Short-term relationships between climate and grapevine trunk diseases in southern French vineyards

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Abstract

An increasing plant dieback has been observed in vineyards these past two decades. Grapevine trunk diseases, mainly esca and Botryosphaeria dieback, are increasingly affecting grapevine mortality and yield loss, but little is known about the effects of climate, hampering our ability to predict future trends in grapevine dieback. Our aim was to test short-term relationships between climate and the incidence of grapevine trunk disease in southern France vineyards. We harmonized and compiled summer surveys of leaf symptom occurrence in a database gathering 50 vineyards, with different plant ages, varieties, soil and climatic conditions. Surveys were conducted during the period 2003-2021, leading to 69 site-by-year plots. Climate data were compiled from Safran daily data of Météo-France and averaged on different time steps to address the temporal window of climate effects. We built a model ensemble to identify the main climatic drivers of esca incidence on a weekly basis. Models indicated an interaction effect of temperature and soil moisture of the last two months preceding symptom expression. The higher the plant transpiration (moist and warm climate), the higher the incidence of new weekly cases. Our results suggest that fungi associated with grapevine trunk diseases benefit from warm conditions but are inhibited by dry conditions, both of which are expected to increase in the near future. Our findings provide important insights to better understand plant-climate-diseases relationships in the field and anticipate trends for the next decades.

Introduction

The pressure of plant pathogens is expected to increase in temperate crops under climate change (Chaloner, Gurr, & Bebber, 2021). Biological processes of pathogen fungi among growth, reproduction, and dispersal lies within a range of suitable temperature and moisture conditions (Schmidt, 2006). Considering both temperature and moisture, increasing drought frequency and intensity with climate change may counterbalance the favourable effects of warming on temperate pathogens, as shown in forest tree fungi (Desprez-Loustau et al., 2007). Therefore, anticipating climate change impacts on crop diseases needs a comprehensive understanding of the relationships between climate and pathogen fungi.

In grapevine, trunk diseases are increasingly affecting vineyard sustainability worldwide through decreasing yield and plant dieback (Guerin-Dubrana, Fontaine, & Mugnai, 2019; Mondello et al., 2018). Esca and Botryosphaeria dieback are the main grapevine trunk diseases reported on adult plants (Bertsch et al., 2013), promoting longitudinal stripe lesions on the trunk and tiger-stripe symptoms on leaves (Lecomte et al., 2012; Mugnai, Graniti, & Surico, 1999). Both are considered as the same disease complex, esca symptoms on leaves succeeding the ones of Botryosphaeria dieback during the summer season (hereafter called "esca" for both, *sensu* Lecomte et al., 2012). Esca leaf symptoms are associated to hydraulic dysfunctions in grapevine leaves and perennial organs by the presence of plant-derived tyloses (Bortolami et al., 2019; 2021a,b), and involve a cortege of wood-inhabiting fungi among *Phaeomoniella chlamydospora*, *Phaeoacremonium minimum*, *Fomitiporia mediterranea*, and Botryosphaeriaceae *sp.* (Bertsch et al., 2013; Larignon & Dubos, 1997).

The incidence of esca leaf symptoms vary among vineyards with high year-to-year variability, underlying the environmental variance of the disease (Andreini, Cardelli, Bartolini, Scalabrelli, & Viti, 2014; Fischer &

Peighami-Ashnaei, 2019). However, little is known about the role of climate in the biology of associated fungi and furthermore in the disease incidence. Here, we aimed to test the relationships between climate and esca leaf symptoms in vineyards of southern France. We hypothesized that climate drives temporal variation in esca incidence by defining to what extent grapevine wood-inhabiting fungi and plant physiology are close or far from their optimal ranges for temperature and moisture. We harmonized and compile a database of 50 vineyards reporting the incidence of esca leaf symptoms on a weekly basis throughout the summer season, and build a model ensemble to identify the main climatic drivers and their interactions.

