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Long-Term Esca Monitoring Reveals Disease Impacts on Fruit Yield and Wine Quality

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Abstract

Esca is a widespread grapevine trunk disease, and a global increase in esca incidence has been observed in recent decades. Estimates attribute considerable economic losses to esca, and the disease is considered one of the major causes of vine mortality and vineyard dieback. However, accurate quantification of esca incidence is difficult due to symptom inconsistency, and there are very few studies precisely quantifying yield losses and impacts on fruit composition and wine quality. This study carried out an extensive esca surveying program; annually monitoring approximately 57,000 vines across 12 estates in the Bordeaux region for 9 years. In conjunction with this surveying program, we quantified the yield losses of vines with known esca symptom histories and assessed their fruit composition and resulting wine quality. The study revealed that, because of year-to-year variation in symptom expression, accurate rates of esca can only be obtained through monitoring over many years. We found that yield losses in individual vines exhibiting esca can reach up to 50% but they are rarely unproductive, and when scaled to the parcel scale yield losses are low, never exceeding 1 hl/ha. In addition, the quality of the grapes produced is similar to that obtained from vines without symptoms. Finally, the majority of mortality observed in vineyards was not due to esca, with only 40% of dead vines exhibiting an esca history. These results suggest that the impact of esca is likely overestimated and that it is necessary to more broadly investigate other factors contributing to vine mortality and vineyard dieback.

Keywords: Cabernet Sauvignon, dieback, grapevine, mortality, wood disease

Grapevine trunk diseases include a host of diseases or syndromes. The three most prominent are esca, Eutypa dieback, and Botryosphaeria dieback (Fontaine et al. 2016). Among these three diseases, esca is the oldest syndrome described on grapevine. In the 1st century C.E., the Roman naturalist Pliny the Elder described the disease that led to the drying out and death of the vine during the summer, emphasizing the relationship between symptoms on the herbaceous parts of the vine and the areas of decayed wood in the trunk (Larignon 2016). The term "esca" was introduced at the beginning of the 20th century to designate that this disease was characterized by the presence of a white rot and by the apoplectic form (Viala 1922).

Despite this long history, esca remains a poorly understood syndrome. Esca is a complex disease involving many putative causal pathogens and triggering environmental factors. The symptoms of esca include vascular necrosis in perennial woody organs such as the trunk and arms, and leaf chlorosis and necrosis that can lead to total canopy loss. Leaf symptoms are commonly classified into two forms: a chronic form where leaves show interveinal discolorations or necrosis (often referred to as a "tiger-striped" pattern), and an apoplectic form where part or the entire canopy rapidly desiccates and is shed from the vine (Dubos 2002). The necrosis observed in wood has been associated with specific fungi, the most prominent being *Phaeomoniella chlamydospora*, *Phaeoacremonium minimum*, *Fomitiporia mediterranea*, *Eutypa lata*, and *Botryosphaeria* spp., and each of these fungi are able to generate the wood necrosis attributed to esca (Choueiri et al. 2014; Cortesi et al. 2000; Larignon and Dubos 1997; Laveau et al. 2009; Mugnai et al. 1999). In addition, other fungi as well as bacteria (Bacillales, Enterobacteriales, and Xanthomonadales) are suspected to be involved in the esca syndrome, highlighting the obscurity regarding the organismal complex responsible for this disease (Bruez et al. 2013, 2015; Hofstetter et al. 2012). Despite this knowledge base, there is still no reliable diagnostic for detecting the presence of esca apart from the presence of visual symptoms.

The pathology leading to leaf symptom expression during esca is unpredictable. Typically, symptoms are only observed on mature vines (approximately >7 years old) (Larignon 2009; Mondello et al. 2018), and within an individual vine symptoms are frequently not consistent year to year. Factors other than pathogens are considered to play an important role in the development of symptoms acting as predisposing factors or triggers (Bertsch et al. 2013; Lecomte et al. 2012; Surico et al. 2006). Factors that influence leaf symptom expression include the grape variety and vine age (Fussler et al. 2008; Grosman and Doublet 2012; Mugnai et al. 1999; Pouzoulet et al. 2014), the rootstock (Andreini et al. 2014; Boso et al. 2008; Gramaje et al. 2010; Laveau and Mary 2015; Limiñana et al. 2009; Mary et al. 2017; Murolo and Romanazzi 2014), and environmental factors such as soil water holding capacity or summer climate (Calvo-Garrido et al. 2021; Destrac-Irvine et al. 2007; Larignon 2009; Surico et al. 2000; Van Niekerk et al. 2011). In particular, environmental factors that produce stressors to the plant appear to be important. Recently, a study investigating drought during two consecutive years showed water stress inhibited the formation of leaf symptoms (Bortolami et al. 2021).

