A Characterization of Grapevine Trunk Diseases in France from Data Generated by the National Grapevine Wood Diseases Survey

L. Fussler, N. Kobes, F. Bertrand, M. Maumy, J. Grosman, and S. Savary

First and second authors: DRAF-SRPV Alsace, 14, rue du Maréchal Juin, 67084 Strasbourg cedex, France; first, third, and fourth authors: IRMA, Université Louis Pasteur, 7 rue René Descartes, 67084 Strasbourg Cedex; fifth author: DRAF-SRPV, Cité Administrative de la Part Dieu, 165 rue Garibaldi - BP 3202 69401 Lyon Cedex 03; and sixth author: INRA, UMR Santé Végétale, IFR 103, ISVV, 71 avenue Edouard Bourleaux 33883, BP81, Villenave d'Ornon cedex, France.

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ABSTRACT

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Farmers' field survey data sets represent extremely valuable information, often having a heterogeneous data format. A large number of methods are available to process this kind of information, which may be combined to address successive, connected hypotheses, with definite objectives. The National Grapevine Trunk Diseases Survey was established in France in order to monitor and analyze the importance and progress of several grapevine diseases, in particular *Eutypa* dieback and Esca decline. Here we report a first series of analyses pertaining to the years 2003 to 2005 to characterize the incidences of the two diseases, as well as grapevine mortality, in relation to grapevine age, crop manage-

ment, cultivars, and growing regions. Information representing 256 individual vineyards indicated mean incidences of 2.23 and 3.25% for *Eutypa* dieback and Esca decline, respectively. A combination of approaches (hierarchical cluster analysis, multiple correspondence analyses, and binomial logistic regressions) indicated distinct patterns of variation in the incidences of the two diseases according to crop management practices; limited linkage of specific crop management practices with diseases, especially Esca decline; a shared contribution of both diseases to mortality; and a weak linkage of the (now banned) arsenite-based pesticides with reduced Esca decline symptoms, but no such association with grapevine mortality. Differences and complementarities of the analytical approaches are discussed, as well as the implications of these analyses on grapevine health.

Characterization of plant health through farmers' field surveys remains a basic activity in phytopathology, as it provides an overview of often complex relationships between crop stands, their management, and diseases, often suggests associations which may lead to better management, and sometimes suggests new research hypotheses. This is particularly true when diseases of complex aetiology are considered. Farmers' field surveys data sets are of immense value to plant pathologists; they, however, are generally heterogeneous in format (being qualitative or quantitative) and/or precision. A number of methods, some now old and seldom used, and others more recent and comparatively easier to use, are available to process this type of information. This article presents a combination of such methods with a definite objective of addressing successive, connected hypotheses.

Esca decline and *Eutypa* dieback are amongst the most frequent grapevine diseases worldwide (15). Esca decline, also called black measles of grapevine, has been termed an 'elusive' disease (14) not only because of the diversity and range of symptoms it is associated with, but also because of their periodicity. While *Eutypa* is caused by a well-defined pathogen (*Eutypa lata*) that was identified long ago (5), the causes of Esca appearance and development still remain controversial today (14). Furthermore, while there are objective means to manage *Eutypa* dieback (primarily through protecting and healing cutting wounds associated with the training of grapevine plants [15]), such means are lacking against Esca. Sodium arsenite, a compound highly toxic to humans, animals, and the environment, had been considered (as

in other crops; J. Grosman, *unpublished data*) for many decades to minimize field symptoms (3), but not to control the disease itself (14). Countries such as Italy, France, and Spain, differed in their thresholds for intervention (from incidences of 0.5 to 2% [14]), with apparently no basis other than regulatory necessity, since the causes of the disease, let alone its epidemiology, were ill-known. Further still, there were hardly any data until recently (8) to indicate the overall importance of Esca in France; but the numbers of dead or dying plants was only too obvious. Even if the symptoms they are associated with differ, the frequent association of *Eutypa* dieback and Esca decline only added to the concern of farmers.

Such was the context when, in 2001, a ban on the use of sodium arsenite was imposed on growers in France. The National Grapevine Wood Disease Survey was created to (i) provide an objective basis to monitor the importance and progress of these diseases, especially Esca, (ii) assess the consequences of the ban on the use of sodium arsenite on the national development of Esca, and (iii) provide avenues for novel disease management approaches.

This article deals with the three first years (2003 to 2005) of data collected by the National Grapevine Wood Disease Survey. Our aim is to (i) synthesize the data collected, (ii) provide an overview of Esca and *Eutypa* dieback incidences, and (iii) analyze possible relationships among diseases and crop management practices.