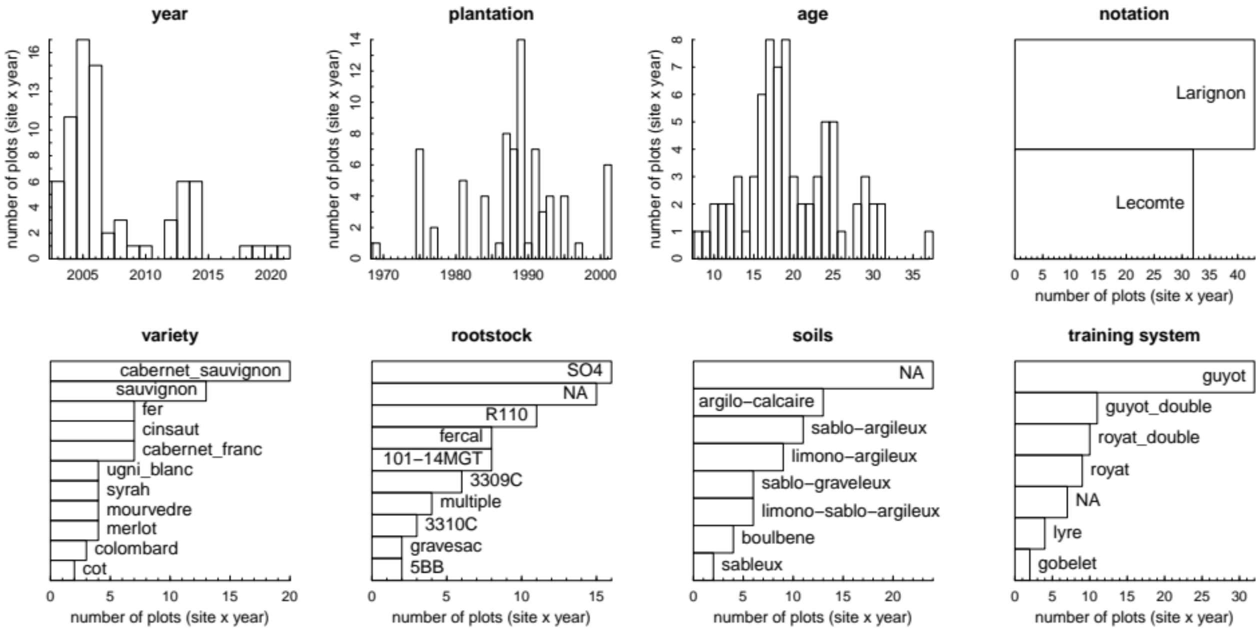

Figure 1. Site description for the monitoring of esca leaf symptoms across 50 southern France vineyards during the period 2003-2021. The number of plots (couple vineyard-year) is described along the year of surveys, year of plantation, plant age, notation network, plant variety, rootstock, soils, and training system.

Materials and methods

Esca database

We gathered occurrence data of esca leaf symptoms across 50 southern France vineyards during the period 2003-2021. Two observation networks leaded by Pascal Lecomte and Philippe Larignon were harmonized and compiled in a single database including vineyards with different plantation years (1969 to 2001), plant ages (8 to 37 years old plants at observation dates), grapevine varieties (n = 11), rootstocks, soils, and training systems (Fig. 1). Environmental conditions range from oceanic climate in the south-west to Mediterranean climate in the south-east of France.

For each of the 69 plots (vineyard-year couples), esca incidence at observation dates was computed by the number of vines newly expressing leaf symptoms over the total number of vines at the origin of the plantation (dead, missing, and alive). Observations were conducted over the summer season (june-september) with different time intervals between surveys (1 to 49 days ; mean = 6.4 days). To standardize data at a weekly scale, we first used non-parametric polynomial regression (Loess) models to fit the cumulative esca incidence against time (days of year) at each plot and then infer esca incidence values at common dates across all plots. Only data in the period mid-june to end-of-august was considered, information outside this period being very scarce among plots. We also set inferred incidences to no data if the number of days between two consecutive surveys (observations) exceeded 10 days, to avoid smoothing esca – climate relationships. Finally, the esca database includes 900 weekly incidence values across plots.