Grapevine trunk diseases are widespread globally. In Europe, Spain, Italy, and France are especially impacted by trunk diseases, with an estimated 19, 14, and 13% incidence, respectively (Fontaine et al. 2016). Although accurately quantifying esca incidence is difficult because of the inconsistency of symptom expression, a global increase in disease incidence has been observed since the beginning of the 21st century. This increase could have resulted in part from the ban on sodium arsenate, a fungicide used to treat esca. For example, in Spain esca incidence grew greater than threefold from 2003 (the year of sodium arsenate prohibition) to 2006 (from 1.8 to 7%) (Martin and Cobos 2007). In France, the national wood disease observatory showed an increase in esca incidence from 1.0 to 3.2% between 2003 and 2008, but in contrast the incidence of Eutypa dieback decreased from 3.4 to 2.5%. However, the increase in esca incidence has also been observed in regions not using sodium arsenate, thus other factors (e.g., climate and management practices) are

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likely involved. In France, the National Institute of Vine and Wine estimates that esca costs approximately one billion euros per year in lost wine production (corresponding to an approximate loss of $1,500 per hectare per year). The cost can be even greater in other regions with a loss of about $2,000 to $3,000 per hectare per year estimated for Californian viticulturists due to esca (Fontaine et al. 2016).

Apart from these extrapolated economic impacts based on disease incidence estimates, there are no long-term studies on the impact, both quantitative and qualitative, of esca on yields and fruit quality at harvest. A 2-year study in Bordeaux using Cabernet Sauvignon showed that esca delayed fruit maturity, reducing sugar content by 10% and increasing total acidity by 20%. There were also differences in the levels of phenolic compounds; in particular, the levels of anthocyanins were 30 to 50% lower (Lorrain et al. 2012). In that study the differences in fruit composition appeared to translate into an increase in the herbaceous notes and a decrease in the fruity character of the resulting wines. However, the thresholds to bring about these differences were extremely variable between the two years of the study, requiring the introduction of 5% of grapes of vines affected by esca in the tank in 2009 but 50% in 2010. Similar studies in white varieties in both Italy and France have shown a similar delay in maturity of fruit from vines affected by esca (Bruez et al. 2021; Calzarano et al. 2004).

To date, no study has assessed the direct impact of esca on fruit yield, and data on the quality of musts and wines are rare. Therefore, this study carried out the most extensive esca surveying program to date; annually monitoring nearly 57,000 vines across 12 different estates in the Bordeaux region for 9 years. In conjunction with this surveying program, we quantified the yield losses of vines with no history of esca, those exhibiting esca in the harvest year, and those not exhibiting esca in the harvest year but with a history of esca, assessing fruit composition and the quality of wines produced from these vines. Faced with the current increase in dieback, the objective of this study was to precisely quantify the yield losses and fruit composition impacts attributable to esca in order to better inform vineyard management strategies.

Materials and Methods

Study parcels

The study was carried out in the Bordeaux region on the southwest side of the Garonne River. Twelve different parcels were chosen among 12 estates (one parcel per estate) because they were identified as exhibiting the greatest amount of esca symptoms according to the vineyard managers. Eleven parcels were planted with Cabernet Sauvignon (CS) and one with Merlot, grafted on different rootstocks with the parcel age ranging from 13 to 51 years old at the start of the study in 2011 (Table 1). The density of plantation varied from 6,667 to 10,000 vines per hectare and all the vines are pruned in double Guyot.

Vineyard observations and measurements

A total of 56,406 vines were individually monitored between 2011 and 2019 over different periods depending on the plot (Table 1). The monitoring was carried out annually after veraison at the end of August by a trio of assessors trained in the recognition of esca. The assessments between the first and the last parcel were spread over a week at a time of year when the appearance of new leaf symptoms is rare. For each individual vine each arm was assigned to one of the following categories: 1) without foliar symptoms or asymptomatic, 2) exhibiting foliar symptoms of the chronic form of esca, 3) exhibiting esca apoplexy, 4) over-grafted, 5) dead, 6) missing, and 7) replanted and not yet productive (usually young plants under two years old). The three last categories constitute the plants unable to produce fruit.

