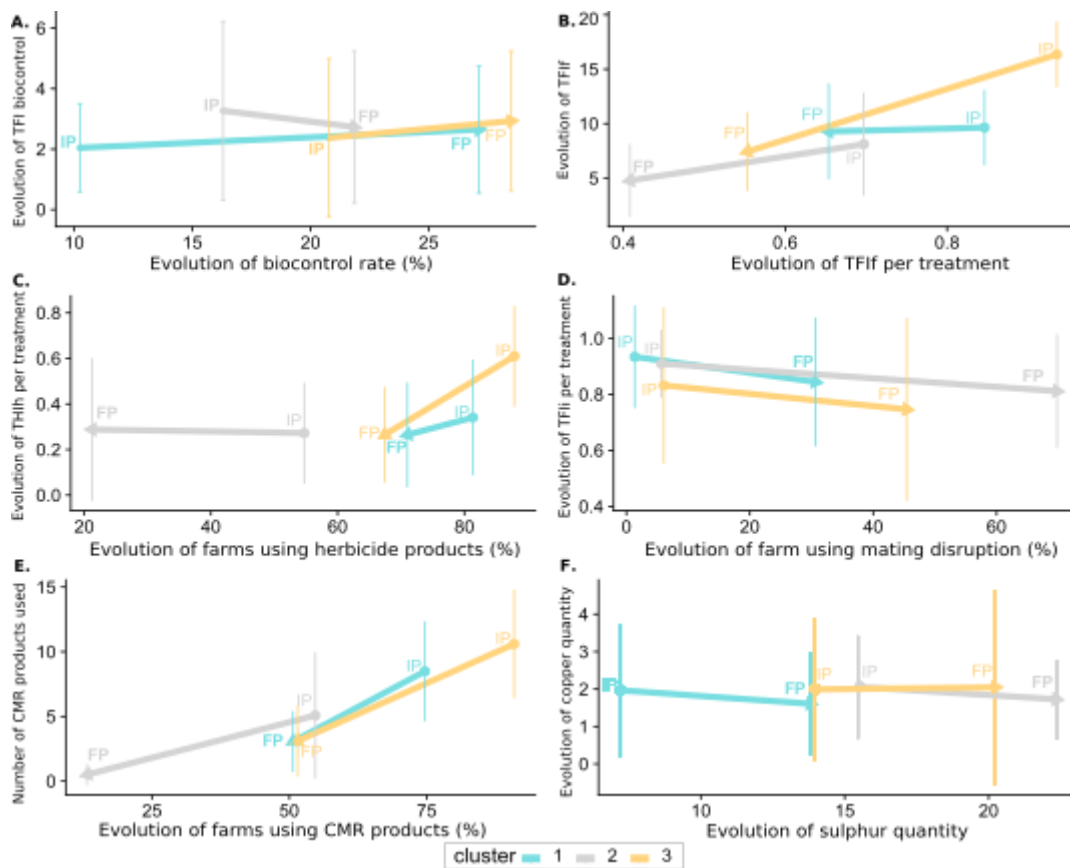
3.2.4 Production modes

463 The proportion of production modes (conventional farming, organic farming or in conversion) between clusters
464 was significantly different at the initial and final points (Pearson's chi-squared test, $p < 0.001$, Table 1, Fig. 4). At
465 the initial point, 100% of the farms in clusters 1 and 3 had a conventional farming system. At the final point, a
466 large majority of the farms had conventional farming systems in cluster 3 (90.6%) and cluster 1 (98.5%). For the
467 cluster 2 farms, a higher proportion of farms had an organic farming system (36.7% at the initial point)
468 compared to clusters 1 and 3 (0% for both). In cluster 2, farming systems in conversion to organic farming
469 appeared as soon as they entered the network. For cluster 3, conversions towards organic farming started in 2016
470 and represented 6.3% of the cluster. The proportion of farming systems in conversion to organic farming in 2019
471 at the final point was 1.5% for cluster 1 and 3.1% for cluster 3. Cluster 1 did not include any farms with organic
472 farming systems at the final point. However, the proportion of farms depending on the production mode were
473 similar between the initial and final points within each cluster (Table 1).