Model ensemble

Relationships between climate variables and weekly esca incidences were tested using a model ensemble approach consisting of N parsimonious mixed-effect linear models (eqn. 1). Esca weekly incidences (I_w) were root-squared transformed before regressing against climate variables (fixed effects). To consider the changing probability of symptoms occurrence along time for each vineyard-year couple (k), we used a quadratic function of the day of year as a fixed-effect covariable (doy). The site (vineyard) was included as a random-effect covariable, as were the plant age and the variety.

$$I_{wk}^{1/2} = \alpha_0 + \alpha_1\, doy_w + \alpha_2\, doy_w^{2} + \alpha_{3:n}\, X_{wk} + 1|site_k + 1|age_k + 1|variety_k + \varepsilon \qquad (1)$$

To identify the climatic factors (including main and interacting effects: X_w) of weekly variation in esca incidence, we used a model selection procedure in two steps:

- Firstly, we evaluated each climatic variable and each time lag in a model with or without a quadratic term, and compared them to a null model (with no climatic variable) using the second-order Akaike information criterion (AICc). We selected the (9 maximum) climatic variables and their associated best time lag (between 7 and 120 days) giving models with the lowest AICc, to set a pool of candidate variables in the second step procedure.
- Secondly, we tested all combinations of climatic variables to build a set of competitive models that will constitute the 'model ensemble', following Fréjaville et al. (2020). Starting from a saturated model form (pool of candidate climatic variables), we created the fully crossed set of models including from two to five climatic terms per model (among linear, quadratic, and interaction terms). We removed models showing high collinearity between climatic variables (Pearson coefficient $r \geq 0.80$), convex quadratic functions, non-significant coefficients for climatic terms (p-value > 0.05) and AICc higher than the null model. The N remaining parsimonious models were used to build the model ensemble, further used to average the effects of selected climatic variables and their interaction on weekly incidences. Models were fitted using the lmer function of the lme4 R package (Bates, Mächler, Bolker, & Walker, 2014).

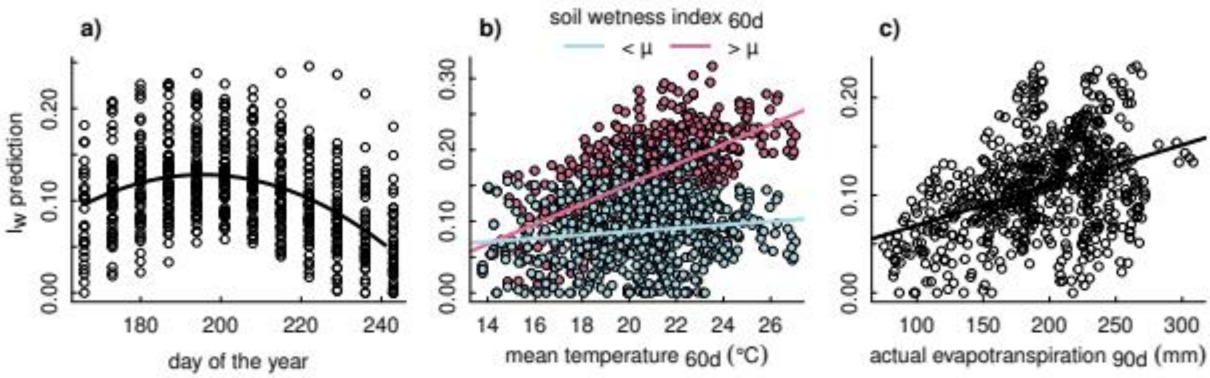

Figure 2. Relationships between weekly esca incidence (I_w), time, and the main climatic factors predicted by the model ensemble. Predicted values are average predictions by all models constituting the model ensemble. The day of the year was included as covariable in all models. The main climatic factors are the mean temperature of the last two months (60d), the soil wetness index of the last two months (60d) and the actual evapotranspiration of the last three months (90d).