To quantify the impact of esca on yield, the number of bunches and their weights were quantified at harvest on nine parcels of 2,927 to 7,536 vines (A, B, C, D, F, G, H, I, and L) across 4 years from 2013 to 2016 (Table 1). The yield of more than 3000 vines was recorded over this period. All bunches with green, nonripe, or shriveled berries were not considered. For each harvest year the health status of each vine was assigned to one of the following four categories:

- Asym = asymptomatic vines since the beginning of monitoring
- Symp = symptomatic vines the year of harvest N for the first time since the beginning of monitoring
- Symp*2 = symptomatic vines two consecutive years, the year of harvest N and the last year N-1
- Previous-Symp = asymptomatic vines the year of harvest N but symptomatic the previous year N-1

Microvinifications and wine analyses

Each of the above four categories was harvested separately and microvinifications from 50 kg of grapes (standard experimental vinifications in little vats) were realized in two parcels in 2012 (B and F = 8 microvinifications) and in three plots in 2013 (B, C, and F = 12 microvinifications). The manual harvest was destemmed, mechanically crushed, and then sulfited at 5 g/hl of SO_2. The microvinifications were carried out in 50-liter vats at a temperature of 28°C with added commercial yeast *Saccharomyces cerevisiae* var. *cerevisiae* (strain 522 Davis) at 20 g/hl. Malolactic fermentation was carried out in a 30-liter container after bacterial inoculation with lactic acid bacteria Vitilactic F at 1 g/hl. Analyses of grape must and wines

Table 1. Characteristics of the parcels of Cabernet Sauvignon (CS) included in the study

Parcel	Location	Varieties/ rootstock	Plantation year	Soil texture	Planting density	Number of vines monitored	Field rating period
A	Cussac-Fort-Médoc	CS / 101-14 MGt	1995	Sandy loam	6,667	6,930	2012 to 2020
B	Saint-Julien-Beychevelle	CS / 3309 C	1996	Gravelly sandy	8,333	5,547	2011 to 2020
C	Saint-Julien-Beychevelle	CS / 101-14 MGt	1987	Gravelly sandy	6,667	5,287	2011 to 2016
D	Saint-Laurent-Médoc	CS / SO4	1988	Sandy	10,000	3,973	2011 to 2016
E	Listrac-Médoc	CS / 101-14 MGt	1989	Clayey	6,667	6,320	2013 to 2016
F	Arsac	CS / 101-14 MGt	1998	Gravelly sandy	8,265	3,777	2011 to 2020
G	Léognan	CS / 420A MGt	1992	Sandy	10,000	7,536	2011 to 2016
H	Margaux	CS / 3309 C	1995	Gravelly sandy	10,000	2,367	2011 to 2016
I	Saint-Julien-Beychevelle	CS / 101-14 MGt	1985	Gravelly sandy	8,695	5,079	2011 to 2020
J	Saint-Estèphe	MN / 5BB	1979	Clayey	7,560	3,736	2011 to 2016
K	Pauillac	CS / 3309 C	1960	Gravelly	8,696	2,927	2012 to 2016
L	Margaux	CS / 101-14 MGt	1997	Sandy	10,000	2,927	2012 to 2020

were performed for each category. Sugar content (g/liter), total acidity (g H_2SO_4/liter), pH, malic acid (g/liter), yeast available nitrogen (mg/liter), quantity of anthocyanins (mg/liter), total polyphenol index (IPT), and modified color intensity, which is the sum of the absorption at three different wavelengths (ICM = A520 + A420 + A620), were assessed.

A sensory evaluation of the wines from the different modalities was carried out in the spring following the harvest. The jury was made up of a panel of 18 professional wine tasters from the Bordeaux region who had been previously trained in sensory analysis for this experiment. The series of wines were tasted following a Latin square serving protocol that eliminates the effects of order of the samples. The tasting was carried out blind (samples identified by a 3-digit code assigned by a person who was not part of the jury). The wines were the subject of a descriptive tasting with the attribution of a rating out of 20 to judge the overall quality of the product.

Statistical analyses

All statistical analyses were carried out in R.4.1.0 (R Core Team 2021). The effect of esca disease history on yield was analyzed by using a linear model for each individual year and also for all years. To assess the effect of esca on the quality rating, a linear mixed model was used where esca disease history was considered as a fixed effect and the judge as a random effect (Pinheiro and Bates 2000). When there was a significant effect of the esca disease history, a post hoc Tukey's HSD was conducted to test differences between each category. Residuals of all linear models were checked in order to meet the assumptions of normality. The linear mixed models were fitted using the lme function in the nlme package (Pinheiro et al. 2021) in R.4.1.0.