MATERIALS AND METHODS

Field data collection and data set. A total of 699 vineyards were monitored during 2003, 2004, and 2005, in several provinces of France (Fig. 1). In each field, 300 grapevines in 10

Corresponding author: S. Savary; E-mail address: ssavary@bordeaux.inra.fr

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groups of 30 each were monitored at two periods of the growing season: from end of May to early June, and end of August. The 10 groups of grapevines were selected at random within each field. These two visits were conducted in order to assess trunk diseases, as well as to interview farmers about their management and

collect additional information. The information to be assembled on each vineyard included (Table 1) the age of the stand (age since planting date, Age), the number of sodium arsenite applications during 1996 to 1999 (Ars), the grapevine cultivar (CEP) and rootstock (rootstock), the training (PRUN), the prepruning (PREPRUN) practice, the management of pruning residues (RES), the incidence of Eutypa dieback (Euty; % affected vines), the incidence of Esca (Esca; % affected vines), and plant mortality (Mort, % dead, missing, or recently replaced vines). The symptoms associated with Esca are extremely diverse, and may vary with the production context (including the grapevine cultivar and plant age) (8,11,14,19). These symptoms were collectively referred to as Esca decline.

Not all surveyed vineyards were documented with this entire set of variables, and only 256 vineyards which were fully documented were retained for the analysis reported here. Table 1 includes a series of variables, some quantitative (Euty, Esca, Mort, and Age), or categorical-ordinal (Ars), and others categorical-cardinal (e.g., vine-growing regions, VGR, or grape cultivar, CEP). The response variables were those pertaining to grapevine health (Euty and Esca) and mortality (Mort), while the rest of the variables were seen as a set of possibly interacting descriptor variables. Different analytical approaches may be considered to process this type of information (10), and we chose a sequence of methods that would allow a series of successive hypotheses to be addressed. The approach used to analyze these data included three main steps: cluster analysis, multiple correspondence analysis, and logistic regression.

Cluster analysis, analysis of variance (ANOVA), and multiple ANOVA (MANOVA). As much of the available information was qualitative (ordinal or cardinal), the quantitative data were categorized, and a hierarchical cluster analysis using a Euclidean distance and the Ward criterion was conducted. All variables were involved in this analysis, except VGR, and the response variables (Euty, Esca, and Mort). The aim of this first analysis was to determine whether there are patterns of crop management that are shared amongst growing regions (thus, the noninclusion of VGR as a cluster-determining variable) and that may correspond to differing levels of disease incidences (Euty and Esca) and of mortality (Mort). The hypothesis of inde-

Fig. 1. Vine growing regions in France and areas surveyed for grapevine trunk diseases by the National Grapevine Trunk Disease Survey. ALS: Alsace; AQT: Aquitaine; BJA: Beaujolais; BRG: Bourgogne; CEN: Centre; DIO: Diois; JUR: Jura; LRO: Languedoc-Roussillon; PAC: Provence-Alpes-Côte d'Azur; PCH: Poitou-Charentes; PDL: Pays de Loire (Table 1). The numbers of individual vineyards included in the analyses are indicated in parentheses.

TABLE 1. List of variables considered in the National Grapevine Trunk Disease Survey, categories, and category boundaries

Symbol	Variable	Categories	Numerical boundary of categories	Units
Euty	Eutypa incidence at the field scale	Euty0; Euty1; Euty2	Euty0: Euty = 0; Euty1: 0 < Euty ≤ 2; Euty2: Euty > 2	%
Esca	Esca or/and black dead arm (BDA) incidence at the field scale	Esca0; Esca1; Esca2	Esca0: Esca = 0; Esca1: 0 < Esca ≤ 3; Esca2: Esca > 3	%
Mort ^a	Proportion of grapevine plant mortality at the field scale	Mort0; Mort1; Mort2	Mort0: 0 ≤ Mort < 3; Mort1: 3 ≤ Mort < 10; Mort2: Mort ≥ 10	%
Age	Age of the grapevine since crop establishment	age0; age1; age2; age3	age0: 0 ≤ age < 15; age1: 15 ≤ age < 25; age2: 25 ≤ age < 40; age3: age ≥ 40	Years
Ars	Number of sodium arsenite treatments during 1996–1999	ars0; ars1; ars2; ars3	ars0: 0 treatment; ars1: 1 treatment; ars2: 2 treatments; ars3: 3 treatments	Number
VGR	Vine growing region	ALS; AQT; BJA; BRG; CEN; DIO; JUR; LRO; PAC; PCH; PDL	ALS: Alsace; AQT: Aquitaine; BJA: Beaujolais; BRG: Bourgogne; CEN: Centre; DIO: Diois; JUR: Jura; LRO: Languedoc-Roussillon; PAC: PACA; PCH: Poitou-Charentes; PDL: Pays de Loire	None
CEP	Grapevine cultivars (cépages)	AUX; CAR; CBF; CBS; CHD; CHE; CIN; GAM; GRE; GWZ; MDH; MEL; MER; MPG; PIN; PLS; RIS; SAU; SAV; SYR; TRS; UB	AUX: Pinot Auxerrois; CAR: Carignan; CBF: Cabernet-Franc; CBS: Cabernet Sauvignon; CHD: Chardonnay; CHE: Chenin; CIN: Cinsault; GAM: Gamay; GRE: Grenache; GWZ: Gewurztraminer; MDH: Muscat de Hambourg; MEL: Melon; MER: Merlot; MPG: Muscat Petits Grains; PIN: Pinot noir; PLS: Poulsard; RIS: Riesling; SAU: Sauvignon; SAV: Savagnin; SYR: Syrah; TRS: Trousseau; UB: Ugni-Blanc	None
Root stock	Rootstock	101-14; 161-49; 3309C; 41B; R110; SO4	As rootstock codes	None
PRUN	Pruning	Cordon de royat; gobelet; guyot	As practices (COR, GOB, GUY)	None
PREPRUN	Prepruning practices	pret0; pret1	pret0: no prepruning; pret1: pre-pruning	None
RES	Management of pruning residues	Grinding, burning, removal	As practices (GRI, BUR, REM)	None

^a Mortality was calculated as the accumulated fractions of dead, missing, or recently replaced vines.

pendence between clusters of cropping practices and diseases was then tested through ANOVAs on both the incidence variables and MANOVA (9) (SAS Institute, Cary, NC) on the (Euty and Esca) response vector.

