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ORIGINAL RESEARCH ARTICLES

Long term analysis of the link between practices and vineyard decline in relation to abiotic factors

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ABSTRACT

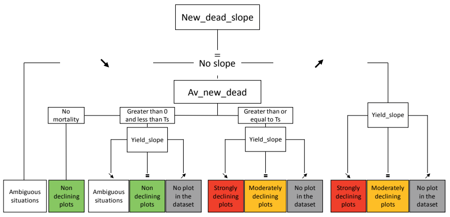
Vineyard decline is one of the main challenges viticulture now faces, especially in the current context of climate change. While decline is often attributed to grapevine trunk diseases and climate change, it also involves a myriad of other interconnected factors, including agricultural practices, whose role in decline remains unclear. This study explored for the first time how various planting conditions and agricultural practices implemented over an extended period of time affect the intensity and dynamics of decline. We analysed a large dataset obtained from 107 plots in the Cognac wine-growing region in western France from 1988 to 2018. The dataset included data on soil and climate conditions, genetic material at planting, annual agricultural practices, and information on annual mortality and yield. This study comprised six steps: dataset building, characterisation of decline categories, selection of explanatory variables to be studied, creation of plot trajectories based on agricultural practices, linking of decline categories and plot trajectories, and analysis of plot characteristics and practices. Using data from 43 plots and 58 variables, we showed that vineyard plots can be classified into three stages of decline depending on the dynamics and intensity of mortality and yield dynamics. We then established 11 trajectories over the plot lifespans (16 to 30 years). A detailed analysis of these trajectories revealed that plots associated with certain trajectories were more subject to decline, which helped us identify strategies that could limit or even prevent decline. We concluded that preventing decline requires adopting an integrated approach from planting to grubbing up, finding the right match between genetic material and soil–climate conditions, ensuring optimal water management, and managing potentially competing vegetation, like cover cropping. By identifying key practices over the vineyard lifespan, this study opens up new avenues for preventing decline by putting the focus on vigour management, water and mineral status of the plant.

KEYWORDS: vineyard, dieback, trajectories, agricultural practices, retrospective study, typology

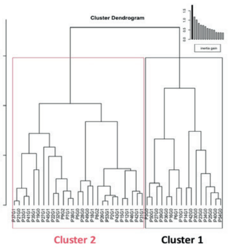
GRAPHICAL ABSTRACT

Objective: Identification of practices associated with vineyard decline situations

1) Plot classification according to decline intensity



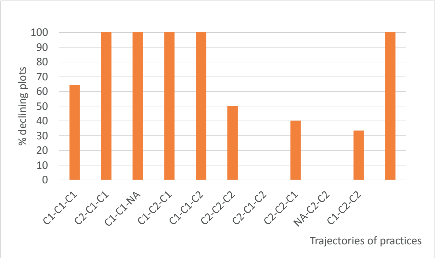
2) Plot clustering according to practices over time



Database
Cognac winegrowing region
30 years of observation
107 plots total – 43 plots analysed
53 variables (42 dynamic, 14 static)

FINAL RESULT

11 trajectories of agricultural practices associated with decline situations to varying degrees



INTRODUCTION

Wine-growing is a major agricultural industry in France and Europe, and throughout the world (OIV, 2024). Although viticulture has continuously adapted to societal, environmental and climate constraints, new challenges are constantly arising. Vineyard decline is one such challenge (Bruez *et al.,* 2013), and it is a serious issue, especially in the current context of climate change and potential shift of wine-growing areas towards new soil and climate zones (Santillán *et al.,* 2019). Vineyard decline, broadly defined by Riou *et al.* (2016) as 'a vine multiannual yield diminution or its premature, brutal or progressive death', occurs in all wine-producing countries around the world (Bruez *et al.,* 2013, De la Fuente *et al.,* 2016). In France, it is of significant concern: in 2014, yield losses exceeding 4.6 hl/ha and 10 % of grapevine plantations were associated with vineyard decline (BIPE, 2016).

Researchers have been studying vineyard decline - specifically that caused by grapevine trunk diseases (GTDs) - for more than 20 years. Grapevine decline is often linked to disease symptoms in many grape-growing regions, including those in Europe (Guérin-Dubrana *et al.,* 2019). GTDs affect the perennial parts of vines, causing a range of problems, like the dieback of shoots and branches and vigour reduction (Lecomte *et al.,* 2012). In France, the most common GTDs are *eutypiose* and esca complex.

One study (BIPE, 2016) has listed sixty highly diverse potential factors of decline, including biophysical aggressions, environmental stresses and practices observed in intensive monoculture. These factors can worsen or even trigger vineyard decline, while other factors can limit the appearance and spread of decline.

Abiotic factors play a significant role in grapevine decline. In fact, environmental factors such as drought, extreme temperature and soil conditions significantly impact vine health and sensitivity to pathogens (Arkam *et al.,* 2021). Drought stress is complex; while it can exacerbate GTDs by weakening grapevine defences (Arkam *et al.,* 2021) in some situations, it has also been found to have the opposite effect (Bortolami *et al.,* 2021).

High temperatures and prolonged heatwaves further stress grapevines (Bernardo *et al.,* 2018). Soil conditions, including nutrient deficiencies and poor drainage, contribute to grapevine stress and pathogen proliferation (Visconti *et al.,* 2024; Darriaut *et al.,* 2022). Vineyard decline is a long and complex process that can span two to three decades (Merot *et al.,* 2023), limiting the possibility of studying the link between vineyard management practices and GTDs. Moreover, various environmental conditions, practices, biotic pressures and stages of vine development (from planting to maturity) occur over this extended period of time. Studying such a complex process requires a significant amount of data, for this reason, and given the many potential explanatory factors of decline, there is an opportunity in exploring existing long datasets.

For this study, we analysed a 30-year data series from the cognac appellation in France to characterise decline prevalence and intensity and establish different situations of decline. We then analysed the specific agricultural practices implemented and the trajectories of decline with which they were associated. The originality of this work was that the final overall effect of the combined cultural practices in the long-term was studied.

MATERIAL AND METHODS

This study comprised six steps: dataset building, characterisation of decline categories, selection of explanatory variables to study, creation of plot trajectories based on agricultural practices, linking of decline categories and plot trajectories, and analysis of plot characteristics and practices (Figure 1).