Results

Global and parcel specific rates of esca incidence

The average percentage of vines exhibiting esca symptoms on the 12 parcels varied from 2.2 to 8.3% depending on the year (Fig. 1A). Over the nine years of the study, the average symptom expression of the chronic form of esca was 5.1% (±0.6%) across all parcels. Importantly, the individual vines exhibiting symptoms from one year to the next were not always the same. Thus, the total percentage of vines that exhibited esca symptoms in at least one of the years was much greater at 14.3% (Fig. 1A; black dotted line). The year 2012, followed by 2014 and 2017, had the highest average esca incidence (all above 5%). In contrast, 2015, followed by 2011 and 2019, were the three years with the lowest incidence (Fig. 1A). The number of vines expressing esca leaf symptoms varied by year and by parcel. The differences in the average symptom expression between parcels ranged from 0.4 to 12.9% (it reached as high as 23.0% for a single parcel in a single year). Parcels A, B, F, H, and L had the highest rates of esca (Fig. 1B). For all parcels the cumulative percentage of vines that exhibited the chronic form of esca was much greater than the observed percentage in any given year (Fig. 1B; red points). The cumulative percentage ranged from 1.6 to 46.7%, which was 1.5 to 2.4 times greater than the maximum level of esca symptoms observed in any one year. The percentage of vines exhibiting the apoplectic form of esca was very low. The average rate of the apoplectic form of esca was 0.36% (±0.04%), and the rate never exceeded 1.0% for any parcel (data not shown).

The relationship between esca symptom history and vine mortality

In addition to esca-symptomatic vines, the percentage of dead, missing, or replanted vines was assessed (taken together we refer to these vines as "nonproductive"). The average rate of nonproductive vines was 10.4% (±0.7%) on average, and it varied from to 2.5 to 30.5% depending on the parcel and year. The percentages of esca-symptomatic and nonproductive vines were not correlated overall, or within any individual parcel (Fig. 2).

The number of times a vine exhibited esca symptoms in the years preceding its death varied between parcels (Fig. 3). Starting in 2017 a vine that died could have exhibited symptoms from zero to seven times since 2011. For some parcels the percentage of dead vines that had never shown esca symptoms was very high, ranging up to 73% for some years (Fig. 3). However, the opposite was also true where in some parcels and years nearly all dead vines had exhibited previous esca symptoms at least once, for example, in parcels A, F, I, and L only 0 to 20% of vines had never exhibited symptoms before their

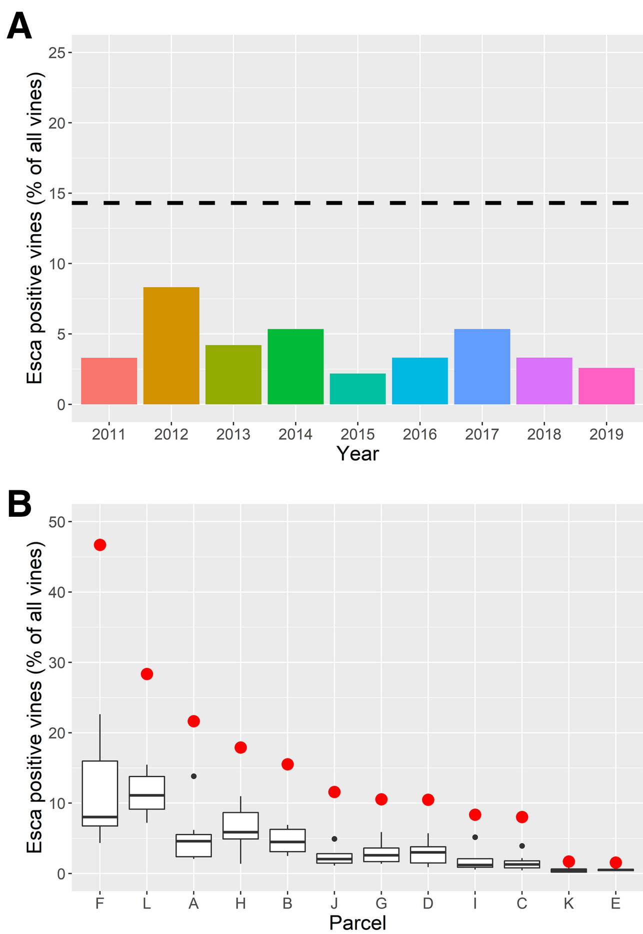

Fig. 1. The rate of vines exhibiting esca symptoms globally and in individual parcels. **A,** Global rate of vines exhibiting esca symptoms for each of the monitored years. The black dotted line corresponds to the total percentage of vines that exhibited esca symptoms in at least one year. **B,** Distributions of the annual rates of esca leaf symptom expression per parcel. The red points represent the cumulative rate of vines that exhibited esca symptoms at least once over this period.

