Towards pesticide-sparing agricultural mosaics: from modelling to regional consultation for the deployment of resistant grape cultivars

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Abstract

In this study, we adapted an existing mathematical model (*landsepi*) to simulate collective deployment scenarios for downy mildew-resistant grapevine cultivars in vine-growing regions. We first used this model to explore the effects of growing cultivars with monogenic and polygenic resistance together in simplified agricultural landscapes, a possibility that is now available to vine-growers. We then applied this model to the Buzet region (a protected designation of origin in South-West France) for the coconstruction, evaluation and comparison of a set of deployment scenarios for the adoption of resistant grapevine cultivars in line with the strategic vision of the "Nous, les vignerons de Buzet" wine co-operative. Finally, we evaluated the effects of these scenarios on epidemic control, resistance durability, the reduction of fungicide treatments and economic performance.

Keywords: resistant cultivars, resistance durability, downy mildew, companion modelling, grapevine mathematical modelling, vine-growing territory, cost-benefit analysis, coconstruction workshops, wine co-operative.

1. Introduction

The management of pest and pathogen populations in most farming systems is currently heavily dependent on plant protection products, particularly for certain perennial crops, such as vines. For example, the mean treatment frequency index (TFI) for French vineyards was 12.4 in 2019, whereas that for wheat, which occupies more than a quarter of all the arable land in France, was 4.9 in 2017 (Agreste, 2019; 2021). Two fungal diseases, powdery mildew and downy mildew, account for almost 80% of the pesticides used on vines (Fouillet et al., 2022). Reducing the use of pesticides is, therefore, a key issue in vine-growing areas and will be essential if we are to meet the high expectations of society in terms of the protection of the environment and human health. The adoption of cultivars resistant to downy and powdery mildew is a promising innovation in this respect, making it possible to decrease IFT significantly (Oscar, 2023). However, their deployment may be challenging, particularly in terms of managing the durability of resistance. Just as the use of antibiotics can lead to the selection of bacteria resistant to antibiotics, the cultivation of resistant cultivars can lead to the selection of pathogens capable of overcoming disease resistance genes.

Pyramiding — the development of cultivars containing several different resistance factors — is one approach that breeders can use to increase the durability of resistance (REX Consortium, 2013). This strategy formed the basis of the ResDur programme, which aimed to select grapevine cultivars combining several genes for resistance to powdery mildew and downy mildew. The first four pyramid varieties obtained by INRAE and IFV — Artaban, Floréal, Voltis and Vidoc — are registered in the national catalogue and have been available since 2018. They combine the Rpv1 and Rpv3 genes conferring resistance to downy mildew (Paineau et al., 2022). Other resistant cultivars developed in older European programmes and containing only the Rpv3 gene (monogenic resistance) were also authorised in the same year. Vine-growers have a number of tools at their disposal for the durable management of resistance, including cultivar choice. The choice of the most appropriate cultivars is important because it directly affects the dynamics of pest adaptation and, thus, the durability of resistance (Zhan et al., 2015). Choosing the most appropriate cultivars becomes even more important when the cultivars available have certain resistance factors in common. Furthermore, the choices made today will determine the success of future generations of resistant cultivars combining three different factors for resistance to downy mildew and powdery mildew, and the success of programmes aiming to breed resistant cultivars adapted to regional characteristics (Newwine programme of the IFV). By 2023, 2280 hectares of French vineyards had been planted with resistant cultivars. Half the cultivars planted had both the Rpv1 and Rpv3 genes, but 1% carried Rpv3 only and 1.3% Rpv1 only (Jacques Gautier, INAO, pers. comm.). The deployment of resistant cultivars remains a new strategy for wine growers, and this situation provides a unique opportunity to devise deployment strategies for managing the long-term efficacy of resistant cultivars.

Strategies for the deployment of cultivars resistant to airborne diseases, such as downy mildew, must be developed at the scale of the entire vine-growing region, for biological reasons above all (Gilligan, 2008). The infectious propagules of airborne pathogens (spores) are often dispersed over distances extending well beyond individual plots. The landscape is, therefore, the most relevant scale for their management. The most suitable scale for study moves up from the landscape to the territory once social, economic and institutional players become involved. The territory is a social construct involving both a landscape and the stakeholders within it that could be useful for reasoning about the deployment of resistant cultivars. Resistance genes are generally described as “common goods” (Hannachi et al., 2021) in that there is a form of rivalry for their use (the massive use of these genes by farmers limits the durability of resistance over time and, therefore, the availability of these genes for other users) but, at the same time, they are freely available from the moment they are multiplied in nurseries and released onto the market. Since the work of Ostrom (1990), who was awarded the Nobel Prize for Economics in 2009, it has been recognised that common goods can be managed sustainably by local players in a competitive situation via collective organisations with common interests that develop common strategies and management tools. Given their role in advising and supporting their members, and even the planting instructions they issue, co-operatives may be considered suitable organisations for the collective and sustainable management of disease-resistant cultivars.