Multiple correspondence analysis. Correspondence analysis (2,6) was then used, in two steps. First, a multiple correspondence analysis (12) was performed on the (categorized) response variables (Table 1), Euty, Esca, and Mort. Vineyard age (age) was added to this set in order to remove time-dependent relationships (16), and so account for the possible dynamic relationship amongst variables. These four variables were used to generate a system of factorial axes. The relationships of these axes with additional variables such as VGR, CEP, Ars, and RES (represented by their levels or categories, Table 1), was achieved by computing the coordinates for the variables and projecting them onto the system of axes. Analysis of relationships within the framework of four variables may provide indications on association (e.g., dynamic relationships) among variables (17), or differing dynamics of diseases over the years, or varying relationships between diseases and mortality.

Logistic regression. The third approach used was binary logistic regression (20), in which the probabilistic dependence of the quantitative responses (Euty, Esca, and Mort) on nonquantitative variables, in particular the frequency of sodium arsenite use, Ars (qualitative-ordinal, Table 1) or crop management variables (qualitative-cardinal, Table 1) can be analyzed. This approach thus enables consideration of incidences of diseases in relation to, for example, age and arsenite use. It also allows examination, in a probabilistic manner (1), of mortality as the outcome of both diseases, with combined effects of age and arsenite use. A major advantage of the approach lies in its parametric nature, in contrast to the previous types of analysis.

The general form of binary logistic regressions can be written as $\text{Logit}[P(Y = 1)] = a + \sum b_i X_i$, where a and b_i are the parameters of the regression, X_i are predictors, and Y is a binary response variable. For example, when testing the effect of predictors on the appearance of a disease, Y represents disease presence or absence, with $Y = 0$ for fields with no disease, and $Y = 1$ for fields where disease is present (incidence > 0).

Three binary logistic models were tested, which refer to the transition between the two first levels of the categorized variables Euty, Esca, and Mort (i.e., euty0-euty1, Esca0-Esca1, and mort0-mort1; Table 1):

$$\text{Logit}(P(\text{Euty}>0)) = a + b_1 \times \text{age} + b_2 \times \text{ars1} + b_3 \times \text{ars2} + b_4 \times \text{ars3}$$

$$\text{Logit}(P(\text{Esca}>0)) = a + b_1 \times \text{age} + b_2 \times \text{ars1} + b_3 \times \text{ars2} + b_4 \times \text{ars3}$$

$$\text{Logit}(P(\text{Mort}>3\%)) = a + b_1 \times \text{Euty} + b_2 \times \text{Esca} + b_3 \times \text{age} + b_4 \times \text{ars1} + b_5 \times \text{ars2} + b_6 \times \text{ars3}$$

The two first models allow assessment of the effects of vineyard age and of the number of sodium arsenite treatments on the presence of disease (Eutypa dieback or Esca decline). The last model allows assessment of the effects of the two diseases, age, and number of sodium arsenite treatments on mortality. For each model, all combinations of independent variables were tested, and the models retained were selected on the basis of two criteria: (i) the G test that all slopes are zero (Minitab 15, 2006, State College, PA), and (ii) that all independent variables in the model have a parameter significantly ($P < 0.10$) different from zero.

The predictive ability of the different models tested was assessed with criteria calculated from the number of concordant, discordant, and tied pairs of observed and predicted values: percent of concordant pairs, and Somer's D rank correlation (7).

RESULTS

Patterns of cropping practices: cluster analysis. Cluster analysis led to identification of six groups (Fig. 2). Cluster 1, the smallest group of the analysis, consists of 18 vineyards mostly

located in Provence-Alpes-Côte d'Azur, and a few in Languedoc-Roussillon and Poitou-Charente provinces. Cluster 2, with 32 vineyards, is much more geographically heterogeneous, and includes individuals from 9 of the 11 considered provinces in the survey. The same applies to cluster 3, the largest group of the analysis with 99 vineyards, where however the Alsace province is strongly represented. Cluster 4 includes 32 individuals, is also heterogeneous with a high frequency of Alsace vineyards. Cluster 5 has only 23 individuals from two provinces only, Burgundy and Jura. Cluster 6, with 52 individuals, is again fairly heterogeneous, with important contributions of the Jura and Burgundy provinces. The different clusters reflect the variation in crop management practices, which were used in the classification procedure (Table 2): clusters 1, 2, and 4 are associated with varying levels of sodium arsenite use, while clusters 3, 5, and 6 are associated with no sodium arsenite use over 1996 to 1999. The oldest vines are found in clusters 5 (mean: 33.7 years) and 1 (30.8 years), while the youngest are found in clusters 6 (22.2 years) and 2 (24.2 years). The training method used does not allow discrimination amongst groups, as all clusters have the same mode (Table 2). Prepruning distinguishes clusters 4 to 6 (with prepruning) from the others, cluster 2 including some vineyards where prepruning is practiced. Residue management contributes to distinguishing cluster 5 (mode: burning), whereas grinding dominates among the other groups. Grapevine variety has a strong effect on cluster determination, as clusters are associated with one, or two, particular dominant varieties (Table 2).