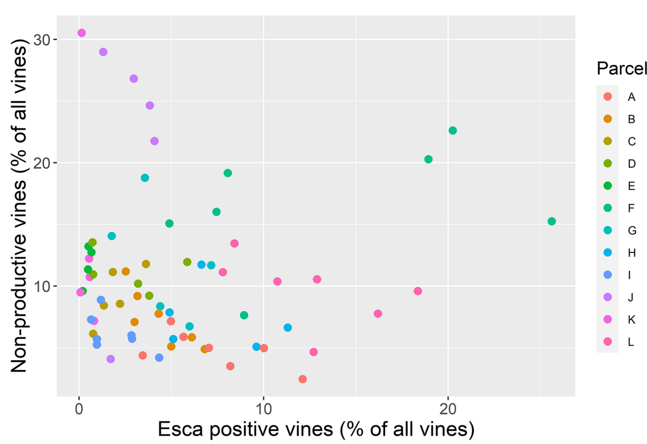

Fig. 2. The relationship between the annual rate of esca symptom expression and the percentage of total nonproductive vines (i.e., dead + missing + replanted vines) for each parcel over the period of monitoring (each point represents a parcel and year).

death in 2018. Across all parcels the proportion of vines that exhibited esca symptoms in more than four years prior to their death was low (i.e., <40%), illustrating that it is common that vines do not exhibit esca symptoms consistently every year (Fig. 3).

The impact of esca on fruit yield

Due to the inconsistency of esca leaf symptom expression, we quantified the yield losses across four categories based on a vine's leaf symptom history (Fig. 4). Overall, the yield loss for esca vines was 41%, comparing vines that had never expressed any leaf symptoms of esca (Asym) and those that have expressed these symptoms at least once. This difference in yield was relatively constant regardless of the year (Fig. 4) and of the parcel (data not shown). The yield losses were higher when the vines exhibited symptoms the year of the harvest (52% on average). Losses were 43% when the vines exhibited symptoms for the first time (Symp) while they increased to 55% when the vines exhibited symptoms in two consecutive years (Symp*2). Moreover, all the bunches with berries that were pink or green or showing wilting were not included in these analyses, so they reflect only fruit of a quality that would be used to make wines. Vines that are asymptomatic the year of harvest, but which had exhibited symptoms the previous year (Previous Symp), also generated yield losses of 28% on average (Fig. 4). This was not small when compared with the 43% average loss for "Symp" vines (Fig. 4). The percentage of vines with zero yield varied from 0.6% for healthy vines to 9.0% for vines expressing esca in the two consecutive previous years (Symp*2), which partly explained the origins of the yield losses. Modalities "Symp" and "Previous-symp" had, respectively, 4.8 and 4.0% of vines with zero yield (data not shown).

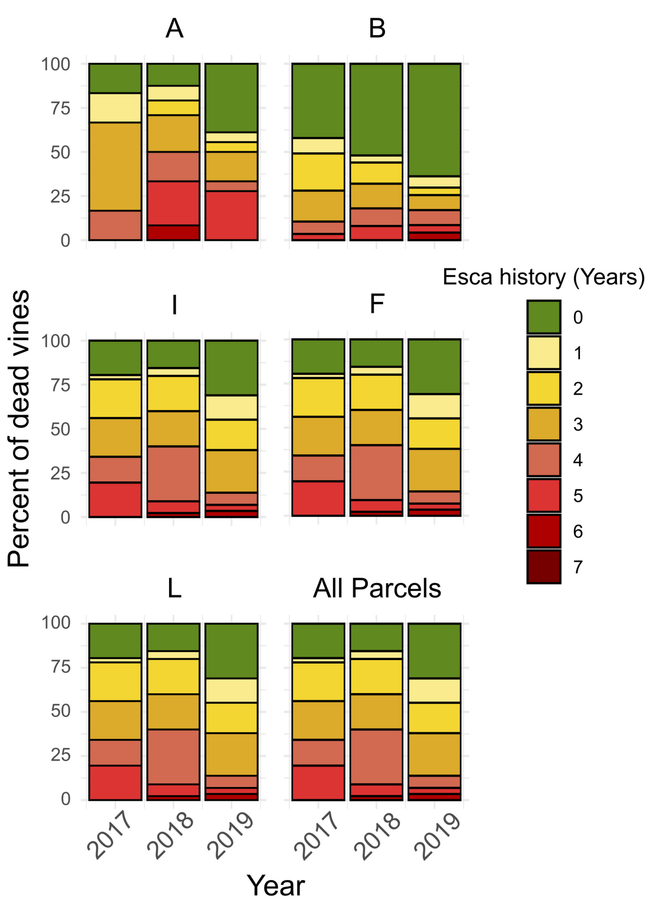

Fig. 3. The esca symptom history in the years preceding a vine's death in 2017, 2018, and 2019 (only parcels that were monitored for the full 9 years of the study were considered for this analysis). "All parcels" represents the average for the five parcels represented.