1. Background information on the studied wine-growing region

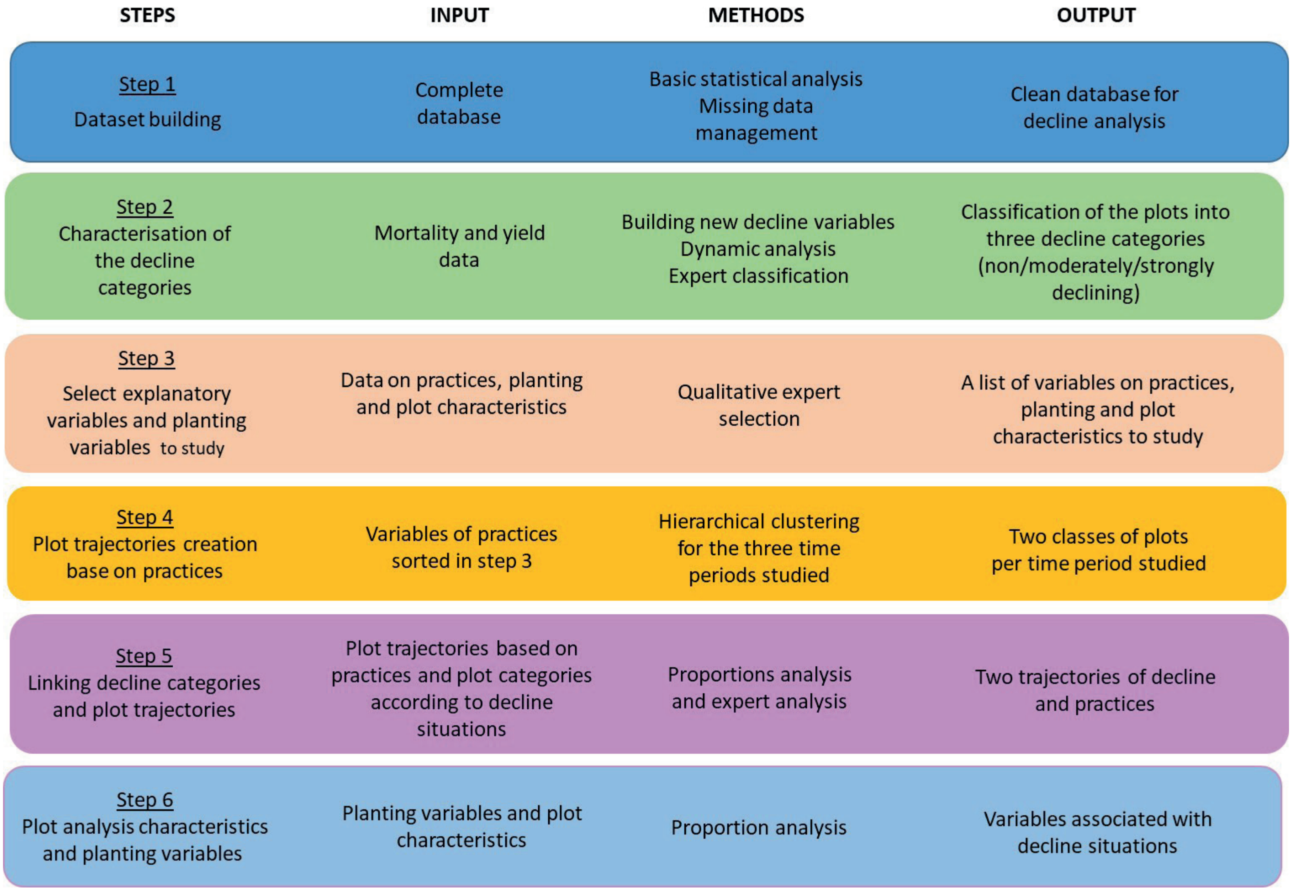
This study was carried out using data from vineyards in the Cognac wine-growing region. The area covered by the Cognac Protected Designation of Origin (PDO) is located in western France along the Atlantic coast and covers more than 80,000 ha. Vineyards grow under a cold Köppen Cfb-type semi-continental climate with no dry season and an extended warm summer (Beck *et al.,* 2018). The average annual rainfall is 860 mm. Prevailing winds are from the south-west and north-west. Around 98 % of the wine produced in this area is made from the Ugni Blanc grape variety, and the average planting density is 3,000 to 4,000 vines per hectare. Diversity in the rootstocks was observed (Fercal, Ruggieri 140, 333 EM, 41 B, 161 49 C, RSB 1, SO4, 1103 Paulsen, Gravesac). The vineyards are extremely vigorous and production targets are quite high, ranging from 120 to 150 hl/ha. The PDO area is characterised by five soil types varying in compaction risk, water retention capacity and mineral content (Table 1).

2. Step 1: Building the dataset

2.1. Raw data presentation

The data were collected cover a 30-year period (1988–2018). Each year, 55 plots were monitored. The plots were not all the same in all the years, as some plots were removed from the network, having been grubbed up, and were replaced in the database by another plot. In total, 107 plots were monitored. Each year in each plot, four subplots of five vines (or vine locations when the vines were dead or missing) were monitored. These locations remained the same throughout the plot lifetime. Data for the monitored plots and locations were pulled from two databases: a plot database and a subplot database.

The plot database initially contained 116 raw variables per plot: 36 (32 %) static descriptive variables describing the plot (*e.g.*, ‘soil type’ or ‘plot location’) and 80 (68 %) dynamic variables, comprising one yield variable (referred to as ‘annual yield’ from this point on) and 79 variables describing the agricultural practices implemented on each plot (*e.g.*, number of phytosanitary treatments). The dynamic variables were collected each year by extension agents alongside the winegrowers. The subplot database contained data on the yearly status of the 20 vine locations monitored in each plot, which was used to quantify mortality.



STEPS	INPUT	METHODS	OUTPUT
Step 1 Dataset building	Complete database	Basic statistical analysis Missing data management	Clean database for decline analysis
Step 2 Characterisation of the decline categories	Mortality and yield data	Building new decline variables Dynamic analysis Expert classification	Classification of the plots into three decline categories (non/moderately/strongly declining)
Step 3 Select explanatory variables and planting variables to study	Data on practices, planting and plot characteristics	Qualitative expert selection	A list of variables on practices, planting and plot characteristics to study
Step 4 Plot trajectories creation base on practices	Variables of practices sorted in step 3	Hierarchical clustering for the three time periods studied	Two classes of plots per time period studied
Step 5 Linking decline categories and plot trajectories	Plot trajectories based on practices and plot categories according to decline situations	Proportions analysis and expert analysis	Two trajectories of decline and practices
Step 6 Plot analysis characteristics and planting variables	Planting variables and plot characteristics	Proportion analysis	Variables associated with decline situations

FIGURE 1. Summary of the six steps of this study.

TABLE 1. Description of the five soil types and four geographical situations in the study region.

Cognac soil types	Soil descriptions
Limestone on chalk	These soils are thin, clayey and chalky on top of soft chalk. They have a good structure and are well drained and mineral rich, with a high calcium content at the surface. Although these soils are thin, lack of water is not a problem, because the subsoil acts as a giant sponge.
Clay	Clay soils have excellent water retention capacity, which limits water deficits during the summer. They are prone to waterlogging and compaction, but provide good nutrient storage when not overly compacted.
Sandy	Sandy soils provide excellent drainage, which helps prevent waterlogging. These soils warm up quickly in the spring, thus extending the growing season.
Clay-limestone	These soils are characterised by their clay-limestone and gravelly composition. They offer excellent drainage and aeration, but have low water retention capacity, which leads to a risk of serious water deficit in summer. If the gravel content is high, these soils can lack essential nutrients.
Silt-clay	The silt-clay soils are characterised by a high cation exchange capacity, enhancing nutrient availability and good water retention. If the clay content is high, these soils can sometimes have drainage and compaction issues. Lack of nutrients can also be observed when the clay or sand content is high. They can also dry rapidly because of the moderate water retention capacity, which can lead to a significant water deficit.
Geographic locations	Location descriptions
Plateau	Plateaux are generally well structured, with a good proportion of different-sized particles, which promotes some aeration while allowing only low water retention.
Mid-hillside	Mid-hillsides offer good drainage due to the slightly inclined position of plots, which helps prevent waterlogging. This situation limits sensitivity to erosion and provides good nutrient retention as well as moderate water retention.
Hillside	Hillsides can be prone to erosion and run-off with reduced nutrient retention, but drainage is supported due to the slope and the location ensures water retention.
Plains	Plains often hold more water, which can be beneficial during dry periods but problematic during heavy rains, potentially leading to waterlogging.

2.2. Preparing the cleaned dataset

The raw database was cleaned and the vineyard plots and variables were sorted. The 107 plots were classified in the first part of the analysis according to decline intensity (see Step 2). Then, for the purposes of the cultural practices analysis (Steps 3 to 6), we selected plots based on the following two criteria: i) at least 10 years of information on the plot was available in the database, and ii) the period of time for which there were data fell within the time frame of when decline is generally observed (which has been shown to occur from 15 to 35 years after planting, Merot *et al.,* 2023). Based on these criteria, 43 of the 107 plots (40 %) were selected for analysis.We then only kept the variables that had less than 50 % of their data missing and that had been monitored for more than 15 years. Variables related to dynamics, specifically those related to intercropping and rootstock, were modified to make them consistent or simpler. This was done when redundant information was reported or when the number of factors was too high for further statistical analysis compared to other nominal variables. We chose to simplify the rootstock variable by considering the rootstock attributes in terms of vigour, sensitivity to total limestone, moisture sensitivity, drought sensitivity and adaptation to the soil in the plot (source French Vine and Wine Institute). The rootstock's adaptation to the plot's soil was established by comparing soil type and the genetic soil-related characteristics. Finally, we created a variable representing annual mortality at plot scale for the 20 locations observed every year, which we refer to here as new_dead. This variable was calculated by comparing the status of each location in year *n-1* with its status in year *n*. The new_dead variable for year *n* corresponds to the number of new dead vines in year *n* in the 20 locations.