ANOVAs and MANOVAs: variation in diseases among clusters. Over the 256 individual vineyards surveyed, the mean Eutypa dieback incidence was 2.23%, with a standard error of the mean of 0.30% (range: 0.00 – 30.91%), while the mean Esca dieback incidence was 3.25% with a standard error of the mean of 0.25% (range: 0.00 – 23.33%).

The different clusters correspond to distinct numerical levels of disease incidences (Table 2, Fig. 3) as well as of plant mortality (Table 2). These variables were not involved in the determination of clusters. The mean incidence of Eutypa dieback (15.5%) is extremely high in cluster 1 (Fig. 3), average in cluster 2 (3.1%), and low in clusters 3, 4, 5, and 6 (0.8, 0.8, 1.5, and 1.0%, respectively). Mean Esca incidences differed less among clusters (Fig. 3), with large variances, being highest in clusters 3 and 6 (3.8 and 4.0%, respectively), medium in clusters 1 and 2 (3.1% in both), and lower in clusters 4 and 5 (1.6 and 1.9%, respectively). ANOVAs on disease incidence values amongst clusters yielded F values of 72.2 ($P < 0.001$) and 2.26 ($P = 0.049$) for Eutypa dieback and Esca, respectively (df = 5 and 255), and MANOVA on the (Euty and Esca) vector of disease responses yielded a Wilks' Lambda value of 0.413, with an F statistic of 177 (2,249 degrees of freedom, $P < 0.001$). These analyses led to a rejection of the null hypothesis of random variation of each disease considered individually, and their combination, across the crop management clusters.

Correspondence analysis: analytical framework. Correspondence analysis first involved Euty, Esca, Mort, and age as (categorized) active variables, i.e., variables that defined axes. The inertias accounted for by individual axes were relatively small, 19.1, 16.0, 13.5, 11.8, and 10.3% for the first five axes, corresponding to singular values of 0.66, 0.60, 0.55, 0.51, and 0.48, respectively. Such small inertias accounted for by individual axes reflect the multiple correspondence procedure, which involves a Burt table (6,12). The accumulated reciprocal contributions to axes 1 and 2 of the various categorized levels however ranged from 32 to 56%, from 9 to 50%, from 35 to 68%, and from 18 to 37% for the Euty, Esca, Mort, and age variable-classes, respectively (Table 3). Examination of axes 1 and 2 therefore addresses an important share of the available information.

Table 3 indicates that axis 1 summarizes contrasts between Euty1 and Euty2, between Esca1 and Esca2, and between Mort1

and Mort2 (large contributions to axes with differences in sign as shown by their coordinates). Axis 1 also contrasts age3 (large contribution to axis 1; positive coordinate) with age1 and age2 (comparatively smaller contribution to axis 1; negative coordi-

nate). On the other hand, axis 2 contrasts Eutypa dieback, Mort0 and the two other levels of mortality, and a gradient of increasing age, from young (age0, with a positive coordinate and a large contribution to axis), to

Fig. 2. Ascending hierarchical cluster analysis of agronomic, management, and cultivar variables. The analysis involves a Euclidean distance and a Ward criterion on variables Age, Ars, CEP, PRUN, PREPRUN, RES (Table 1). The distribution of different grape growing regions among different clusters is indicated for six clusters.

medium-young (age1, smaller, positive coordinate), to medium-old (age2, smaller and negative coordinate), and old (age3, still smaller and negative coordinate).

Figure 4 provides a graphical display of relationships documented in Table 3. Interpretation of correspondence analysis graphs is based on proximity among class-variables, variable linkages being strongest when positioned away from the origin of the axes and close to one another (2,6,12). When a series of classes representing successive levels of a categorized quantitative variable (or successive levels of an ordinal one) is considered, a path of increasing levels can be drawn, and the movement along this path may be examined in relation to positions of other class-variables, paths, and axes (17). Figure 4 shows the relationships among axis-determining variables (Euty-i, Esca-j, Mort-k, and age-l), that is, it accounts for the upper part of Table 3. A path of increasing age is indicated, which first (vertically) follows axis 2 (in the negative direction), departs, and continues in the direction of axis 1 in the positive direction. This path may be seen as the overall age trend of the sample of surveyed vineyards. Two paths of disease increase are drawn for Esca decline and Eutypa dieback, which may conventionally be described in terms of disease appearance (levels 0 – 1) and intensification (levels 1 – 2; [17]). The paths of increasing Esca decline and Eutypa dieback are initially oriented in the same overall (vertical) direction along axis 2; but their courses differ along axis 1, with Esca2 graphically close to age1, while Euty2 is close to age2. Overall, therefore, both paths for Esca decline and Eutypa dieback are similarly associated in their appearance phase (0 – 1) with increasing grapevine age, however intensification (1 – 2) of Esca decline is opposite to increasing age of vineyards (Esca2 is positioned closely to age1), while that of Eutypa dieback only partly correlates with increasing age (and Euty2 is close to age2). A fourth path (not shown in Fig. 4) is that of vine mortality, which increases with increasing age (along axis 2) until Mort1, and changes course abruptly, the highest levels of mortality (Mort2) being located half-way between the maximum levels of Esca decline and Eutypa dieback, and away from the maximum age level (age3).