The impact of esca on fruit composition and wine sensory attributes

The potential alcohol of the wines, which results from the sugar level after alcoholic fermentation, in 2012 and 2013 reveals a slight delay in maturity for the two categories that exhibited esca symptoms the year of the harvest (Symp and Symp*2), but the differences were only significant for "Symp*2" in 2013 (Table 2). There was no difference in the composition of the wines from healthy vines (Asym) and vines that were asymptomatic in the year of the harvest but had esca symptoms the previous year (Previous Symp). Concerning phenolics, the amount of anthocyanins in the wines was lower in the categories that exhibited symptoms the year of the harvest, but again these differences were only significant in 2013 (Table 2). Although there was also less IPT in wines from these modalities, the differences were not significant. Moreover, the concentration of anthocyanins and tannins for "Symp*2" was lower than for "Symp" but without a significant difference.

Wines from the four categories were subjected to sensory analysis by a jury of experts to assess wine quality differences (Fig. 5). In 2013, it was impossible to vinify the "Symp*2" on parcel B because of the low number of vines and low yield. Although the Asym and Previous Symp generally received slightly better quality ratings than the categories exhibiting esca the year of the harvest, most of these differences were not statistically significant.

Discussion

In this study we carried out an extremely robust esca monitoring program assessing approximately 57,000 vines for 9 years across 12 estates in the Bordeaux region representing approximately 800 ha. The study revealed that, because of substantial year-to-year variation in esca symptom expression, incidence rates obtained in one year of monitoring greatly underestimated the real esca incidence. Thus, accurate rates of esca can only be obtained through monitoring over many years. We found that although yield losses in individual vines exhibiting esca can reach up to 50%, they are rarely unproductive, and when scaled to the parcel scale yield losses are low, never exceeding 1 hl/ha. In addition, berry composition is only slightly affected by the presence of esca (when normal cluster sorting criteria are applied). Finally, the majority of mortality observed in these vineyards was not due to esca, with only 40% of dead vines exhibiting an esca history. Together, these results suggest that the impact of esca is likely overestimated.

In individual vines, our study showed a significant loss of yield due to esca, reaching levels of approximately 40 to 50% depending

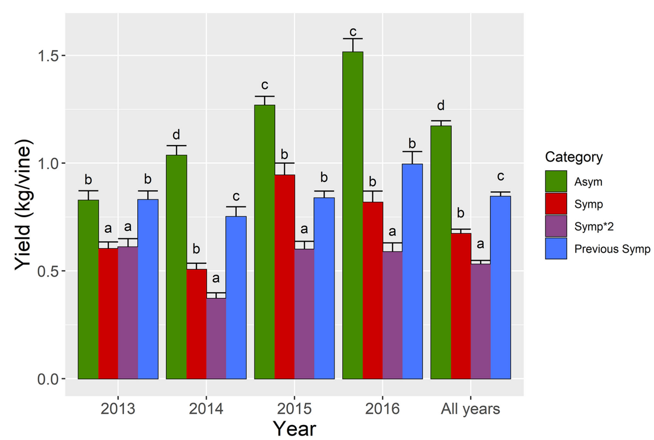

Fig. 4. Average yield per vine as a function of the vine's esca symptom history: esca asymptomatic (Asym in green), esca symptomatic (Symp in red), esca symptomatic two consecutive years (Symp*2 in purple), and esca symptomatic the previous year (Previous Symp in blue). "All years" represents the average for the 4 years presented. Bars represent the average yield per vine and error bars represent the standard deviation. Different letters above bars indicate significant differences between modalities within each year (Tukey's HSD, $P < 0.05$).

on a vine's history of symptom expression. Yield reductions are well-characterized in the literature (Bertsch et al. 2013; Gramaje et al. 2018), but this is the first time that it has been quantified on such a large number of vines and over 4 consecutive years, which accounts for natural yield variations due to the vintage. Contrary to what is often assumed, we showed that yield losses rarely reach 100% on an individual vine affected by esca, and this is true even when a vine exhibited symptoms for several consecutive years. One of the remarkable results of this study is an approximate 30% yield loss on vines that had no symptoms in the harvest year, but that had exhibited symptoms the previous year. This may result in part from a decrease in stored carbohydrate reserves brought about by esca (Bortolami et al. 2021). This demonstrates that growers cannot expect full production once a vine has exhibited esca leaf symptoms. Although leaf symptoms are generally restricted to mature vines (Larignon et al. 2009; Mondello et al. 2018), they have also been observed on young vines (Dubos 2002; Fussler et al. 2008; Romanazzi et al. 2009; Surico et al. 2006), suggesting that if managers want to take action to replace or renew vines once esca leaf symptoms have been observed they should do so quickly to remedy this loss of production.