The study thus focused on the 'cleaned' database containing the 62 remaining variables (59 %): 44 dynamic variables related to agricultural practices, 18 static variables describing the plots, 3 yield variables and 3 vine mortality variables (Supplementary data). Missing values accounted for less than 2 % of the data.

3. Step 2: Characterising decline categories

The aim of Step 2 was to categorise the plots studied based on the level of decline observed before exploring the agricultural practices associated with these different levels. We first built yield and mortality indicators based on the official definition of decline (Riou *et al.,* 2016); we then used these indicators to categorise the plots in terms of decline intensity.

3.1. Building mortality and yield indicators to characterise decline intensity

We considered two processes related to mortality in the plots: i) a high level of mortality observed for all years or during specific years, and ii) a situation where mortality increased over time. We characterised each of these processes using a static indicator built from the new_dead dynamic variable. The first indicator calculated for each plot was the average number of new dead vines per year (av_new_dead). Av_new_dead is the total new_dead in all 20 vine locations during the plot observation period divided by the number of years of observation. The second indicator, new_dead_slope, characterises changes in new dead vines over time.

We also calculated two indicators of yield dynamics that described i) the change in yield over time, and ii) yield loss, in the same way as for mortality.

Based on the annual_yield variable, expressed in hl/ha for each plot, we first calculated an indicator for the change in yield (yield_slope). Yield_slope was calculated applying the same approach used for new_dead_slope. For each plot, yield_slope corresponds to the slope of the linear regression of the annual_yield for the observation period. We then calculated the average yield ratio (av_yield_ratio, in %) for each year in each plot to determine potential yield losses. For this purpose, we determined a yield achievement ratio for each year/plot combination, which equals the ratio between the annual_yield and a chosen reference value (in this case, this was the annual average yield of the Cognac PDO) (Personal communication, Bureau National Interprofessionnel Cognac). The av_yield_ratio of a plot is the calculated mean of the yield achievement ratio over the observation period.

3.2. Building the typology of plot decline intensity

The indicators for changes in mortality and yield were arranged in a decision tree to characterise and categorise the plots according to their decline intensity (Figure 2). We divided the plots into three categories of decline: non-declining, moderately declining and strongly declining. Moderately declining plots are those that showed a decline in terms of the mortality indicator but not of yield. Based on the results of Merot *et al.* (2023), we first grouped plots together according to mortality indicators - specifically new_dead_slope, which is useful in characterising a progressive and easily observable decline phenomenon. By doing this, we distinguished plots characterised by a positive new_dead_slope from the others (Figure 2). Among plots with a positive new_dead_slope, we were able to clearly identify strongly declining plots with a negative yield_slope. This first group of strongly declining plots was important in our analysis, because it allowed us to set the ‘Ts threshold’ that we would later use in the other branches of the decision tree. The Ts threshold was calculated as the mean value of av_new_dead for the first group of strongly declining plots with clear decline characteristics (increasing mortality and decreasing yield over time), and was found to equal 0.47 new dead vines per year in the 20 vine locations. Plots with a positive new_dead_slope but no change in yield over time were categorised as moderately declining plots.

For the plots that still needed to be categorised, we considered that no change in new_dead (new_dead_slope = 0) was associated with decline phenomena when average yearly mortality (av_new_dead) reached a high level; i.e., when the value was greater than the Ts established previously. For plots with this characteristic, those with a negative yield_slope were considered as strongly declining plots. Those that did not show any change in yield (yield slope = 0) were considered as moderately declining plots.

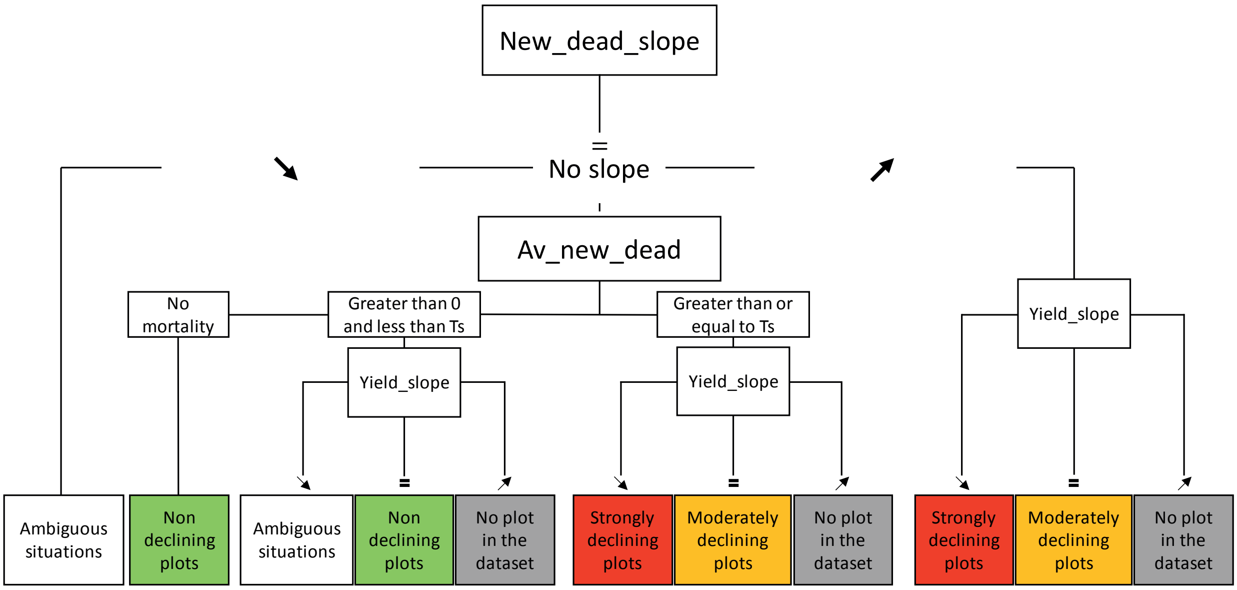


FIGURE 2. Decision tree of the different plot categories.

The black downward arrow indicates a decrease in the variable over time (negative slope) and the black upward arrow indicates an increase in the variable over time (positive slope). The absence of a slope is indicated by the equal sign and “No slope”. Green boxes = non-declining plots; orange boxes = moderately declining plots; red boxes = strongly declining plots; grey boxes = situations with no plot in the dataset; and white boxes = plots with ambiguous situations of decline. Ts = average value of av_new_dead for the first group of strongly declining plots that showed clear decline characteristics (increasing mortality and decreasing yield over time).

Finally, plots characterised by a low level of mortality over time and a stable yield (yield_slope near 0) were considered to be in non-declining situations. The other combinations of yield and mortality characteristics were not considered in this study, because the decline phenomena were too ambiguous or not represented in the database.

3.3. Characterising the three plot categories over time

To better highlight the critical periods of grapevine lifespan in terms of decline, we built a timeline of decline status as a function of plot age (defined as number of years after planting). This timeline showed i) the year young vines became fully productive vines, ii) the first year any dead vines were observed, iii) the year in which mortality dynamics began, mortality dynamics being defined as a three-year period with at least two years of new dead vines, and iv) the three consecutive years marking the potential start of a yield decrease, defined as a three-year period during which the annual yield was equal to or lower than the median yield of the plot during the observation period. These timelines were cross-referenced between plots for the three decline categories and qualitatively analysed.

4. Step 3: Selecting explanatory variables from the cleaned dataset

Step 3 consisted in selecting potential explanatory variables from the cleaned dataset.

