On the utility of treating a vineyard against *Plasmopara viticola*: a Bayesian analysis

Lorenzo Valleggi, Federico Mattia Stefanini

1. Introduction

Plasmopara viticola is the causal agent of the downy mildew, the most severe disease of the grapevine leading to economic damages (Wong et al., 2001). In order to prevent downy mildew, fungicide treatments are required, but they are dangerous for the environment and human health (Kab et al., 2017). Optimal scheduling and selection of treatments is the key to managing downy mildew in an eco-friendly way (Chen et al., 2020). This goal is quite difficult to achieve due to the variability shown by downy mildew among years. Indeed *Plasmopara viticola* growth mostly depends on variables like temperature and rain, plant's genotype and soil conditions. The latter are usually assumed to be homogeneous in the considered vineyard, possibly because of the difficulty in obtaining local measurements. Meteorological variables are typically measured at whole-field levels, despite that *Plasmopara viticola* growth depends on microclimate (Bove et al., 2020a). Simulations of the key steps in the biological process of the pathogen have been performed to obtain information about airborne sporangia, sporangia availability, relative severity and number of lesions in secondary infection cycles (Brischetto, et al., 2021) (Bove et al., 2020b). Unfortunately these important deterministic models do not also provide information on the variability of the above attributes describing events related to the infection.

In this work, we propose a Bayesian prior-predictive approach (Gelman, et al., 2017) where future environmental conditions and the probability of infection both depend on the selected treatment. A multi-attribute utility function taking the three most important variables as argument has been elicited to describe the utility of consequences following the decision to treat the vineyard (Lavik, et al., 2020): the expected values under alternative decisions enable the winemaker to take the optimal decision of treating the vineyard or not.

2. Methods

In this section the approach followed to support the decision maker is described.

2.1 Scenarios

In this study intervals of temperature values and of humidity promoting the disease were defined by exploiting the information available in the literature. The following scenarios were defined: (i) a temperature favorable for pathogen's growth but not for humidity, (Temperature > 10°C and < 30°C, Humidity ≤ 0.8) labeled as "Useful, N-Useful"; (ii) a temperature not favorable for pathogen's growth and a favorable humidity (Temperature < 10°C or > 30°C Humidity ≥ 0.8), labeled as "N-Useful, Useful"; (iii) a temperature and humidity both favorable for pathogen's growth, labeled as "Useful, Useful"(Temperature > 10°C and < 30°C, Humidity

Lorenzo Valleggi, University of Florence, Italy, lorenzo.valleggi@unifi.it, 0000-0002-8529-3046
Federico Mattia Stefanini, University of Milan, Italy, federico.stefanini@unimi.it, 0000-0003-4248-6275

Referee List (DOI 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Lorenzo Valleggi, Federico Mattia Stefanini, *On the utility of treating a vineyard against* Plasmopara viticola*: a Bayesian analysis*, © Author(s), CC BY 4.0, DOI 10.36253/979-12-215-0106-3.41, in Enrico di Bella, Luigi Fabbris, Corrado Lagazio (edited by), *ASA 2022 Data-Driven Decision Making. Book of short papers*, pp. 233-237, 2023, published by Firenze University Press and Genova University Press, ISBN 979-12-215-0106-3, DOI 10.36253/979-12-215-0106-3

≥ 0.8); (iv) neither temperature nor humidity favorable for pathogen's growth (Temperature < 10°C or > 30°C with Humidity ≤ 0.8), labeled as "N-Useful, N-Useful". Given that scenario e_j ($j \in \{1, 2, 3, 4\}$) is realized in the vineyard, the expert must take the decision "to treat", a_1, or "not to treat", a_0.

2.2 States, actions, consequences

Expected values of the probability $\pi_{i,j}$ of infection for one leaf sampled from the vineyard given each environmental scenario e_j and decision $a_i, i \in \{0, 1\}$, were elicited under the assumption that all of these combinations of temperature and humidity lasted from dawn to sunset just before taking the decision. After assuming that $(\pi_{i,j} \mid e_j, a_i) = Beta(\alpha_{i,j}, \beta_{i,j})$, the values of model parameters $\alpha_{i,j}$ and $\beta_{i,j}$ were defined for each pair scenario-treatment i, j by fitting a Beta distribution to the elicited quantile 0.9 and the elicited expected value of $\pi_{i,j}$ given a_i, e_j, i.e. pairs made by an action and a temperature-humidity scenario (Table 1). The implied credible intervals were checked by the expert (Table 1) without finding any need of refinement.