474

475 Fig. 4. Change in the TFI by cluster and production mode. Outliers are not represented. Whiskers display the
 476 5th and 95th percentiles. Horizontal bars indicate the first quartile, median and third quartile.



477
 478 Fig. 5 (A.) Change in the biocontrol rate based on the $TFI_{biocontrol}$ between the initial point (IP) and final point
 479 (FP) for each cluster. (B.) Change in the fungicide dose based on the TFI_f change between the IP and FP for
 480 each cluster (C.) Change in the TFI_h and the percentage of farms using herbicide products between the IP and
 481 FP for each cluster. (D.) Change in the percentage of farms using mating disruption depending on the mean TFI_i
 482 per treatment between the IP and FP for each cluster. (E.) Change in the percentage of farms using
 483 carcinogenic, mutagenic, or toxic for reproduction (CMR) products based on the number of CMRs used between
 484 the IP and FP for each cluster. (F.) Change in the applied sulphur quantity based on the applied copper quantity
 485 between the IP and FP for each cluster.

486 3.3. Change intensity

487 Looking at each type, we observed that cluster 1 corresponded to farms that were already using pesticides
 488 efficiently when they entered the network: their normalized initial TFI was lower than 1 at the initial point. It
 489 seems that these farms did not implement new levers, and a large majority of them continued using CMR
 490 products and herbicides (Fig. 4). However, a progressive transition towards reducing herbicide, insecticide and
 491 fungicide doses was observed. These farms moved towards greater efficiency and substitution.

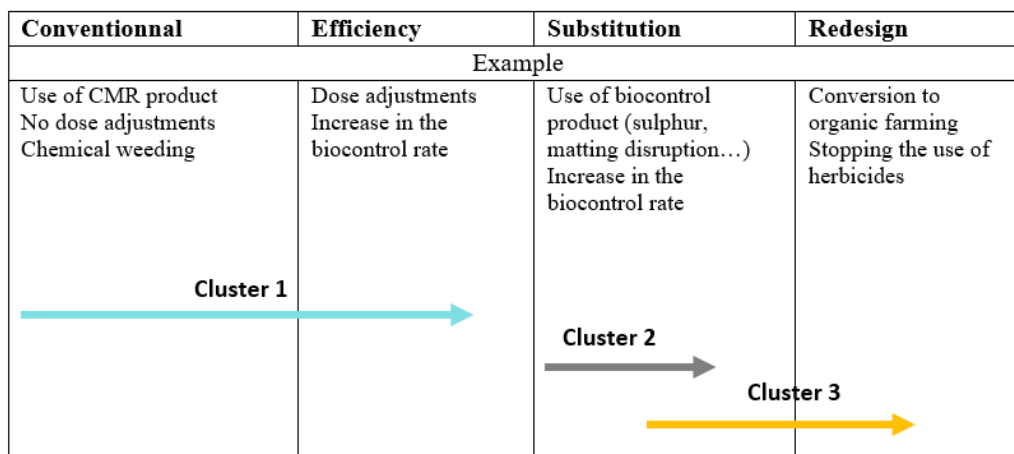
492 When we looked at cluster 2 farms, we noticed that they were already well advanced in terms of efficient
 493 pesticide use (Fig. 5). In all, 36.7% of farms were engaged in organic farming at the initial point and 55.2% at
 494 the final point. A few farms were already using CMR and herbicidal products (58.5%). A high dose reduction of

495 TFI_f was observed and associated with an increase in efficiency. The reduction in the sprayed fungicide dose
 496 with no decrease in the quantity of copper products used demonstrated efficiency-based strategies. At the final
 497 point, a large majority of the farms were using mating disruption and biocontrol products. These changes were
 498 related to the large of the farms in organic farming or in conversion to organic farming. The technical levers
 499 associated with this mode of production were the use of copper and sulphur, the cessation of systemic products
 500 and the implementation of soil tillage when farms stopped using herbicides.