Despite significant yield losses on individual vines expressing esca symptoms, the total number of vines affected in most parcels was low (5% on average), so the loss of yield per hectare was limited. Based on average designation of origin controlled (AOC) yield limits in Bordeaux, these losses correspond to less than 1 hl/ha. Importantly, it is likely that the yield losses quantified here represent a worst-case scenario, and that yield losses in other contexts would be less. This is because in this study we chose one of the most sensitive grape varieties in the Bordeaux region, Cabernet Sauvignon, on parcels with the maximum age range of esca expression (Fussler et al. 2008) and mostly grafted onto a rootstock favorable to the expression of leaf symptoms (Laveau and Mary 2015). In addition, the parcels included in the study were proposed by the vineyard managers because they were the parcels on their estates with the highest rate of observed esca leaf symptoms.

In addition to yield, the value of wine grapes is heavily dependent on fruit and wine quality. This study demonstrates that the impact of esca on fruit composition and the quality of wines was minor. For the same harvest date (determined for each parcel by the manager) there was a slight delay in maturity that did not lead to significant differences in the finished wines, with the exception of slightly lower alcohol and anthocyanins for wines from vines exhibiting esca symptoms the year of harvest. These results are consistent with the results obtained by Calzarano et al. (2004) in Italy and Bruez et al. (2021) in France on white grape varieties, and by Lorrain et al. (2012) in Bordeaux on the same grape variety studied here, Cabernet Sauvignon. However, in contrast to these studies, we did not find any significant differences in total acidity regardless of the year or parcel considered. For vines that exhibited esca only the year before harvest (but not during the year of harvest; Previous Symp), the quality of the wines was similar or even better than those from healthy vines. This could have resulted in part from yield reductions. Despite the minor impacts of esca on the wines quantified in this study, Lorrain et al. (2012) showed herbaceous notes and a reduction in the fruity character of wines from vines affected by esca. Therefore, it seems prudent that future studies should look more deeply into the impact of esca on the aroma profiles of red wines by assessing a broader range of aroma- and flavor-related molecules.

Over the 9 years of the study, the average rate of foliar esca symptoms was 5%, and only four parcels regularly exceeded this rate. Our study did not aim to elucidate the conditions that favor the expression of esca leaf symptoms. However, we did observe that the four parcels with the highest rates of esca (Fig. 1; parcels B, F, H, and L) are all Cabernet Sauvignon grafted on 101-14 MGt or 3309C, planted at the end of the 1990s, and on predominantly sandy soils. It has often been considered that the strong demand for vines in France at the end of the 1990s could have contributed to the increase in symptoms observed 10 years later (Gramaje and Armengol 2011). In our study, parcels planted before 1990 (C, D, E, I, J, and K) or at the start of the 1990s (G) exhibited lower rates of esca. There was also significant interannual variation in esca incidence, with high expression years such as 2012, 2014, and 2017 and low expression years such as 2011, 2015, and 2019. It is complicated to relate esca incidence to vintage climate. Surico et al. (2006), Bruez et al. (2013), and Songy et al. (2019) report that climate variability can sometimes exacerbate esca leaf symptom expression. Surico et al. (2000) reported that leaf symptom expression is associated with hot periods in the summer following rainfalls. Lecomte et al. (2012) reported that there was an evolution of leaf symptoms associated with a progressive increase of mean temperatures in early summer. As the presence of esca was noted only at the end of summer in our study, it is impossible

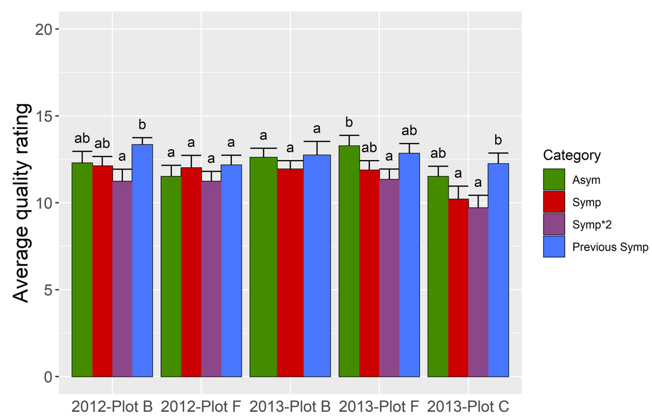

Fig. 5. Average wine quality ratings as a function of the vine's esca symptom history: esca asymptomatic (green), esca symptomatic (red), esca symptomatic two consecutive years (purple), and esca symptomatic the previous year (blue). Bars represent the average yield per vine and error bars represent the standard deviation. Different letters above bars indicate significant differences between categories within each year (Tukey's HSD, $P < 0.05$).