Higher levels of variability characterize the prior-predictive distribution under no chemical treatment (a_0) in comparison to the decision of treating (a_1). In Table 1, the expected value of the probability of infection is shown for each scenario, $p(\pi_{t+1} \mid a_i, e_j)$, together with other elicited quantities.

Table 1: Elicited expected values of the probability of infection in the considered scenarios; "Useful" ("N-Useful") means able (unable) to produce the infection; T=Temperature and H=Humidity.

Treatments	Scenarios $e_1, \dots, e_4$		Probability	Credibility	Parameters
$\{a_0, a_1\}$	T	H	$E[\pi_{i,j}]$	Interval: 0.8	$(\alpha_{i,j}\beta_{i,j})$
0	Useful	N-Useful	0.75	$(0.67296, 0.80032)$	$(40.50, 13.50)$
0	N-Useful	Useful	0.70	$(0.62413, 0.74968)$	$(43.17, 18.50)$
0	N-Useful	N-Useful	0.06	$(0.00066, 0.10263)$	$(0.19, 3.00)$
0	Useful	Useful	0.80	$(0.72362, 0.84969)$	$(38.00, 9.50)$
1	Useful	N-Useful	0.50	$(0.46957, 0.52000)$	$(221.50, 221.50)$
1	N-Useful	Useful	0.40	$(0.3696, 0.42000)$	$(169.33, 254.00)$
1	N-Useful	N-Useful	0.10	$(0.06991, 0.12001)$	$(14.89, 134.00)$
1	Useful	Useful	0.30	$(0.2696365, 0.32002)$	$(50, 112.50)$

Two attributes were defined to quantify the impact of a selected treatment on soil and biodiversity of the vineyard at the subsequent time point $t + 1$ (e.g. next week) after the decision-action:

- s_{t+1} : a score that classifies the degree of cleanness of soil after chemical treatment (including derived side products), $\Omega_{s_{t+1}} \in \{1, 2, \dots, 5\}$, where s_{t+1} = 1 for the worst state after 10 years from treatment, and $s_{t+1} = 5$ for the cleanest case after 10 years;
- b_{t+1} : a biodiversity score to classify the degree of biological diversity, $\Omega_{b_{t+1}} \in \{1, 2, \dots, 5\}$, thus $b_{t+1} = 1$ refers to the worst state of biological diversity after 10 years from treatment and $b_{t+1} = 5$ is the best diversity class after 10 years from treatment.

Given that the winemaker is willing to consider the two attributes on equal footing, a value function averaging and rescaling biodiversity and soil scores was considered as an environmental summary of the future state: $f_{s,b,t+1} = ((s_{t+1} + b_{t+1})/2 - 1)/4$, with $\Omega_{s,b} = [0, 1]$. In order to recognize the inherent uncertainty of $f_{s,b,t+1}$, a prior distribution was elicited by restricting

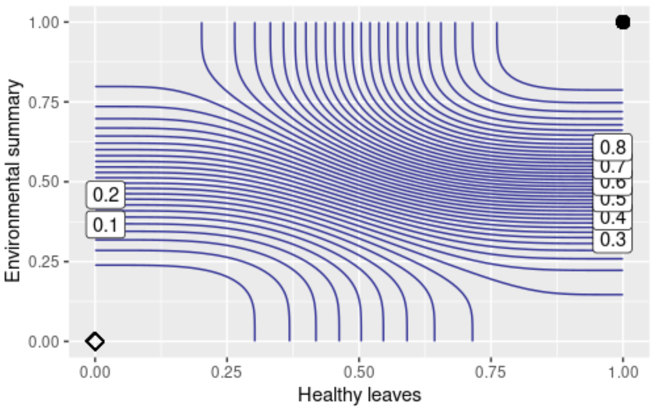

Figure 1: Contour plot of the utility function.

the attention to the decision of treating, $p(f_{s,b,t+1} \mid a_1) = Beta(\phi_1, \phi_2)$, because the decision of no treatment a_0 is associated with no change of biodiversity and nor of soil: a degenerate probability distribution follows under a_0. For this reason the value of $f_{s,b,t}$ was also calculated at the time of decision, thus $p(f_{s,b,t+1} \mid a_0) = I_{f_{s,b,t}}(f)$. The elicited value of the two parameters is $\phi_1 = 57, \phi_2 = 22$, thus the treatment has a medium impact on the environment (quantile 0.1 of $f_{s,b,t}$ is 0.6559175; quantile 0.9 of $f_{s,b,t}$ is 0.7846756). Hereafter, the probability of healthy leaves $\widetilde{\pi}_{i,j} = 1 - \pi_{i,j}$ will be considered in the utility function.