501 Cluster 3 farms entered the DEPHY network with a high consumption of pesticide products and experienced the
 502 highest TFI decrease (Fig. 5). Looking at the changes occurring over the 10-year study period, we observed a
 503 high dose reduction affecting all phytosanitary treatments (insecticides, fungicides and herbicides). The
 504 reduction of the TFI_h and the slight reduction of the number of farms using herbicides indicated a decrease in the
 505 weeded strip (only under the row) rather than a total cessation of herbicide use as observed in cluster 2. The
 506 biocontrol rate over the global TFI increased while the TFI biocontrol remained stable. These changes indicate a
 507 reduction of the TFI without substituting biocontrol products. All these elements indicate substantial efficiency
 508 gains and substitution in these farms.

509 In summary, based on the ESR framework from Hill and MacRae (1996) the pesticide reduction strategies for
 510 cluster 1 and cluster 3 were mainly based on efficiency and substitution and differed in their initial levels of
 511 pesticide use when entering the network (Fig. 6). Cluster 2 farms undertook deeper changes, moving towards
 512 more redesign-based changes (Fig. 6).

513



514

515 Fig. 6: Summary of changes observed between the initial point (IP) and final point (FP) for each cluster based
 516 on the Efficiency, Substitution, Redesign (ESR) framework (Hill & MacRae, 1996). The phytosanitary strategies
 517 of each cluster are positioned on an ESR gradient, which also includes conventional (corresponding to an
 518 absence of phytosanitary strategy reasoning). Practices corresponding to each strategy were associated with
 519 each letter (conventional, E, S, R). Cluster 1 is represented by the blue arrow, cluster 2 with the grey arrow and
 520 cluster 3 with the yellow arrow.

521

522

523

524

525 **4. Discussion**

526 This paper aimed to characterize and understand the various pesticide use trajectories within the DEPHY
527 network. The method used allowed us to identify three types of pesticide use trajectories. The three types were
528 significantly differentiated by their initial TFI, the path taken (slope, decrease, variability, and rupture) and their
529 final TFI. The farms were categorized into the different types and are found across all winegrowing regions. The
530 typology developed was both robust and exceeded the winegrowing region effect, a factor that can impact
531 pesticide use intensity (Fouillet et al., 2022). This means that the three types of trajectories identified were the
532 result of the winegrowers' own strategies rather than the consequences of the particularities of the winegrowing
533 region even if some minor differences in term of inter-annual variability was observed as in 2015 - 2019 for
534 clusters 1 and 3.

535 All three trajectory types showed a significant reduction in pesticide use, but the reduction differed in intensity.
536 The farming systems in cluster 1 experienced the smallest TFI decrease (-14.7%). Farming systems from cluster
537 2 managed to reduce their TFI by 40.7%, while the cluster 3 farming systems experienced the highest TFI
538 decrease of 68.8%.

539 The differences in TFI reductions between clusters can be explained by the potential for improvement expressed
540 at the initial point. Indeed, the farming systems from the three clusters differed in terms of the initial point. We
541 observed that cluster 3 farms entered the DEPHY network with a high normalized TFI, indicating pesticide use
542 that exceeded the national average. Cluster 1 and 2 farming systems both started with a lower initial TFI
543 compared to the national average TFI value. However, their pesticide use reduction was different. Thus, the
544 initial point appears to be a key point of the transition towards a low-input farming system. Ross et al. (2008)
545 formalized that the path taken strongly depends on the initial state. Merot et al. (2020) showed by using a
546 typology of technical changes for vineyards in conversion to organic farming that the path taken by farms was
547 also highly dependent on the initial state. Our results suggest that it is easier for systems starting with a high TFI
548 to reduce their TFI than for those starting with a low TFI to achieve further decreases. For winegrowers with an
549 overuse of pesticide (Cluster 3), the modification of the phytosanitary strategy (dose reduction, change of
550 product) is based on simple levers but with a high impact on the TFI. As the winegrowers from the cluster 3 had
551 a use of pesticide product higher than the national average, it is therefore easier to reduce the pesticide use
552 compared to those who are not overusing pesticide (cluster 1 and cluster 2). Also, slope breaks, reflecting a
553 change in slope (increase or decrease) in the TFI trajectory, were observed in farms from all clusters rapidly after
554 engaging in the network. The slope break may also indicate a slowdown in the TFI decrease (*i.e.* abrupt decrease
555 followed by a stagnation). For all clusters, the mean year of rupture takes place before 2014.