Results and discussion

Our modelling approach retained 213 parsimonious mixed-effect models constituting the model ensemble. The explained variance of weekly esca incidence by climate and the day of year (fixed effects) ranged from 20% to 41%. Adding the site, age, and variety random effects, explained variance ranged from 57% to 83%. These results showed that climate explained a substantial part of esca incidence in southern France vineyards, and that cultural factors and other environmental conditions may explained another substantial part. The model ensemble indicated that mean temperature, soil wetness index, and actual evapotranspiration best explained the climate effect on weekly esca incidences (Fig. 2). The strongest effects of these variables arose with a time lag of 60 days for mean temperature and soil wetness index, and 90 days for actual evapotranspiration. These results showed that variation of esca incidence among weeks depended on the last 2/3 months of climatic conditions that preceded leaf symptom expression. In other words, short-term conditions (≤ 30 days) less explained symptom expression among weeks.
The model ensemble showed that weekly esca incidence peaked around mid-july on average in southern France vineyards (Fig. 2a), as found by Lecomte et al. (2020). We found a positive effect of mean temperature, soil wetness index and their interaction (Fig. 2b). Taking all together, esca incidence increased with temperature of

the last two months in high soil moisture conditions (red points in Fig. 2b), whereas low soil moisture inhibited the positive effect of temperature (blue points in Fig. 2b). Moreover, esca incidence increased with increasing actual evapotranspiration of the last three months (Fig. 2c) ; low evaporative conditions inhibiting symptom expression.

These results indicated that productive conditions for both plants (high transpiration) and fungi (warm and moist climate) increased the weekly incidence of esca in southern France vineyards. This corroborated findings in Italian vineyards where precipitation increased annual esca incidence while high temperature in summer (warm-dry conditions) reduced symptom expression (Calzarano, Fabio, Baranek, & Di Marco, 2018). Similarly, under controlled conditions, Bortolami et al. (2021b) found that grapevine under drought do not express esca leaf symptoms. Hence, the fate of grapevine trunk diseases in response to a warming climate would largely depend on moisture conditions, that would limit their incidences, particularly for esca disease, if drier conditions prevail in the near future.

Conclusion

We aimed to test *in situ* relationships between esca incidence and climate, in addition to other factors of variation as time, plant age, and variety. Our modelling approach provided important findings to understand the climatic variation of esca among weeks and vineyards. We found that the positive interaction between air temperature and soil moisture chiefly drove the incidence variation of esca leaf symptoms. Warm and moist conditions during at least two months increased the weekly incidence of esca in parallel to the plant evapotranspiration. But whether the underlying factor is plant transpiration or fungal activity, or both, needs further exploration. Our study suggests that drier conditions with climate change may limit the increasing effect of warming on the incidence of grapevine trunk diseases.

References

Andreini, L., Cardelli, R., Bartolini, S., Scalabrelli, G., & Viti, R. (2014). Esca symptoms appearance in *Vitis vinifera* L. : Influence of climate, pedo-climatic conditions and rootstock/cultivar combination. *Vitis 53(1)*, 33-38. https://doi.org/10.5073/vitis.2014.53.33-38

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv preprint arXiv:1406.5823*.

Bertsch, C., Ramírez-Suero, M., Magnin-Robert, M., Larignon, P., Chong, J., Abou-Mansour, E., … Fontaine, F. (2013). Grapevine trunk diseases : Complex and still poorly understood. *Plant Pathology*, *62*(2), 243-265. https://doi.org/10.1111/j.1365-3059.2012.02674.x

Bortolami, G., Gambetta, G.A., Delzon, S., Lamarque, L.J., Pouzoulet, J., Badel, E., … Delmas, C. E. L. (2019). Exploring the hydraulic failure hypothesis of esca leaf symptom formation. *Plant physiology*, 181(3), 1163-1174. https://doi.org/10.1104/pp.19.00591