Vineyard agricultural practices were characterised in the cleaned database using 44 dynamic variables divided into six themes: ‘pruning practices’, ‘soil management’, ‘weed management’, ‘vine vigour’, ‘fertilisation’, and ‘pest and disease control’. From these variables, we selected those that best discriminated the plots grouped in the ‘non-declining plots’ and ‘strongly declining plots’ categories, based on the assumption that these two plot categories at the opposite extremes of decline intensity were also the most suitable for identifying different agricultural practices that would explain the decline. For this selection, we identified the variables in a multi-step process. For each categorial variable, we first looked at the plots one-by-one in the ‘non-declining plots’ and ‘strongly declining plots’ categories. For each plot, experts selected the main category observed for each 5-year period (0 to 5 years, 6 to 10 years, 11 to 15 years, etc.), and we the associated the main category with the group of plots being analysed. Finally, we discarded the variables represented by the same category in both plot categories. For quantitative variables, we directly averaged the values associated to the variable for each plot in a given five-year period. This selection process was carried out by two independent experts, whose results were compared to make the final choice of variables that would be used to characterise the agricultural practices.

We used a comparable approach for the two experts’ independent analyses on static variables related to the plots. The cleaned database contained 18 static variables related to static plot properties describing both planting conditions and plot characteristics. Again, we focused on each of the two extreme plot categories and selected the most frequent category in the category for each variable. We then discarded the variables represented by the same category in both plot categories. The final variable selection produced four static variables and 15 dynamic practice variables (see Supplementary Data).

5. Step 4: Creating plot trajectories based on agricultural practices

We analysed the four static variables and the 15 dynamic variables that had been selected separately due to the divergent nature of the data. To analyse the dynamics related to agricultural practices, we focused on the full production period across the plot lifespan, ruling out the juvenile period, during which yield has not been completely established and for which there is a lack of data, and the later period when decline and ageing can be confused (Merot *et al.,* 2023). Thus, for our analysis we selected the 16–30-year period, which also contained fewer missing data in our database. We divided this period into three five-year periods (16–20 years, 21–25 years, 26–30 years). To assign each five-year period a single value, each of the agricultural practice variables selected during Step 3 was averaged per plot when numeric or assimilated to the preponderant modality when a categorial variable. For each five-year period, we then identified two classes of agricultural practices implemented in the plots (see the statistical analysis section (8) for further details), and we analysed the values associated to the most explanatory variables for each cluster and for each age class.

We then linked each plot to the series of classes of agricultural practices to which it belonged in the three five-year periods. This constitutes the plot’s practice-based trajectory over the 16–30-year period.

6. Step 5: Linking practice-based trajectories and decline categories

To study the link between the dynamics of the implemented agricultural practices and the level of decline in the plots, we calculated the proportion of strongly declining plots, moderately declining plots and non-declining plots on each practice-based trajectory. This allowed us to link practice-based trajectories to decline trajectories.

7. Step 6: Analysing plot characteristics and planting variables

We analysed the values for the four selected variables and described them in terms of proportion of strongly declining plots, moderately declining plots and non-declining plots.

8. Statistical analysis

All statistical analyses were performed with R software version 3.5.0 (R Core Team, 2020). To calculate new_dead_slope and yield_slope for each plot, we used a linear mixed-effects model (Pinheiro *et al.,* 2024). We assumed that the new_dead and annual_yield variables varied year to year (fixed effect) in the same plot, with the plot used as a random effect to account for the repetitive nature of the observations. We checked for normality and homoscedasticity assumptions. An analysis of variance (ANOVA) was used to investigate the significance of the change in the new_dead value over time. We considered significance at the classic level of $p = 0.05$. If a significant result was obtained, we considered the slope calculated by the model.

Typologies for each five-year period were obtained by performing a principal component analysis with the selected practice variables followed by ascendant hierarchical clustering to identify classes of agricultural practices among plots with the FactoMineR package (Lê *et al.,* 2008). We chose to differentiate between only two classes in each five-year period to identify the agricultural practices with the sharpest differences supporting the hierarchical tree.

Finally, we performed an ANOVA to evaluate significant differences between the means of the studied indicators of decline for the different categories of decline. We considered significance at the classic level of $p = 0.05$.

RESULTS

1. Characterising situations of decline in plots

Three categories of decline were identified in the studied plots: non-declining (44 plots), moderately declining (47 plots) and strongly declining (30 plots). These categories, the strongly declining plots (Figure 3A), non-declining plots (Figure 3B) and moderately declining plots (Figure 3C), showed clear differences in terms of yield and mortality rate. The starting point of the mortality increase and yield decrease was identified in most plots. When a mortality increase and a yield decrease were observed, we also noticed a time delay between the two processes: yield decrease occurred a few years after the mortality increase (2 to 5 years depending on the plot category).

1.1. Strongly declining plots

Strongly declining plots showed long-term evidence of decline. Strongly declining plots were characterised by a high mortality rate (Figure 4), with an av_new_dead value of 0.51 new dead vine per year. The first dead vine appeared at an average plot age of 22 years and the mortality increase was positive (Figure 4). With regard to yield, we observed that the starting point for the yield decrease for this plot category was 23 years on average, which was similar to the age the first dead vine appeared (Figure 5). However, the yield_ratio for this plot category remained at a satisfactory level (100.5 %). The yield decrease was −2.6 hl/ha per year.

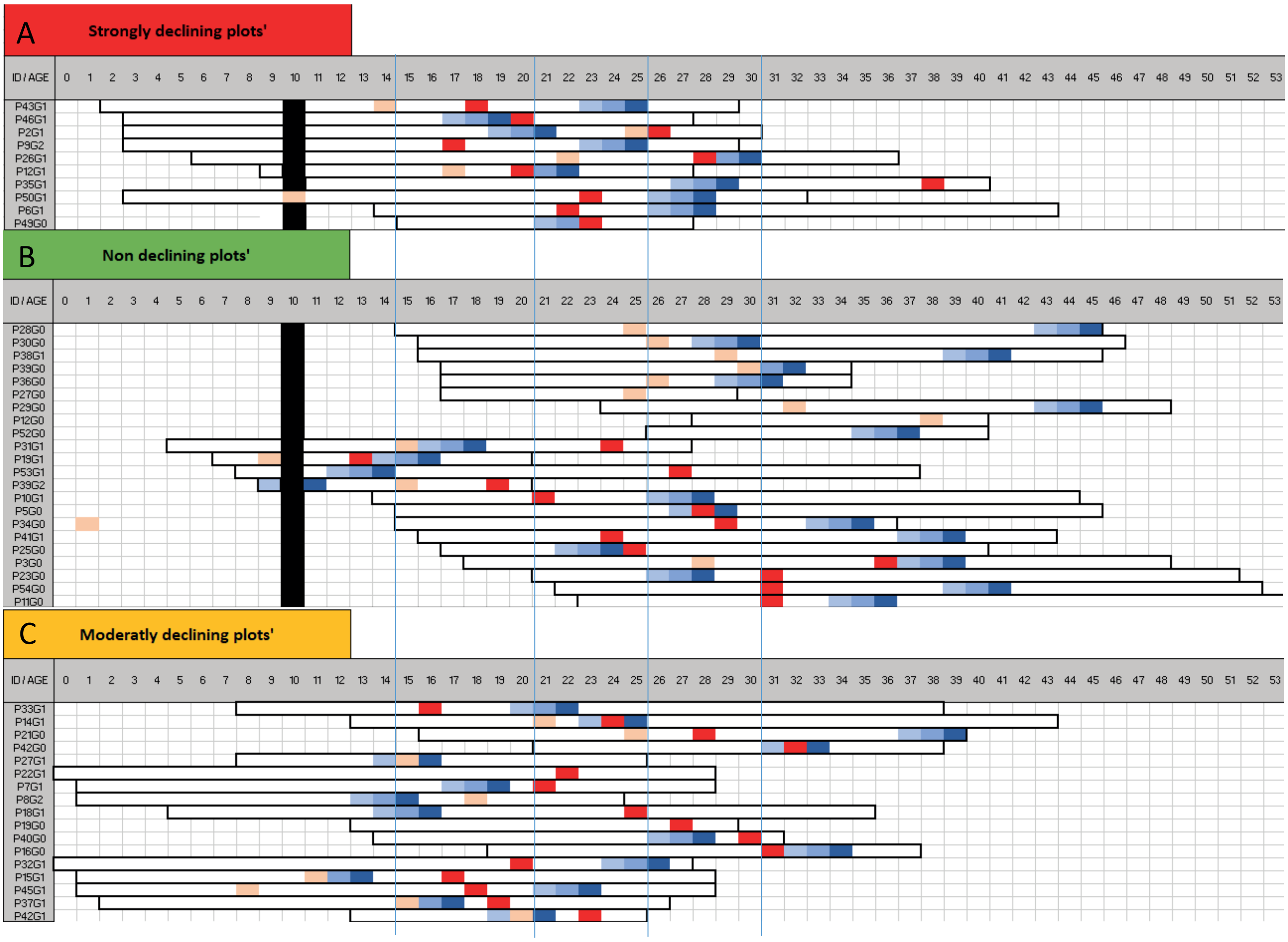


FIGURE 3. Yield and mortality trajectories of three plot categories (strongly declining plots (A), non-declining plots (3B) and moderatly declining plots (3C)) during the observation period of the plots in the database that were studied in Steps 3 to 6 .