556 The three clusters were also characterized by the variability around the slope, which provided information about
557 the specific farming system's sensitivity and adaptation to abiotic and biotic hazards over time (Martin et al.,
558 2017). These variabilities were partly linked to the adaptation of treatments to pest and disease pressure. The
559 year effect on pesticide use was substantial (Mailly et al., 2017). An increase in the TFI was observed in 2016
560 and again in 2018 when winegrowers contended with severe infestations of downy mildew (Fouillet et al., 2022).

561 Differences in climatic conditions also lead to variability in practices over time and space (Mailly et al., 2017).
562 The highest variability around the slope was observed for cluster 2 farms. Cluster 1 corresponded to the farms
563 with the smallest maximal variability and SSD. For clusters 2 and 3, we observed a high dose reduction of
564 fungicide treatments indicating that winegrowers in these clusters adapted their pesticide treatments depending
565 on the period or pest and disease pressure (Fouillet et al., 2022). Thus, looking at the difference in term of
566 variability between clusters, we can assume that winegrowers who adapted their pesticide treatment according to
567 pest and disease pressure experienced a higher variability of pesticide use. The more the winegrowers reduced
568 their pesticide use the more the TFI varied within cluster: TFI increases were higher in years with high pressure,
569 while TFI decreases were greater in years with low pressure. Unlike cluster 1 farms, the cluster 2 farms managed
570 to adapt their phytosanitary practices according to the climatic conditions and pest and disease pressures.

571 In our study, we considered an initial TFI (the year of entry into the network) and final TFI. The initial and final
572 TFI are arbitrary because farmers may have started to reduce their pesticide use before entering the network and
573 continued to implement technical levers after the final point. Unlike the conversion to organic farming, the
574 reduction of pesticide use does not have a specific legal compliance period (Lamine et al., 2009). The speed and
575 intensity of change was therefore different for each farmer. Practices can more easily be readjusted from one
576 year to the next, such as when they are adapted to disease risks. Based on the example of the cluster 1 farms for
577 which we did not observe redesign change, changes were mainly based on efficiency and substitution. Thus,
578 change at a slow speed and low intensity was observed on farms already using pesticides efficiently before
579 entering the DEPHY network. At the initial point, it seems that cluster 1 and 2 farms had already begun
580 transitioning towards reducing their pesticide use based on their initial TFI and management strategies.
581 Meanwhile, cluster 3 farms started with a high initial TFI, and the analysis of their pesticide strategies at the
582 initial point indicated limited adjustments of phytosanitary treatments. The high TFI decrease indicated that
583 entering the DEPHY network was associated with a trigger event (Sutherland et al., 2012) for the cluster 3
584 winegrowers. Entering the network seemed to have less impact for farms in cluster 1, while farms in clusters 2
585 and 3 managed to quickly reduce their TFI. However, cluster 1 winegrowers maintained a low TFI throughout
586 the 10-year period when entering the DEPHY network. However, farms that were already in organic farming
587 when entering the network had lower pesticide use than conventional farms