Under conditional independence of future attributes, the prior predictive distribution is

$$p(f_{s,b,t+1}, \widetilde{\pi}_{i,j} \mid f_{s,b,t}, \phi_1, \phi_2, e_j, a) = \\ Beta(\widetilde{\pi}_{i,j} \mid \alpha_{i,j}, \beta_{i,j}) \cdot \left[Beta(f_{s,b,t+1} \mid \phi_1, \phi_2)\; I_1(a) + I_{f_{s,b,t}}(f)\; I_0(a) \right] \quad (1)$$

thus the expected value of the utility function $U(f_{s,b,t+1}, \widetilde{\pi}_{i,j})$ is

$$E[U(f_{s,b,t+1}, \widetilde{\pi}_{i,j}) \mid a_i, e_j] = \int_\theta U(f_{s,b,t+1}, \widetilde{\pi}_{i,j})\; p(f_{s,b,t+1}, \widetilde{\pi}_{i,j} \mid f_{s,b,t}, \phi_1, \phi_2, e_j, a_i)\; d\theta$$

where θ is the vector of all model parameters. In the following, the current value of environmental summary is $f_{s,b,t} = 1$ under a_0, i.e. a fully unmodified environment is in place.

2.3 Elicitation of the utility function

An utility function was elicited with arguments the environmental summary and the probability of healthy leaves: under mutually utility independence (French et al., 2000) (Keenye et al., 1993):

$$U(f_{s,b,t+1}, \widetilde{\pi}_{i,j}) = k_1 U_1(f_{s,b,t+1}) + k_2 U_2(\widetilde{\pi}_{i,j}) + k\; k_1\; k_2\; U_1(f_{s,b,t+1}) \cdot U_2(\widetilde{\pi}_{i,j})$$

where k satisfies $1 + k = \prod_{r=1}^{2}(1 + k\; k_r)$; $U_i(x_i) = \int_0^{x_i} Beta(z \mid \psi_{1,i}, \psi_{2,i}) dz, i = 1, 2$ are marginal utility functions which depend on parameters $\psi_{1,i}$ and $\psi_{2,i}$; the best x_i^* and worst x_i^0 cases take value equal to 1 and 0 respectively; the weights are elicited so that $k_1 = u(f^*_{s,b,t+1}, \widetilde{\pi}^0_{i,j})$ is the utility value associated to the best value for the environmental summary and the worst value for the probability of a healthy leaf; similarly, $k_2 = u(\widetilde{\pi}^*_{i,j}, f^0_{s,b,t+1})$ is the utility value associated to the best value for the probability of a healthy leaf and the worst for the environmental summary. After eliciting U_1 and U_2 a graphical exploration was performed with the expert to check for the need of refinement (Figure 1). The optimal decision $a^\uparrow$ under condition e_j follows from the expected values of the utility function: $a^\uparrow = \arg\max_{i \in \{0,1\}} E[U(f_{s,b,t+1}, \widetilde{\pi}_{i,j}) \mid a_i, e_j]$.

3. Results

The expected values of the utility function were computed for each scenario as described in the previous section. In Table 2 the main results are shown.

By comparing the different scenarios under different decisions, it was found that for $e_1 =$ ”Useful N-Useful”, the expected utility was higher in the ”not treat” case ($a = 0$), than ”treat” case; when $e_2 =$ ”N-Useful Useful”, the expected utility was higher in the ”treat” case ($a = 1$), than ”not treat” case; for $e_3 =$ ”N-Useful N-Useful”, the expected utility was higher in the ”not treat” case ($a = 0$), than ”treat” case; finally, when $e_4 =$ ”Useful Useful”, the expected utility was higher in the ”treat” case ($a = 1$), than ”not treat” case.

4. Discussion and conclusion

Optimal scheduling and managing of treatments is a way to reduce the environmental impact of agriculture. This goal is quite challenging while dealing with phytopathogens that have high infectious potential and that may produce extensive and severe damage. *Plasmopara viticola*, the main enemy of viticulture, is one of these phytopathogens requiring the adoption of highly tuned prevention strategies. The wide adoption of treatments based on copper and sulphuric compounds is leading to over-accumulation in the soil, especially of copper, which causes a phytotoxic effect on the grapevine. They also have a negative impact on biodiversity by reducing the number of species and weakening the ecosystem in the long term.