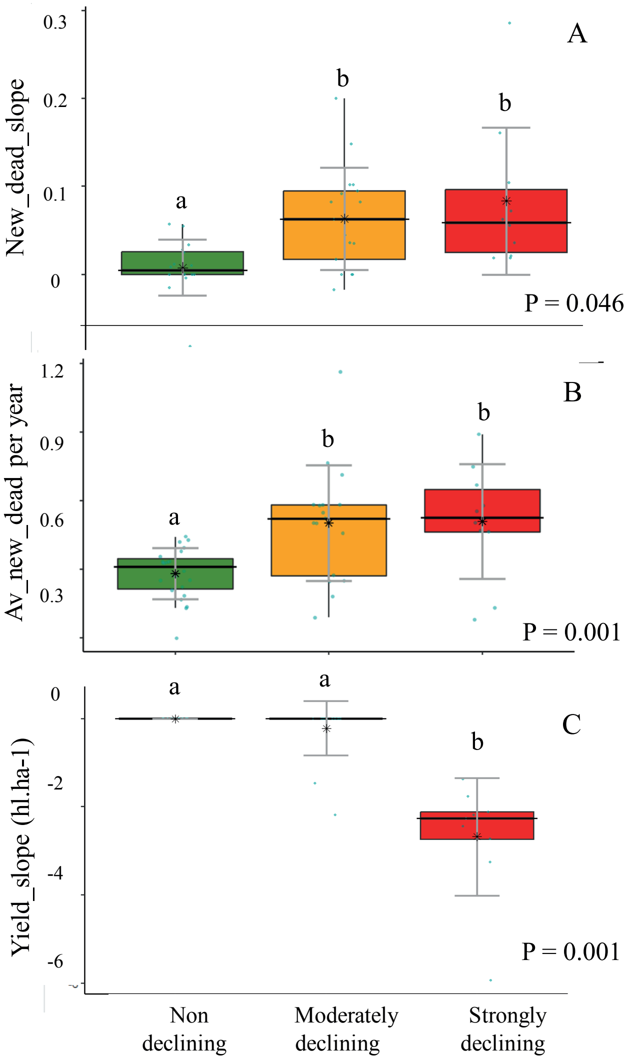


FIGURE 4. Characteristics of the three categories of plot decline (non-declining, moderately declining and strongly declining) based on three variables (new_dead_slope, av_new_dead per year, yield_slope) used to differentiate the categories of decline during the observation period.

A) Average increase in new dead vines during the observation period (new_dead_slope), B) average new dead vines per year (av_new_dead per year), C) average yield decrease during the observation period (yield_slope). Lower-case letters a and b indicate statical differences at a significance level of $p = 0.05$; error bars represent the standard error of the mean.

The studied plots are represented in rows. The period meaningful for decline observation is shown by a black outline. The salmon-coloured boxes indicate the first year new dead vines were observed in the plot. The red boxes indicate the starting point of mortality dynamics. The blue gradients represent a yield decrease for three years in a row. The black vertical lines represent the year young vines became fully productive vines, which we determined as the age of 10 years.

The variables represented are: A) average yield over the observation period, B) average yield ratio for each plot category over the observation period, C) plot age when the first new dead vine(s) were observed, and D) plot age when a yield decrease was observed for the first time in the plot. Lower-case letters a and b indicate statical differences at a significance level of $p = 0.05$; error bars represent the standard error of the mean.

1.2. Non-declining plots

In non-declining plots, both vine death and mortality increase tended to occur later than in other plot categories. The first vine death appeared at the average age of 24.6 years, and the mortality increase was observed after 26 years (4 years after the strongly declining plots; see Figures 4 and 5). The strongly declining and non-declining plots had considerably different mortality rates. In the non-declining plots, the av_new_dead value was nearly half that in strongly declining plots, with 0.28 new dead vine per year (Figure 5). The yield indicators of the non-declining and declining plots also tended to differ: as can be seen in Figure 3, yield decrease in the non-declining plots started 6 years later than in the strongly declining plots, at an average age of 29 years. The yield_ratio was 102.2 % for non-declining (Figure 5).

1.3. Moderately declining plots

The yield indicators for the moderately declining plots were in between the strongly declining and non-declining plots, and the mortality indicators of the moderately declining plots were similar to strongly declining plots. The plot age at which the first new dead vine was observed in the moderately declining plots was not significantly different ($p > 0.05$) to the strongly declining plots, but it tended to be earlier than for the non-declining plots (Figure 5). The av_new_dead and new_dead_slope values for this category were also similar to those for the strongly declining plots (Figure 4), but significantly higher than for the non-declining plots. In terms of yield, the moderately declining and strongly declining plots differed (Figures 4 and 5). The yield_ratio value tended to be similar to that of the strongly declining plots but lower than that of the non-declining plots (Figure 5). The av_yield value was in between the strongly and non-declining plots (Figure 5). Finally, just as in the non-declining plots, a yield decrease (yield_slope close to 0) was not clearly observed in the moderately declining plot category (Figure 4).

2. Two distinct classes of agricultural practices identified for each five-year age period

When analysing decline, the fifteen agricultural practice variables fell into two distinct classes (C1 and C2) for each five-year age period. For each five-year age period, the 11 significant variables in the two classes are presented in Table 2. Regarding the 16–20-year period, C1_16-20 and C2_16-20 differed in terms of six variables: vegetation volume in the inter-row, amount of potash applied (in majority mineral applications), total number of all treatments against pests and diseases, volume of pesticide sprayed, number of treatments for powdery mildew and number for treatments for downy mildew. Plots in C2_16-20 were more often intercropped, with vegetation in the inter-row, and competition due to vegetation development was higher in the inter-row. The same results were observed under the row with nearly double