588 Furthermore, the typology allowed us to characterize differences in technical changes that were implemented. In
589 fact, clusters of TFI trajectories differed in terms of technical lever implementation and the intensity of change
590 (Fig. 4 and 5). Winegrowers managed to reduce their pesticide use by combining these different technical levers.
591 The difference in terms of TFI reduction between clusters can be explained by the initial point as discussed
592 previously as well as by the intensity of the changes implemented. The levers mobilized by all farms – dose
593 reduction and use of non-CMR products – constituted a first step in reducing pesticides. These changes mostly
594 centred on efficiency and substitution. Other levers were, however, mobilized in clusters 2 and 3, such as mating
595 disruption. Other levers, such as stopping herbicidal product applications, were distinctive for cluster 2, which
596 saw the lowest pesticide use at the final point. The implementation of mechanical weeding indicated a higher
597 intensity of change: the more herbicides were stopped, the more the TFI decreased. Implementation of
598 mechanical weeding was the sign of changes on all cultural practices that contributed to pesticide use. Within
599 cluster 2, a majority of farms had a production method associated with organic agriculture whose control of

600 cryptogamic diseases relied mainly on the use of copper and sulphur. While organic farming practices in
601 vineyards are seen as a way of reducing pesticide use, they lead to an increase in the application of other
602 products such as copper and sulphur (Merot and Wery, 2017). However, the intensive use of these substances
603 can be controversial (*e.g.* there is some debate on the ecotoxicity of copper). A study by Karimi et al. (2020)
604 showed that the maximum authorized yearly dose of copper in France (6 kg/ha) had no significant impact on the
605 soil quality function. Regardless, reducing the use of these products requires the implementation of deeper
606 change such as preventive measures (Jeuffroy et al., 2022). We found that the main levers implemented by the
607 winegrowers were not disruptive practices. We observed that the more intensively these levers were
608 implemented and combined, the more the TFI decreased. And the more these levers were implemented and
609 combined, the more difficult it was to reduce TFI.

610 Looking at the difference of initial point, the change intensity and the final point, we can assume that there was a
611 kind of continuity between the TFI trajectories. By starting with a high pesticide use and experiencing a high TFI
612 decrease by implementing changes of low intensity (cluster 3 TFI trajectory), winegrowers had two possible
613 pathways: i) a low pesticide use reduction linked to the implementation and adaptation of technical levers mainly
614 based on efficiency and substitution (cluster 1 TFI trajectory) or ii) achieving a greater pesticide use reduction by
615 implementing levers associated to redesign strategy (cluster 2). We also hypothesized that the trajectory from
616 cluster 2 could even be the continuity of cluster 1 trajectory. While it was easy to reduce the TFI by
617 implementing simple levers such as dose reduction or the use of biocontrol, to reduce the TFI sustainably,
618 clusters 1 and 3 had to implement deeper changes.

619 The three types of trajectories showed a connection to knowledge and learning. Trajectories of changes are not
620 simply due to a willingness to adopt a new practice – they also depend on farmers' knowledge and efforts to
621 learn (Sutherland et al., 2012). In terms of implementation, several studies showed that knowledge of change
622 was acquired progressively in connection with a learning process (Chantre, 2014; Chantre et al., 2015; Coquil et
623 al., 2014). Some practices require special equipment, new skills and specific knowledge (Blesh and Wolf, 2014;
624 Salembier et al., 2020). For example, mechanical weeding is more complex than chemical weeding. This
625 practice requires new knowledge about the state of the soil, vegetation and suitable equipment (Garcia et al.,
626 2018). In terms of risks taken, mechanical weeding increases the costs of production and labour time (Jacquet et
627 al., 2019). Changes in management strategy combined with technical changes increase the complexity of the
628 farming operations (Aouadi et al., 2021). Obstacles related to the farm context (*e.g.* farm size, commercialization
629 mode) also impact the technical changes. Thus farmers need support from advisors or a peer group when
630 implementing new practices and a system redesign aimed at pesticide reduction (Darré, 1985; Guichard et al.,
631 2017). Advisory services provided by the network engineer in the DEPHY farm network played a key role in
632 reducing TFI. Advisors supported and organized the learning process and knowledge capitalization (de
633 Tourdonnet et al., 2015).