Correspondence analysis: projection of additional variables. The framework age - Euty - Esca - Mort is used in Figure 5A to D to analyze additional variables, vine-growing region

(VGR), cultivar (CEP), sodium arsenite use (ars), and residue management (RES). Strong differences among provinces are apparent in Figure 5A, where, for instance, PCH is strongly associated with high Eutypa, and also with high mortality and Esca, while JUR is strongly associated with high Esca, and also with high mortality, but with all possible levels of Eutypa (and Euty0, in particular), and BRG corresponds to moderate levels of the two diseases and mortality, while being associated with the oldest vines. Similarly, the framework maps out strong differences among vine varieties, UB, CIN, and AUX being closest to highest Eutypa levels (and mortality), while PLS corresponds to highest levels of Esca (and, by projection on axis 1, of mortality too). In contrast, MER corresponds to the lowest levels of both diseases, and of mortality; the rest of the varieties occupy intermediate positions. Figure 4C does not suggest any specific pattern of relationships between the four levels of sodium arsenite use and the variables involved in the analytical framework: any level of chemical use, being close to the origin of axes, is as close to, or distant from, the active variables, including Esca. Figure 4D

Fig. 3. Mean incidences of Eutypa dieback and Esca decline, and standard error of the mean of incidences for six clusters determined from an ascending hierarchical cluster analysis. Incidences are indicated as disease proportions.

TABLE 2. Description of clusters generated by a hierarchical cluster analysis of agronomic, management, and cultivar variables from the National Grapevine Trunk Disease Survey

Variable	Cluster ^a																	
	Cluster 1 (N ^b = 18)			Cluster 2 (N = 32)			Cluster 3 (N = 99)			Cluster 4 (N = 32)			Cluster 5 (N = 23)			Cluster 6 (N = 52)		
	Mean (SEM)	Median	Mode	Mean (SEM)	Median	Mode	Mean (SEM)	Median	Mode	Mean (SEM)	Median	Mode	Mean (SEM)	Median	Mode	Mean (SEM)	Median	Mode
Ars ^c	0.89 (0.21)	1	–	1.59 (0.16)	1	–	0.00 (0.00)	0.00	–	1.47 (0.12)	1	–	0.00 (0.00)	0	–	0.00	0	–
Age ^c	30.8 (1.6)	33.0	–	24.2 (1.9)	21.5	–	26.2 (1.3)	23.0	–	26.2 (1.8)	25.0	–	33.7 (3.1)	32.0	–	22.2 (1.3)	21.6	–
PRUN ^c	–	–	GUY	–	–	GUY	–	–	GUY	–	–	GUY	–	–	GUY	–	–	GUY
PREPRUN ^c	–	–	pret0	–	–	pret0	–	–	pret0	–	–	pret1	–	–	pret1	–	–	pret1
RES ^c	–	–	GRI	–	–	GRI	–	–	GRI	–	–	GRI	–	–	BUR	–	–	GRI
CEP ^c	–	–	UB	–	–	SAU	–	–	AUX	–	–	CHD, MEL, PDL	–	–	PIN	–	–	GWZ
VGR	–	–	PCH	–	–	CEN	–	–	ALS	–	–	PDL	–	–	BRG	–	–	JUR
Euty	0.155 (0.021)	0.163	–	0.031 (0.008)	0.006	–	0.008 (0.003)	0.001	–	0.008 (0.006)	0.002	–	0.015 (0.007)	0.012	–	0.010 (0.004)	0.002	–
Esca	0.031 (0.006)	0.023	–	0.031 (0.008)	0.013	–	0.038 (0.004)	0.031	–	0.016 (0.007)	0.006	–	0.019 (0.008)	0.005	–	0.040 (0.006)	0.032	–
Mort	0.045 (0.019)	0.013	–	0.058 (0.011)	0.041	–	0.059 (0.007)	0.036	–	0.084 (0.014)	0.058	–	0.071 (0.016)	0.045	–	0.057 (0.085)	0.057	–

^a Clusters were derived from an ascending hierarchical cluster analysis of agronomic, management, and cultivar variables with a Euclidean distance and a Ward criterion on variables Age, Ars, CEP, PRUN, PREPRUN, RES (Fig. 2).

^b N, number of fields per cluster.

^c Variable involved in the definition of clusters.