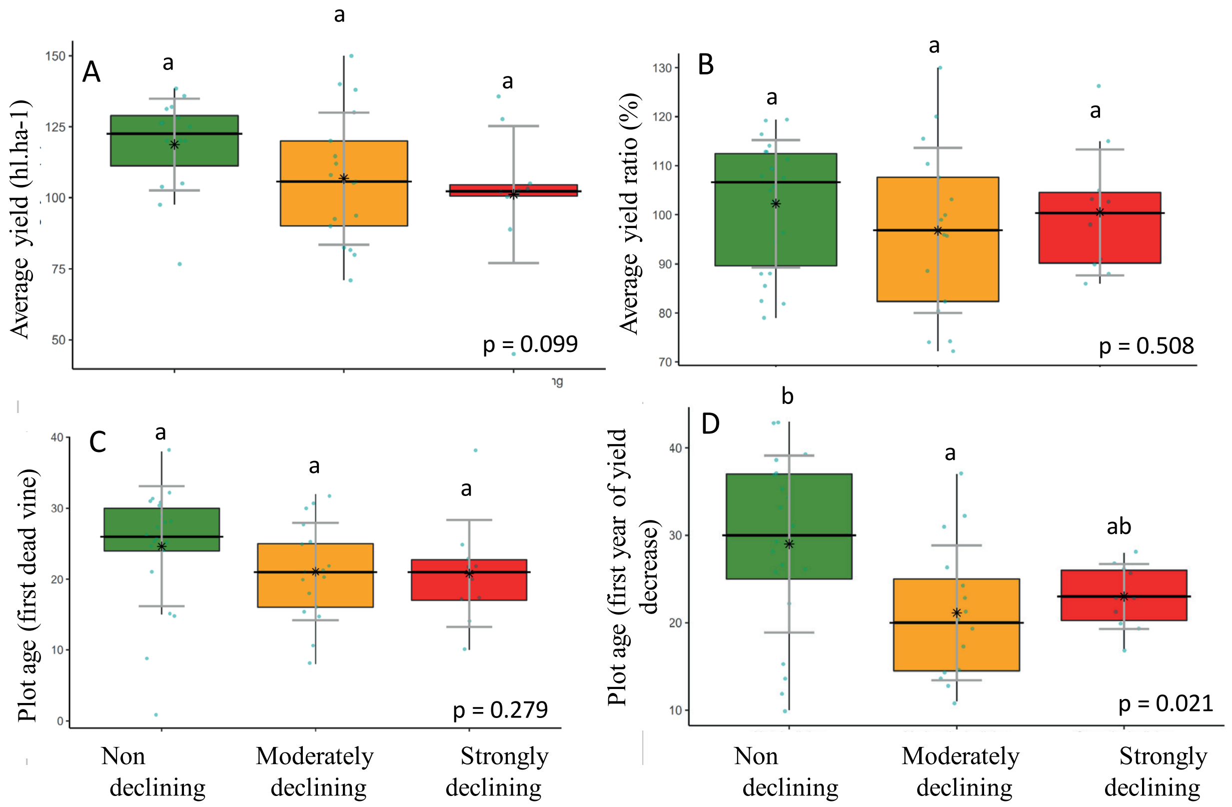


FIGURE 5. Characteristics of the three categories of plot decline (non-declining, moderately declining, strongly declining) for four variables.

the vegetation in C2_16-20 than in C1_16-20. Vegetation in class C2_16-20 plots was also trimmed less frequently (2.9 times compared to 3.6 times in the C1_16-20 plots); however, we did not find any significant differences with respect to observed vigour. Pre-pruning, which consists in roughly and mechanically cutting vine shoots before the manual winter pruning, was not carried out in the C2_16-20 plots. Potash application was higher in the C2_16-20 plots. Finally, in the C2_16-20 plots, the number of treatments for powdery and downy mildew was lower.

The findings from the 21–25-year period were similar to those from the 16–20-year period. We observed that the C2_21-25 plots were more often intercropped with vegetation in the inter-row, but the reported competition was higher in the C1_21-25 plots. Potash application was also higher in the C2_21-25 plots, as was the volume of pesticide sprayed. Conversely, the C1_21-25 plots showed a higher number of treatment applications against powdery and downy mildew, which is consistent with the 16–20-year period. With regard to sodium arsenite applications, C2_21-25 contained plots that were treated, while the C1_21-25 plots were not treated at all.

Finally, in the 26–30-year period, the two classes were differentiated by the quantities of potash applied (the C2_26-30 plots received nearly double those of the C1_26-30 plots) and the total number of treatments against pests and diseases, with the C2_26-30 plots receiving two more treatments on average than the C1_26-30 plots. The volume of pesticides that was sprayed was also higher in C2_26-30 and sodium arsenite was not used in the C1_26-30 plots. The same trends were observed for vegetation volume and competition in the inter-row and row.

The differences observed in each five-year period showed a link throughout the 16–30-year period between the three classes C1_16-20, C1_21-25 and C1_26-30, as well as between the C2_16-20, C2_21-25 and C2_26-30. In fact, C1_16-20, C1_21-25 and C1_26-30 could be considered as a part of a single management strategy and the same applies toC2_16-20, C2_21-25 and C2_26-30.

3. Plot trajectories of agricultural practices

By linking the succession of classes to which each plot belonged over the three five-year periods, we identified 11 practice-based trajectories that were followed by the plots in the database (Table 3). Three of these 11 practice-based trajectories were followed the most often by 43 plots: C2_15-20/C2_21-25/C1_26-30 (5 plots), C1_15-20/C1_21-25/C2_26-30 (8 plots) and C1_15-20/C1_21-25/C1_26-30 (14 plots). Three practice-based trajectories included a period during which a plot could not be assigned to C1 or C2; these plots were labelled 'NA' (NA-C2_21-25-C2_26-30, C1_15-20-C1_21-25-NA and NA-C2_21-25-C1_26-30). Of the 11 trajectories, five were associated with only one or two plots, which was particularly difficult to interpret; therefore, these five trajectories were not analysed. The next section focuses on the six main observed trajectories labelled with their summary names (Table 3).

TABLE 2. Mean values of the dynamic variables* and their confidence intervals by category and age class.

	16–20-year age period		21–25-year age period		26–30-year age period	
Variables	C1_16-20	C2_16-20	C1_21-25	C2_21-25	C1_26-30	C2_26-30
Proportion of vine pre-pruned in the plot (between 0 and 1)	**0.4 ± 0.2**	**0 ± 0**	0.4 ± 0.2	0.6 ± 0.3	0.3 ± 0.2	0.2 ± 0.3
Amount of grass cover in the inter-rows at veraison (visual notation)	**2.1 ± 0.3**	**3 ± NA**	**1.8 ± 0.3**	**2.6 ± 0.3**	1.9 ± 0.3	2.3 ± 0.5
Competition between grass cover and vine at veraison in the inter-row (visual notation)	1.7 ± 0.3	2.0 ± 0.05	1.9 ± 0.3	1.5 ± 0.4	2 ± 0.3	1.5 ± 0.6
Competition between grass cover and vine at veraison in the row (visual notation)	**0.8 ± 0.1**	**1.7 ± NA**	1.0 ± 0.2	0.6 ± 0.4	1.0 ± 0.2	0.7 ± 0.4
Mineral potassium fertiliser (H_2O unit per ha)	78.0 ± 17	122 ± 56	**45.5 ± 13**	**89.9 ± 24.1**	**43.5 ± 12.2**	**90.5 ± 17.4**
Number of trimmings per year	**3.6 ± 0.4**	**2.9 ± 0.1**	3.39 ± 0.37	3.4 ± 0.5	3.5 ± 0.4	3.6 ± 0.8
Total number of treatments during the growing season	**9.7 ± 0.6**	**7.6 ± 1**	9.5 ± 0.7	8.7 ± 1.1	**8.7 ± 0.8**	**10.7 ± 1.2**
Volume of pesticide sprayed (m3 per ha - indicated a higher amount of active agent in the whole season)	145 ± 24	227 ± 87	**144 ± 18**	**192 ± 24**	152 ± 16	182 ± 39
Number of treatments against downy mildew	**9.4 ± 0.4**	**6.6 ± 0.6**	9.2 ± 0.6	7.8 ± 0.9	8.3 ± 0.6	9.5 ± 0.7
Number of treatments against powdery mildew	**6.6 ± 0.3**	**5.0 ± 0.9**	6.6 ± 0.5	5.6 ± 0.6	5.9 ± 0.4	6.4 ± 1.1
Sodium arsenite (number of treatments)	0.04 ± 0.08	0 ± 0	**0.01 ± 0.02**	**0.27 ± 0.12**	**0.03 ± 0.03**	**0.4 ± 0.2**

* Only the 11/15 variables showing significant differences between C1 and C2 for each five-year period are presented in detail in the table. No differences were found for pruning date, pruning mode, magnesium application or observed vigour. Values in bold indicate ta significant difference based on the confidence interval. Values underlined are significantly different according to the principal component analysis.