Bortolami, G., Farolfi, E., Badel, E., Burlett, R., Cochard, H., Ferrer, N., … Delmas, C. E. L. (2021a). Seasonal and long-term consequences of esca grapevine disease on stem xylem integrity. *Journal of Experimental Botany*, 72(10), 914-3928. https://doi.org/10.1093/jxb/erab117

Bortolami, G., Gambetta, G. A., Cassan, C., Dayer, S., Farolfi, E., Ferrer, N., … Delmas, C. E. L. (2021b). Grapevines under drought do not express esca leaf symptoms. *Proceedings of the National Academy of Sciences*, *118*(43). https://doi.org/10.1073/pnas.2112825118

Calzarano, F., Fabio, O., Baranek, M., & Di Marco, S. (2018). Rainfall and temperature influence expression of foliar symptoms of grapevine leaf stripe disease (esca complex) in vineyards. *Phytopathologia Mediterranea*, *57*(3), 488-505. https://doi.org/10.14601/Phytopathol_Mediterr-23787

Chaloner, T. M., Gurr, S. J., & Bebber, D. P. (2021). Plant pathogen infection risk tracks global crop yields under climate change. *Nature Climate Change*, *11*(8), 710-715. https://doi.org/10.1038/s41558-021-01104-8

Desprez-Loustau, M.-L., Robin, C., Reynaud, G., Déqué, M., Badeau, V., Piou, D., … Marçais, B. (2007). Simulating the effects of a climate-change scenario on the geographical range and activity of forest-pathogenic fungi. *Canadian Journal of Plant Pathology*, *29*(2), 101-120. https://doi.org/10.1080/07060660709507447

Fischer, M., & Peighami-Ashnaei, S. (2019). Grapevine, esca complex, and environment : The disease triangle. *Phytopathologia Mediterranea*, *58*(1), 17-37. https://doi.org/ 10.13128/Phytopathol_Mediterr-25086

Fréjaville, T., Vizcaíno-Palomar, N., Fady, B., Kremer, A., & Garzón, M. B. (2020). Range margin populations show high climate adaptation lags in European trees. *Global Change Biology*, *26*(2), 484-495. https://doi.org/10.1111/gcb.14881

Guerin-Dubrana, L., Fontaine, F., & Mugnai, L. (2019). Grapevine trunk disease in European and Mediterranean vineyards : Occurrence, distribution and associated disease-affecting cultural factors. *Phytopathologia Mediterranea*, *58*(1), 49-71. https://doi.org/10.14601/Phytopathol_Mediterr-25153

Larignon, P., & Dubos, B. (1997). Fungi associated with esca disease in grapevine. *European Journal of Plant Pathology*, *103*(2), 147-157. https://doi.org/10.1023/A:1008638409410

Lecomte, P., Darrieutort, G., Liminana, J.-M., Comont, G., Muruamendiaraz, A., Legorburu, F.-J., … Fermaud, M. (2012). New insights into esca of grapevine : The development of foliar symptoms and their association with xylem discoloration. *Plant Disease*, *96*(7), 924-934. https://doi.org/10.1094/PDIS-09-11-0776-RE

Mondello, V., Larignon, P., Armengol Fortí, J., Kortekamp, A., Váczy, K. Z., Prezman, F., … Fontaine, F. (2018). Management of grapevine trunk diseases : Knowledge transfer, current strategies and innovative strategies adopted in Europe. *Phytopathologia Mediterranea*, *57*(3), 369-383. https://doi.org/ 10.14601/Phytopathol_Mediterr-23942

Mugnai, L., Graniti, A., & Surico, G. (1999). Esca (black measles) and brown wood-streaking : Two old and elusive diseases of grapevines. *Plant disease*, *83*(5), 404-418. https://doi.org/10.1094/PDIS.1999.83.5.404

Schmidt, O. (2006). *Wood and tree fungi*. Springer.

Vidal, J., Martin, E., Franchistéguy, L., Baillon, M., & Soubeyroux, J. (2010). A 50-year high-resolution atmospheric reanalysis over France with the Safran system. *International Journal of Climatology*, *30*(11), 1627-1644. https://doi.org/10.1002/joc.2003