TABLE 3. Multiple correspondence analysis of relationships among incidence levels of two grapevine trunk diseases, grapevine mortality, and age of grapevine stands, and with a few agronomic and geographical variables

Variable ^a	Classes ^a	Relative weight	Axis 1 ^b			Axis 2 ^b		
			Contribution		Coordinate	Contribution		Coordinate
			To axis	Reciprocal		To axis	Reciprocal	
Euty	Euty0	0.085	0.003	0.009	-0.131	0.253	0.552	1.035
	Euty1	0.103	0.066	0.192	0.525	0.050	0.123	-0.420
	Euty2	0.062	0.068	0.156	-0.687	0.090	0.172	-0.720
Esca	Esca1	0.139	0.079	0.306	0.493	0.028	0.092	-0.271
	Esca2	0.098	0.158	0.446	-0.833	0.021	0.049	0.277
	Esca0	0.012	0.029	0.053	0.992	0.024	0.037	0.826
Mort	Mort1	0.010	0.109	0.313	0.686	0.014	0.034	-0.227
	Mort2	0.121	0.198	0.657	-0.840	0.007	0.018	-0.140
	Mort0	0.030	0.084	0.164	1.105	0.147	0.240	1.335
Age	age3	0.026	0.141	0.270	1.537	0.065	0.103	-0.950
	age2	0.094	0.015	0.042	-0.264	0.088	0.204	-0.582
	age1	0.107	0.022	0.065	-0.296	0.044	0.111	0.386
	age0	0.024	0.028	0.053	0.713	0.168	0.267	1.595
Region	ALS	—	—	0.005	-0.114	—	0.005	0.115
	AQT	—	—	0.001	0.113	—	0.013	0.485
	BJL	—	—	0.006	0.704	—	0.008	-0.818
	BRG	—	—	0.098	0.693	—	0.034	-0.409
	CEN	—	—	0.004	0.182	—	0.015	-0.368
	DIO	—	—	0.028	0.620	—	0.002	-0.183
	JUR	—	—	0.061	-0.560	—	0.052	0.518
	LRO	—	—	0.001	-0.225	—	0.000	0.018
	PAC	—	—	0.000	-0.049	—	0.003	0.242
	PCH	—	—	0.068	-0.971	—	0.056	-0.883
	PDL	—	—	0.000	-0.014	—	0.028	0.749
CEP	GWZ	—	—	0.002	-0.151	—	0.014	0.375
	RIS	—	—	0.001	0.091	—	0.023	0.522
	AUX	—	—	0.006	-0.254	—	0.025	-0.497
	MER	—	—	0.013	0.887	—	0.015	0.973
	CBS	—	—	0.010	-0.644	—	0.002	-0.285
	SAU	—	—	0.025	-0.474	—	0.001	-0.114
	GAM	—	—	0.006	0.704	—	0.008	-0.818
	CHD	—	—	0.035	0.639	—	0.005	-0.243
	PIN	—	—	0.123	1.307	—	0.028	-0.622
	CBF	—	—	0.035	0.880	—	0.004	-0.313
	CHE	—	—	0.000	0.014	—	0.001	-0.278
	MPG	—	—	0.031	0.639	—	0.000	-0.034
	SAV	—	—	0.041	-0.709	—	0.050	0.782
	TRS	—	—	0.002	-0.182	—	0.001	0.155
	PLS	—	—	0.023	-0.790	—	0.009	0.487
	SYR	—	—	0.001	-0.225	—	0.000	0.018
	MDH	—	—	0.000	0.131	—	0.001	0.228
	CAR	—	—	0.001	0.347	—	0.000	-0.126
	GRE	—	—	0.003	0.578	—	0.000	0.116
	CIN	—	—	0.003	-0.821	—	0.001	-0.602
	UB	—	—	0.068	-0.971	—	0.056	-0.883
	MEL	—	—	0.000	-0.009	—	0.035	0.924
Ars	ars0	—	—	0.006	-0.049	—	0.020	0.089
	ars2	—	—	0.000	0.069	—	0.000	-0.015
	ars1	—	—	0.009	0.220	—	0.036	-0.430
	ars3	—	—	0.001	-0.163	—	0.001	0.190
Rootstock	SO4	—	—	0.000	-0.011	—	0.014	-0.146
	161-49	—	—	0.000	0.012	—	0.001	-0.088
	3309C	—	—	0.002	0.057	—	0.014	0.144
	41B	—	—	0.013	-0.446	—	0.002	-0.195
	101-14	—	—	0.000	0.008	—	0.001	-0.198
	R110	—	—	0.001	0.162	—	0.013	0.533
PREPRUN	pret1	—	—	0.009	0.105	—	0.002	-0.047
	pret0	—	—	0.009	-0.085	—	0.002	0.038
RES	grinding	—	—	0.076	-0.154	—	0.009	0.052
	removal	—	—	0.003	0.223	—	0.002	0.202
	burning	—	—	0.074	0.570	—	0.017	-0.270
PRUN	guyot	—	—	0.003	0.015	—	0.000	0.004
	gobelet	—	—	0.004	0.493	—	0.003	-0.416
	cordon de royat	—	—	0.009	-0.384	—	0.000	0.058

^a Table 1 provides variable symbols and categories.

^b The procedure used is a multiple correspondence analysis, and thus, a Burt table. Several more axes were generated, with decreasing singular (lambda) values. Only axes 1 and 2 are shown here.