4. Practice-based trajectories associated with trajectories of decline

The cross-referencing of the practice-based trajectories and the categories of decline in Step 5 of the method (Table 3) resulted in the trajectories falling into two groups. Trajectories C1-C1-C1, C1-C1-C2 and C1-C1-NA were associated with a higher percentage of declining plots (strongly or moderately declining). These trajectories all contained C1 at least twice and with the following characteristics: lower competition between vines and associated vegetation in the 16-21-year period; higher competition in the 21-25-year period; and lower potash application, a lower volume of pesticides sprayed and less sodium arsenite in the 21–30-year period. By contrast, the trajectories C1-C2-C2, NA-C2-C2 and C2-C2-C1 comprised mainly non-declining plots. These three trajectories were largely associated with C2 classes during the study period. The two trajectories with the higher proportion of non-declining plots were those with C2 in the 21-25-year period.

5. Planting and soil–climate variables moderated decline expression in the agricultural practice trajectories

Four variables describing plot characteristics and planting were selected for the analysis during Step 6: rootstock sensitivity to water deficit, vine vigour conferred by the rootstock, soil type and geographic location. Five soil categories (Table 1) were identified in the Cognac wine-growing region. Strongly declining plots were largely found in the silt-clay and clay-limestone soil categories; nutrient availability and aeration can be an issue in these soils. Conversely, limestone on chalk, and sandy and clay soils were found mostly in non-declining plots (Figure 6A); vines in these areas were characterised by a lower sensitivity to water deficit. Non-declining plots were

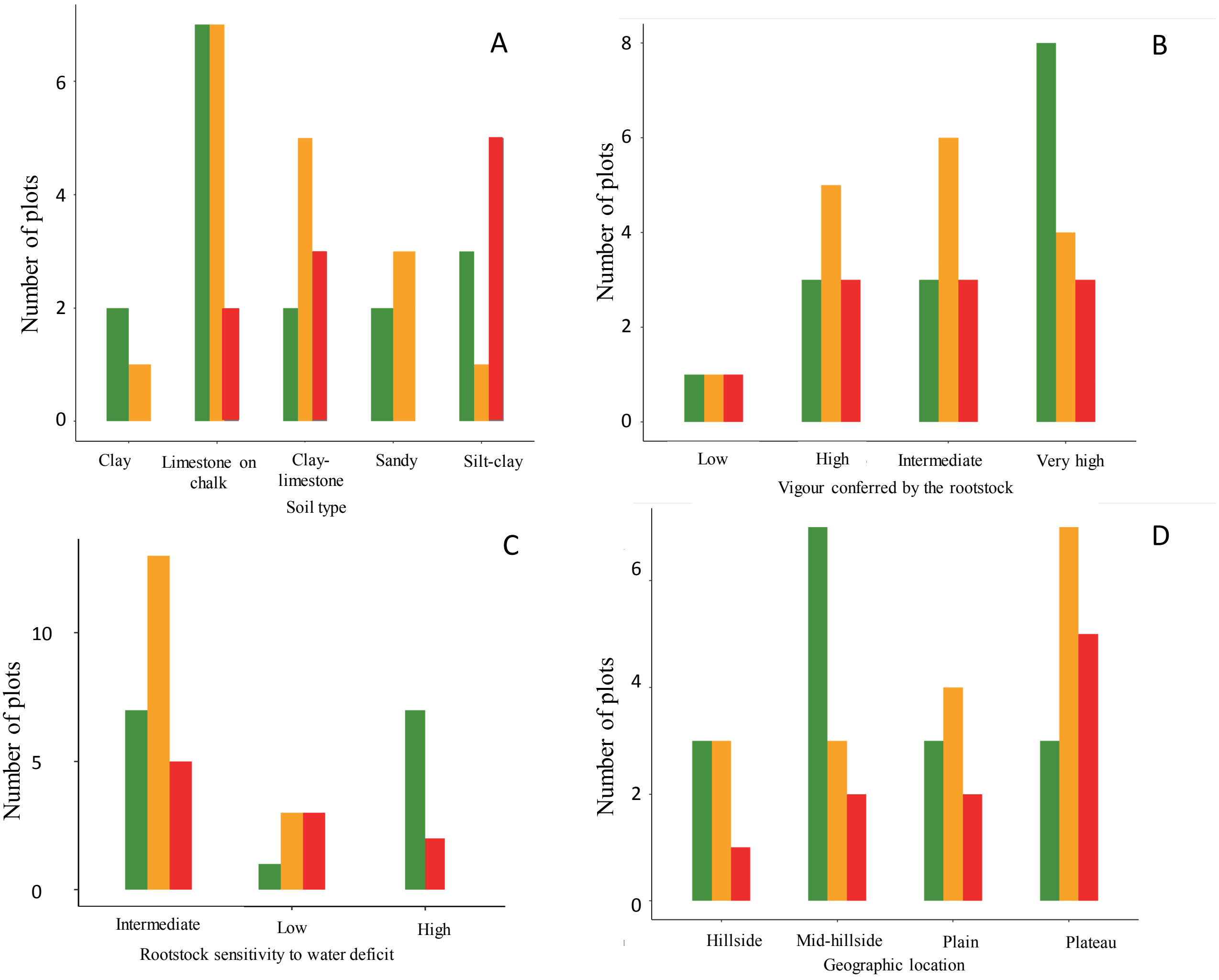


FIGURE 6. Distribution of decline categories for the four planting variables studied.

Distribution of strongly declining (red bars), moderately declining (yellow bars) and non-declining (green bars) plots for each of four static variables related to planting and soil–climate conditions: A) soil type, B) vigour conferred by the rootstock, C) rootstock sensitivity to water deficit, D) geographic location.

also mainly located on mid-hillside areas, whereas a higher proportion of strongly declining and moderately declining plots was associated with a hillside location (Figure 6D). With regard to vine indicators, most non-declining plots were associated with strongly vigorous rootstocks (Figure 6C), whereas strongly declining plots of the C2-C2-C2 trajectory (a trajectory mainly associated with non-declining plots) were all associated with low-vigour rootstocks. It was also interesting to note that, conversely, on the strongly declining trajectory C1-C1-C1, plots also characterised by strongly vigorous rootstock at planting were identified as non-declining plots. Finally, a high level of sensitivity to water deficit conferred by the rootstock was associated with non-declining plots, whereas plots with a low level of sensitivity to water deficit conferred by the rootstock were often strongly or at least moderately declining (Figure 6B). Our data indicate that the plots in which rootstock were sensitive to water deficit were also those with lower water deficit, which could mean that winegrowers paid less attention to the water sensitivity of the rootstock in plots not highly exposed to water deficit; while showing a trend in this regard, our results were not conclusive, warranting further research.

DISCUSSION

We investigated the relationships between agricultural practices and vineyard decline in the western French wine-growing region of Cognac. Our analysis was based on an original temporal analysis that began from the time of planting and spanned several important decades for vineyards. It also considered combined practices instead of individual ones. This study is the first analysis of a large dataset of agricultural practices over an extended period of time; it offers an explicit approach based on practice-based trajectories to better understand vineyard decline.

1. Different plot trajectories in terms of yield and mortality

In this study, we show different plot decline trajectories that are characterised by both yield and mortality dynamics, regardless of the cause of decline. We identified three main situations of decline: non-declining plots, moderately declining plots and strongly declining plots. Non-declining plots and declining plots were differentiated by mortality dynamics and intensity of decline, confirming some results of Merot *et al.* (2023), which showed that mortality dynamics is an early indicator of decline in a plot.

The yield decrease appeared later. The yield of vines near dead vines likely increases due to reduced competition between vines, temporarily offsetting the yield loss related to dead vines at plot level. In this case, the offsetting effect is only temporary, because the ability of the remaining productive vines to offset losses is limited by agricultural practices, soil–climate conditions and physiology. Thus, it can be hypothesised that as mortality continues to increase, the remaining productive vines will no longer be able to compensate for the mortality-related yield loss, and a decrease in yield will begin to be seen in the plot. This was not clearly observed in Merot *et al.* (2023), but assuming it to be true, it would mean that the management of remaining vines must be adapted to preserve reserve accumulation and sustain productivity. This shows that unlike mortality dynamics, yield dynamics should not be used as a reliable indicator of vineyard decline. When a yield decrease is observed in a plot, it is already too late to limit decline and it may be more advantageous to grub up the plots (Kaplan *et al.,* 2016; Gramaje *et al.,* 2018).