The optimal decision about treatment with chemicals rests on the available (prior) information about the risk of infection at decision time, the probability of observing a healthy leaf after treatment and the expected impact on the environment. The availability of data collected in the vineyard of interest is the natural next step to improve the performance of the decision process by better calibrating expectations and beliefs: here the advent of low cost sensors for oospores could lead to decisions taken for local microenvironments. Furthermore, agronomist’s preference scheme over prospects coded into the elicited utility function is crucial in order to define a trade-off between environmental sustainability and yield, both for quantity and quality. Here the four most fundamental scenarios of climatic conditions have been considered but a multi value discrete scale on more intervals for several other variables could increase the resolution of the description, when needed. Similarly, a direction for further research could be a more detailed description of both environmental changes and end products, grapes, by choosing key chemical components required to produce high valued wine.

Table 2: Expected values of the utility function for each scenario considered; ”Useful” (”N-Useful”) means able (unable) to produce the infection; T=Temperature and H=Humidity.

Treatments $\{a_0, a_1\}$	Scenarios $e_1, \dots, e_4$ T	H	Expected Value of Utility function
0	Useful	N-Useful	0.251
0	N-Useful	Useful	0.253
0	N-Useful	N-Useful	0.959
0	Useful	Useful	0.250
1	Useful	N-Useful	0.231
1	N-Useful	Useful	0.374
1	N-Useful	N-Useful	0.902
1	Useful	Useful	0.581

The proposed utility function was based on cumulated Beta distributions resembling to s-shaped curves. This is not the only possible choice, e.g. logistic functions could be used instead, as well as many other functions. Nevertheless, the fundamental feature that we believe should not change is the presence of high utility values only when high values are present both for the environmental attributes and for the leaves: this is quite expected in view of the increasing importance of environmental sustainability in agricultural decision-making processes.

The end-user should not take the elicited functions as a black box reference ready to be exploited. The elicitation of soil and biodiversity classes is strongly dependent on the considered vineyard and on the selected chemical, e.g. more or less impacting and more-less effective against *Plasmopara viticola*. Furthermore, our utility function could be extended to include more specific sustainability indexes, more attributes describing quality and yield of grapes, and even alternative types of chemical treatment. Any extension in the above directions should always put the individual preference scheme of the winegrower at the core of an unbiased elicitation procedure.

Acknowledgements. We thank prof. Silvia Bacci and all reviewers for comments that helped to improve the manuscript.

References

Brischetto, C., Bove, F., Fedele, G., and Rossi, V. (2021). A weather-driven model for predicting infections of grapevines by sporangia of plasmopara viticola. *Frontiers in Plant Science*, **12**:636607.

Bove, F., Savary, S., Willocquet, L., and Rossi, V. (2020a). Simulation of potential epidemics of downy mildew of grapevine in different scenarios of disease conduciveness. *European Journal of Plant Pathology*, **158**, pp. 599-614.

Bove, F., Savary, S., Willocquet, L., and Rossi, V. (2020b). Designing a modelling structure for the grapevine downy mildew pathosystem. *European Journal of Plant Pathology*, **157**, pp. 251-258.

Chen, M., Brun, F., Raynal, M., and Makowski, D. (2020). Forecasting severe grape downy mildew attacks using machine learning. *PLOS ONE*, **15(3)**:e0230254.

French, S., Rios Insua, D. (2000). *Statistical Decision Theory. Kendall's Library of Statistics 9. Oxford University Press Inc., New York.*

Gelman, A., Simpson, D., Betancourt, M. (2017). The Prior Can Often Only Be Understood in the Context of the Likelihood. *Entropy*, **10**:555.

Kab, S., Spinosi, J., Chaperon, L., Dugravot, A., Singh-Manoux, A., Moisan, F., and Elbaz, A. (2017). Agricultural activities and the incidence of Parkinson's disease in the general French population. *European Journal of Epidemiology*, **32**, pp. 203–216.

Keeney, R.L., Raiffa, H. (1993). *Decisions with Multiple Objectives: Preferences and Value Trade-Offs. Cambridge University Press.*

Lavik, M.S., Hardaker, J.B., Lien, G., Berge, T.W. (2020). A multi-attribute decision analysis of pest management strategies for Norwegian crop farmers. *Agricultural Systems*, **178**:102741.

Wong, F. P., Burr, H. N., and Wilcox, W. F. (2001). Heterothallism in Plasmopara viticola. *Plant Pathology*, **50**, pp. 427–432.