Fig. 4. Multiple correspondence analysis of incidences of trunk diseases (Esca decline, Esca, and Eutypa dieback, Euty), grape age (Age), and grape mortality rate (Mort). Variations in the levels of each variable are indicated as paths from one level to the next.

displays the three categories of residue management in positions that are relatively close to the origin of axes. BUR (residue burning) however appears to be furthest away from the origin, and closer to medium levels of diseases and mortality, as well as older ages.

Logistic regressions: relationships for disease appearance and mortality. Logistic regressions performed on the appearance of Eutypa dieback yielded the selection of a model with only age as an independent variable (Table 4, equation 1). This model leads to an overall satisfactory description of the variation of Eutypa dieback ($G = 26.8$, $P < 0.001$), and indicates that the probability of Eutypa dieback to occur increases with vineyard age. Sodium arsenite levels were not significant ($P < 0.10$) in the other models tested for Eutypa appearance, either as treatments alone, or in combination with vineyard age. On the other hand, all models tested for Esca decline led to poorer descriptions of the variation of Esca appearance. The model retained (Table 4, equation 2) is the one which yielded the smallest probability ($P = 0.19$) associated with the G test. This model indicates a link between the probability of Esca decline occurrence and arsenite treatment levels (some of them contributing more to the odds of disease appearance). Age was not associated with a significant probability of Esca decline occurrence in any of the models tested. These two selected models (Table 4, equations 1 and 2) indicate the overall stronger effect of age and sodium arsenite on the odds of appearance of Esca dieback and Eutypa decline, respectively. They indicate quite different behaviors in the probability of the two

Fig. 5. Multiple correspondence analysis of disease incidences (Esca decline and Eutypa dieback), grape age and mortality, with vine growing regions (VGR, **A**), grape cultivars (CEP, **B**), arsenite use (Ars, **C**), and crop residue management (RES, **D**). **A to D**, Additional variables are projected onto the background of axes and patterns generated by active variables (Esca, Eutypa, Age, Mort; Table 3 and Fig. 4). Paths of active variables (Fig. 4) are indicated in **A**.

diseases occurring, as well as greater difficulty in satisfactorily describing the appearance of Esca decline than Eutypa decline using age and sodium arsenite as predictors.

Two models (Table 4, equations 3 and 4) were retained when considering mortality within vineyards. The first one (Table 4, equations 3), involving Esca incidence and vineyard age, provides a fair ($G = 53.5$, $P < 0.001$) description of grapevine mortality. The second model (Table 4, equation 4) involves both diseases, with a parameter associated with Esca decline (240.43) smaller than that associated with Eutypa dieback (411.14). This model also describes variation in mortality well, with G and P values similar to those obtained in the third model. Arsenite treatments never contributed significantly to the different models tested for mortality.

DISCUSSION

This analysis provides an overview of vineyards' health in France, from the standpoint of wood diseases. Two main diseases were distinguished, Eutypa dieback and Esca decline. No attempt was made here to distinguish the many different, and variable, symptoms Esca decline is associated with (8,11,14,19). This is because there are reasons to believe these many symptoms to be related (14) (P. Lecomte, *personal communication*), and also because the transition from one symptom to another may be so progressive that field observers did not attempt to assess them separately. This study therefore focuses on one typical wood disease caused by a well-known fungus, and a syndrome whose development is not yet fully understood (8,11,14,19). It may be interesting to note that, while Eutypa dieback is a relative newcomer amongst the many pathogens of grapevine in France (5), Esca decline is an ancient malady (14), which may have existed in French vineyards since they were cultivated.

Cluster analysis on grapevine crop management practices amongst French provinces indicates common patterns (clusters, Fig. 2), shared among many provinces (clusters 2, 3, and 4 involve individuals from 9 out of the 11 provinces considered in the study). There is therefore a large fraction of shared practices among different provinces, together with a fraction of practices (clusters) that are closely linked to particular provinces. In this analysis, provincial specificity is mostly attributable to cultivars (Table 2).

Overall, the mean incidences of the two diseases are of the same order of magnitude, 2.23 ± 0.30 and $3.25 \pm 0.25\%$ for Eutypa dieback and Esca decline, respectively. The two diseases are not distributed similarly among clusters of crop management, however: while there are wide variations in Eutypa dieback

among clusters, this is not so with Esca decline. The very high level of Eutypa dieback in cluster 1 (Fig. 3) may be associated with the grapevine cultivar that dominates this cluster, although other factors, which were not included in this analysis, should also be considered. In spite of statistically significant ($P < 0.05$) differences among clusters, the numerical variation in mean Esca decline incidence among clusters is small. This suggests a fairly homogeneous, widespread, distribution of the disease in France.

Cluster analysis and MANOVA lead to overall conclusions that are similar in the case of grapevine in France as in other crops, such as peanut in West Africa, coffee in Central America, rice in tropical Asia, or wheat in France: syndromes of multiple diseases reflect syndromes of crop management (18). Very few crop management variables however were involved in this analysis. Additional variables might allow a clearer analysis of the importance of cultivars on Eutypa dieback, and the possible variation crop management practices could impose on Esca decline.