The different plot decline trajectories described in this study were particularly interesting given the homogeneous production context and the climate, as well as the small number of soil types observed within a limited geographical area. The genetic material was also homogeneous, with only one cultivar grown and a limited number of rootstocks (which were also well described in the database). As such, the agricultural practices and the way they are combined and implemented in a plot over time are the main reasons for the differences in plot decline trajectories.

2. Trajectories of agricultural practices associated with situations of decline

By analysing the agricultural practices carried out in the vineyards, we identified combinations of practices that were associated with decline. Analysing practices with a view to understanding decline was complex, because both long-term characteristics of decline and interannual variability had to be taken into account. We adopted an original approach to identify trajectories of practices over several decades. Instead of studying practices one by one to explain the link between mortality and practices, we characterised each time period using two distinct combinations of practices. We showed that the plots managed for at least two decades using the C1 combination of practices (C1_16-20 or C1_21-25 or C1_26-30) were the most subject to decline. Meanwhile, plots managed for at least two decades with the C2 combination of practices (C2_16-20 or C2_21-25 or C2_26-30) were the least subject to decline. In all of these trajectories, the practices identified for their potential role in vineyard decline were related to inter-row management, potash application, cryptogamic disease control, and GTD control.

3. Distinct agricultural practices implemented in declining and non-declining plots

First, we noted that inter-row management differed in terms of the volume of vegetation in the inter-row, as did the resulting competition between the inter-row vegetation and vines. A higher volume of vegetation in the inter-row can cause higher water uptake from the soil, potentially exacerbating water stress if not properly managed, but it can also lead to better water storage (Celette *et al.,* 2008; Ripoche *et al.,* 2010). Water stress is a key issue with regard to inter-row management in a context of climate change and climate mitigation (Schultz, 2016). Water stress greatly affects grapevine production (Merot *et al.,* 2023) and reserve accumulation as several physiological processes are impacted (Ollat *et al.,* 2019). When plants experience water stress, their ability to assimilate and transport carbohydrates is reduced, compromising the production and storage of reserves, such as sugars, lipids and proteins (Pellegrino *et al.,* 2005). Over the long term, a high volume of vegetation in the inter-row can compromise reserve accumulation and promote decline.

We also found that potash application was nearly twice as high in trajectories of practices associated with non-declining plots. This finding is particularly noteworthy, because potassium plays a crucial role in vineyard growth and productivity. Potassium is essential for transporting sugar from leaves to other parts of the plant, promoting plant growth and grape-cluster development (Keller, 2015), and increasing yield (Hu *et al.,* 2023). Potassium also plays a role in stomatal regulation, thereby influencing grapevine water-use efficiency (Marschner, 2012) and response to water stress (Hu *et al.,* 2023). Finally, sufficient potassium levels can enhance disease resistance in grapevine (Wang *et al.,* 2024) and improve cold hardiness (Moyer *et al.,* 2018). Insufficient potassium supply can thus promote decline over several decades.

Downy and powdery mildew are major fungal diseases that attack different vine organs, including leaves, clusters and shoots, which can lead to substantial yield losses, impair photosynthesis and weaken the vine (Gessler *et al.,* 2011). Disease control was a third factor identified in this study that contributed to differentiating the trajectories of practices associated with strongly declining and non-declining plots. More downy and powdery mildew treatments were applied in trajectories of practices associated with plots experiencing greater decline, while the volume of mixture in the sprayer was higher in non-declining plots. In fact, Holzapfel and Smith (2012) showed that the favoured period for carbohydrate reserve regeneration was between harvest and leaf fall. C reserves are regenerated as early as veraison and often even at flowering in the roots and trunk (Zufferey *et al.,* 2015). Lateral leaves are very important at the end of the season for photosynthesis and C-reserves in trunk and roots. This is also a period when powdery mildew can develop on leaves if not well controlled during the growing season (Poeydebat *et al.,* 2022), potentially impacting reserve regeneration with significant consequences over the long term.

A fourth key difference found between declining plots and non-declining plots was related to the control of GTDs, which are one of the main known causes of vineyard decline. Trajectories of practices associated with decline in this study did not include sodium arsenite treatment against GTDs, such as esca and *Eutypa* dieback, during the 21–30-year period. Sodium arsenite was highly effective against GTDs, because it could penetrate deeply into the grapevine trunk. However, France banned the use of sodium arsenite in vineyards in 2001 due to its toxicity. GTD prevalence is significant in France: esca prevalence of infected vines generally varies between 10 % and 30 % and can even reach 40 % (Mondello *et al.,* 2018; Gramaje *et al.,* 2018), while *Eutypa* dieback affects between 5 and 20 % of vines (Bertsch *et al.,* 2013; Laveau *et al.,* 2009). While there are currently few alternatives for the control of GTDs (Mondello *et al.,* 2018), pruning is a key practice implemented by winegrowers. The way pruning is performed affects pruning wounds, which are entry points for the pathogens that cause GTDs. Our analysis did not show any differences between the practice-based trajectories in terms of pruning methods, but differences in pre-pruning were noted in the 16–20-year period, with a higher proportion of pre-pruning carried out in declining plots. Dewasme *et al*. (2024) showed that esca incidence was driven by climate change, as well as by hidden factors before plots reached the age of 25 years. Pre-pruning and the other abovementioned factorscould be among these hidden factors. Unfortunately, it was not possible to analyse the period of 0 to 15 years, a long period of time during which practices could impact the vine implementation and consequently its longevity.

4. Aggravating or moderating drivers of decline among fixed factors

Analysis of the fixed factors at planting along with plot characteristics showed that some of the factors studied could influence changes in decline in vineyards. These factors included i) the role of water deficit sensitivity and intrinsic vigour related to genetic factors, and ii) vine exposition to water deficit related to the combination of soil and climate characteristics. Rootstocks conferring water stress resistance and strong vigour to the vine were clearly identified as factors that limited decline in the study area, with its specific soil and climate conditions. Soil characteristics were also a key factor aggravating decline, with more strongly declining plots containing soils known to be sensitive to water stress in this temperate climate zone. Our results indicate that, at the time of planting, it is important to choose genetic material that is suited to the current soil and climate conditions of the vineyard, and to take into account the effects of climate change to minimise the risk of decline, which could be high, given the lifespan of grapevine.

Vine decline is a complex phenomenon resulting from multiple interacting factors. Water deficit, exacerbated by climate change, prolongs drought periods and increases the vine's sensitivity to decline. Intercropping aggravates this situation by increasing competition for water and nutrients between vines and the vegetation cover. Meanwhile, GTDs, such as esca and *Eutypa,* progressively weaken the vines, increasing mortality and decreasing yield. These factors are not independent; they interact in a complex way. Water stress, especially when severe, can make vines more vulnerable to pathogenic infections, and root competition can exacerbate the effects of water deficit. Combating vine decline requires an integrated approach that combines optimal water management, control of competing vegetation, and effective strategies for the prevention and treatment of GTDs, as well as overall soil health management. Only an in-depth understanding of these interactions will ensure that vineyards remain healthy and productive in the face of current and future challenges.

CONCLUSION

This study, which drew on more than 30 years of data on yield, mortality and agricultural practices in vineyards, highlights the complexity of the grapevine decline phenomenon and the myriad interactions between environmental characteristics, planting material and agricultural practices. We showed that grapevine trunk diseases and practices defined by water availability are key factors in triggering or promoting ongoing grapevine decline. Our findings indicate that water dynamics must be managed throughout the entire vineyard lifespan, from planting to grubbing up; this would involve, for example, making choices for the better management of soils with poor water retention capacity and choosing less drought-sensitive rootstocks and less competitive ground cover species. These results are all the more significant as vines are increasingly subject to water stress due to climate change, which affects both rainfall and temperatures.

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