634 Finally, we showed that the normalized initial point indicated a potential of improvement available to
635 winegrowers. To help winegrowers reduce their pesticide use, qualifying their initial point is a necessary step.
636 Doing so can allow advisors to better guide winegrowers towards the levers they need to implement by
637 identifying the levers they are already using and the levers which can be intensified. Whatever the trajectory type
638 considered, this study showed that a deep redesign is complex to implement and implies taking risks that impact

639 all performances (e.g. yield loss) and the organization of farm operations (Aouadi et al., 2021; Jacquet et al.,
640 2022). The implementation process is a key issue to support farmers in their change process. For farms wishing
641 to engage in an agroecological transition, our results show that the support offered within the framework of the
642 DEPHY network allowed farms to either reduce their TFI or maintain a lower TFI than the average.
643 Nevertheless, these results show that the levers implemented and the changes made do not permit farmers to
644 completely stop using pesticides. Other changes and innovations seem necessary to achieve this objective.

645 Our study was based on the evolution of performances to identify the potential changes of practices. Agrosyst
646 database, is a good tool to assess the evolution of performances and monitor the pesticide use evolution at the
647 DEPHY-scale. This database has generated “big data” on farms moving towards pesticide use reduction, and the
648 information it gathers makes it a unique source worldwide (Lamichhane et al., 2019). The typology used in this
649 study allowed us to go beyond winegrowing region specificities and to gain knowledge in terms of genericity.
650 This method makes it possible to see the general pesticide use trajectory of farms to better support farmers in
651 their transition process. According to Perrot et al. (1993), the methodological decisions will determine the
652 typology depending on the objectives, the nature of data and the sample. Our method can be completed with : (i)
653 the use of Partial Least Square to explain the diversity (Martin et al. 2017, Perrin et al.) ; (ii) the use of linear
654 mixed model with a selection of explanatory variable. There are only few approaches that take dynamics and
655 trajectory into account. Dardonville et al. (2022) identified other methods to explore: the KLM method, a
656 longitudinal data clustering algorithm to identify different type of trajectories or the KmlShape method, which
657 groups time series into trajectories according to their shape and the intensity of variations, taking into account
658 the time lag between variations in different series. However, these methods still need further development. The
659 data provided by the Agrosyst database give users information to study the impact of pesticide use reduction on
660 other performances (*i.e.* yield, net margin...).

661 The use of other performances could be interesting to understand the diversity of the trajectory of other
662 performances linked to the pesticide use reduction but also to identify the lock-ins link to agro-ecological
663 transition such as organizational (Merot et al., 2019), economical (Chèze et al., 2020) or behavioral lock-ins
664 (Dessart et al., 2019). However, this information is important to fully understand the process of change but are
665 still missing in the database. The drivers of these changes are not observable in the database, for example
666 information on the behavior (*e.g.* decision rules) and behavioral triggers (*e.g.* impact of the advisors on the
667 change implementation). The database allows to work on a large scale and on data of 10 years which allows to
668 gain in genericity by working on a large number of production systems but does not contain important
669 information to understand some changes and the farmer’s motivations to implement these changes. To guide
670 policy design a better knowledge of the drivers influencing practices is necessary (Dessart et al., 2019; Finger
671 and Möhring, 2022). This important information has to be accessed through survey instead, on a reduced sample.

672 **Conclusion**

673 The method constructed in this study allowed us to identify three pesticide use trajectories by integrating the
674 dynamics in a large diversity of production contexts. The trajectories differed in terms of the types and intensity
675 of changes implemented during the vineyard transition towards production systems with low pesticide use. We
676 observed that levers used by farmers resulting in a pesticide use reduction were mainly based on efficiency (e.g.
677 reducing fungicide dose) and substitution (use of biocontrol products). The same levers that were implemented

678 in all types but with differences in terms of intensity explain the difference of pesticide use reduction. We found
679 that the lower the TFI and the more intensively these levers were combined, the more the pesticide reduction was
680 slow. The pesticide use reduction depended on the initial point and the levers implemented. These indicators
681 should be take into account by advisors when supporting winegrowers in their pesticide use reduction. The types
682 identified provide a solid foundation for further in-depth studies of the transition away from pesticide-intensive
683 production systems to more precisely identify the levers implemented and their implementation over time.

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