Multiple correspondence analysis (Table 3, Figs. 4 and 5) allows the nonlinearity of relationships among variables to be analyzed. It highlights the similarity and the differences in the appearance-intensification processes of the two diseases. Significantly, the highest levels of Eutypa dieback are associated with medium-old (age2) grapevines, whereas the highest levels of Esca decline are associated with medium-young (age1) grapevines. This analysis concurs with former, preliminary analyses (8), with respect to the distribution of the two diseases among French provinces, as well as their levels in various cultivars. This multiple correspondence analysis however fails to indicate strong management (e.g., sodium arsenite use or residue management) relationships with disease incidences and plant mortality. Although multiple correspondence, being based on a Burt table, yields more robust results (6,12), one of its drawbacks is the large number of axes it generates that do not differ much in the inertia they account for. Consideration of axis 3 (13.5% of total inertia, not shown) would show not a departure, but an opposition of the intensification paths of Esca decline and Eutypa dieback. This third axis may explain why, for instance, the first two axes of multiple correspondence analysis did not show relationships between Eutypa decline and sodium arsenite use.

One very important advantage of (multiple) correspondence analysis is that this type of method, in addition of not assuming any particular shape of relationships among variables, is based on contingency tables, enabling simple and flexible tests. For instance, one hypothesis test was whether sodium arsenite use (ars1-2-3) or nonuse (ars0) was distributed independently from high levels (Esca2), or low levels (Esca0-1), of Esca decline. The

TABLE 4. Summaries of binary logistic regression models of the appearance of grapevine wood diseases (Eutypa dieback and Esca decline) in relation with grapevine age and sodium arsenite treatments, and of grapevine mortality in relation with grapevine age, sodium arsenite treatments, Eutypa dieback, and Esca decline

Equation	Dependent variable ^a	Independent variables considered ^a	Independent variables retained ^a	Parameters	SE ^b	Pparm ^c	G ^d	Pslope ^e	% Concordant	Somers' D
1	Logit(P(Euty)>0)	Age, ars1, ars2, ars3	Constant	-1.17	0.40	0.004	26.8	<0.001	68.3	0.39
2	Logit(P(Esca)>0)	Age, ars1, ars2, ars3	Constant	0.07	0.02	<0.001	6.13	0.19	45.4	0.30
3	Logit(P(Mort)>0.03)	Euty, Esca, Age, ars1, ars2, ars3	Constant	3.38	0.42	<0.001	53.5	<0.001	96.4	0.93
4	Logit(P(Mort)>0.03)	Euty, Esca, Age, ars1, ars2, ars3	Esca	-1.13	0.67	0.09	48.3	<0.001	94.6	0.90
			ars3	-2.00	0.89	0.03				
			Constant	-2.87	1.08	0.008				
			Esca	246.47	94.98	0.004				
			Age	0.16	0.05	0.001				
			Constant	-0.08	0.50	0.87				
			Euty	411.14	186.00	0.027				
			Esca	240.43	90.35	0.008				

^a Age: age of vineyard; ars1: i treatments with arsenite; Esca: incidence of Esca decline; Euty: incidence of Eutypa decline; Mort: mortality.

^b Standard error of parameter.

^c Pparm: P value testing the null hypothesis that the parameter equals zero.

^d G: statistic to test the null hypothesis that all slopes equal zero (Minitab 15, 2006, State College, PA).

^e Pslope: P value associated with the G test.

resulting contingency table led to a chi-square value of 18.9, and rejection ($P < 0.0005$, 1 df) of the hypothesis of independence. Similarly, the occurrence of high mortality (Mort2) versus low (Mort0-1) was tested against arsenite use (ars0 versus ars 1-2-3). The chi-square value in that case was 2.12, leading to the non-rejection ($P > 0.10$, 1 df) of the hypothesis of independence. Additional specific tests thus suggest that intensification of field symptoms of Esca decline is not independent from arsenite use, but that sodium arsenite use is not related with high mortality levels.

Logistic regressions have been recently used to analyze relationships between disease prevalence and predictors (e.g., weather, cropping practices [4,13]). Although results obtained from logistic regressions can be interpreted in a probabilistic way and used to develop tools to predict the probability of disease from observations of indicator variables, the technique was used here in a more descriptive way, to address complex relationships between disease occurrence, cropping practices, crop features (such as age), and mortality.

The different statistical approaches used here are complementary, providing different ways to describe relationships between the different variables (quantitative and qualitative) addressed. As such, the identification of the three logistic models tested was largely based on the results obtained from multivariate analyses, which provided a first description of associations among variables. In turn, results from the logistic regressions provided a way to test more specific hypotheses that could not be tested with, for example, cluster analyses. One output from these combined analyses is the characterization of the effects of sodium arsenite treatments. Results (Table 4) indicate that Eutypa levels are independent from these treatments; that lower levels of field symptoms of Esca decline are in some way associated with arsenite use; and that plant mortality is independent from these treatments. This can be interpreted as follows: treatments with sodium arsenite had some effect in reducing Esca symptoms, but not on reducing plant mortality, which is in turn strongly linked with Esca. In other words, sodium arsenite treatments would affect Esca symptoms, but not the impact of the disease on mortality.

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