Table 2. Composition of the wines from 2012 and 2013 for the four categories (Asym, Symp, Symp*2, Previous-Symp)[z]

Harvest year	Categories	Potential alcohol	Total acidity	Anthocyanins	IPT
2012	Asym	12.1 (±0.5) a	2.9 (±0.1) a	682.0 (±72.0) a	62.0 (±11.0) a
	Symp	11.6 (±0.2) a	2.9 (±0.1) a	616.5 (±22.5) a	61.5 (±8.5) a
	Symp*2	11.5 (±0.1) a	2.9 (±0.1) a	577.5 (±33.5) a	60.0 (±8.0) a
	Previous-Symp	12.2 (±0.7) a	2.9 (±0.0) a	670.5 (±71.5) a	60.5 (±10.5) a
2013	Asym	11.8 (±0.1) b	3.2 (±0.1) a	522.7 (±15.9) a	58.7 (±7.3) a
	Symp	11.1 (±0.2) ab	3.1 (±0.1) a	416.3 (±11.3) b	54.7 (±6.2) a
	Symp*2	10.6 (±0.2) a	3.3 (±0.0) a	353.0 (±8.2) b	46.5 (±1.2) a
	Previous-Symp	11.9 (±0.1) b	3.2 (±0.1) a	507.3 (±24.6) a	60.3 (±7.4) a

[z] Parameters include potential alcohol (%), total acidity (g H_2SO_4/liter), anthocyanin concentration (mg/liter at pH = 3.2), and total tannins (IPT). Values are the mean ± the standard deviation. For each variable, analyses were carried out per year. Different letters indicate significant differences between categories (Tukey's HSD, $P < 0.05$).

for us to verify these relationships, but we did not observe any vintage that conspicuously promoted much higher rates of esca.

This study demonstrated that there was significant year-to-year variability in the expression of esca leaf symptoms. For example, within parcel esca incidence varied considerably, with coefficients of variation ranging from 26 to 80% across years, and the cumulative rate of esca was 1.5- to 2.5-fold higher than the maximum rate of esca in any single year (Fig. 1). Therefore, in order to accurately assess esca incidence in any parcel it is important to assess symptoms over several years to arrive at a cumulative rate. Calzarano et al. (2004) noted the same and reported cumulative rates similar to what we report here. These results may be extended to other perennial crops and highlight the need to monitor dieback diseases over several years to correctly quantify their incidence and impact.

By monitoring nearly 57,000 individual vines, we showed that approximately 50% of vines either never expressed esca or expressed symptoms only once or twice during the 7 years preceding their death. In some parcels, 73% of dead vines never expressed esca during the 7-year period prior to their death. In addition, our study clearly showed that the percentage of nonproductive vines was not correlated with the rate of esca in any parcel. Over the past 2 decades, grapevine trunk diseases have been viewed as a major problem for the wine industry. The cost of replacing dead vines around the world has been estimated at over $1.5 billion per year, which some authors contend is significantly underestimated (Ouadi et al. 2019). In France, the unproductive area attributed to wood diseases increased from 6% in 2006 to 13% in 2013 (Bruez et al. 2013; Fussler et al. 2008). The contribution of dead, missing, or replaced vines (i.e., the plants unable to produce fruit) is greater than 50% of this estimate. Lack of productivity cannot be solely attributed to grapevine trunk diseases. In particular, viral and other diseases, decreased fertilization and soil fertility, plowing (especially after many years of chemical weeding), excessive cover cropping, and other poor management practices all contribute to the decline of vineyard health and increased dieback. Considering the complexity of factors contributing to dieback, a particular disease symptom observed just before the death of a vine is not necessarily the sole contributing cause of death.

Our study allowed the robust quantification of esca disease incidence, the resulting yield loss, and the impact on fruit and wine composition in the Bordeaux region across almost a decade. We conclude that, for the context of Cabernet Sauvignon in the Bordeaux region, the impacts of esca on yield losses at the parcel scale and the impact on the quality of wines obtained from vines with esca symptoms are both likely grossly overestimated. This study suggests that in order to accurately assess and address the causes of increased dieback it is critical to broaden our scope of investigation beyond esca and other trunk diseases to include other potential causes.

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