The aim of the Médée project "Towards pesticide-sparing agricultural mosaics: from modelling to territorial consultation for the deployment of resistant grape cultivars" was to improve our understanding of the obstacles and levers for the deployment of resistant grape cultivars at the landscape and territorial scales (AAP Ecophyto - Leviers Territoriaux, 2019-2023). Experimentation, as traditionally defined, is not an effective approach for comparing deployment strategies at these scales, so this project was instead based on mathematical modelling combining biophysical epidemiological mechanisms and economic analyses to simulate deployment scenarios for cultivars with monogenic and polygenic resistance to downy mildew in vine-growing areas. The model developed can be used to assess the effects of different deployment scenarios on the control of epidemics, the durability of resistances, the reduction in the number of fungicide treatments and economic performance at multiple scales (plot, farm, region). This model has also been used for theoretical explorations of the effects of the potential co-existence of monogenic and polygenic cultivars in simplified agricultural landscapes. Modelling is also of educational value, as it can raise awareness of the concept of “resistance durability” and shed light on the biological mechanisms at work. We used the 'Nous, les vignerons de Buzet' co-operative winery (Buzet PDO) territory and plots for the coconstruction, evaluation and comparison of a set of collective scenarios for the deployment of mildew-resistant vines according to the strategic visions of the stakeholders.

2. Methods used in the Médée project

2.1 Development of the *landsepi* model to simulate deployment strategies for mildew-resistant vine cultivars in wine-producing regions

This project was based on an existing mathematical model — the *landsepi* "Landscape Epidemiology and Evolution" model — developed at INRAE by the BioSP and Plant Pathology units (Avignon centre), in collaboration with the CSIRO (Canberra centre, Australia) (Rimbaud et al., 2018a). It is based on a SEIR architecture that distinguishes several categories of plants (or plant parts, typically leaves) according to their health status: healthy (S), latent (E), infectious (I), inactive (R) (in the epidemiological sense). The model is spatiotemporal, demogenetic and stochastic. It simulates the spread and evolution of a pathogen in an agricultural landscape following the deployment of one or more resistant cultivars. This makes it possible to compare a set of deployment strategies according to epidemiological (plant health), evolutionary (durability of resistance) and economic (profitability of production systems) criteria, and to measure the impact of the landscape organisation, the epidemiological-evolutionary context and the pathosystem considered on the performance of the strategies (Rimbaud et al., 2018b). It is programmed in the R and C languages and can be freely installed and used via the R package of the same name (https://CRAN.R-project.org/package=landsepi). At the start of the Médée project, the *landsepi* model was parameterised for cereal rusts (caused by fungi of the genus *Puccinia*).

The first stage of the project involved adding four functionalities to the *landsepi* model. Two of these new functions were biology-related, making it possible to include sexual reproduction stages in the life cycle of the pathogen and proposing values for parameters specific to downy mildew on grapevines. Another module was added to facilitate dialogue and appropriation of the model by technicians and vine-growers through simulation of the effect of fungicide treatments on epidemics. The final addition was an economic analysis module (cost/benefit of deployment strategies).

Addition of sexual reproduction. The *landsepi* model, initially developed for the deployment of rust-resistant wheat cultivars, did not include a representation of mixed reproductive regimes, as found in other pathogens, such grapevine downy mildew, which alternates between asexual phases during the growing season and a sexual phase in autumn/winter. The architecture of the model was therefore modified to take such life cycles, which are typical of many pathogens in temperate climates, into account (Figure 1). The modifications made to the model are presented together with a theoretical study aiming to improve our understanding of the effect of genetic recombination (specific to the sexual phases of reproduction) on the evolutionary and epidemiological consequences of the main strategies of deployment for two major resistance genes (pyramiding, rotation, mixtures and mosaics) in Zaffaroni et al. (2024a).

Parameterisation for grapevine downy mildew. Zaffaroni et al. (2024a) also defined a parameterisation for downy mildew on vines to enable simulations that are as realistic as possible for this pathosystem. Two sources of information were used. The first, derived from the selection and careful analysis of 18 references, was used to provide the values of 14 life-history traits/parameters for grapevine downy mildew. The second used the network of the *Observatoire National du Déploiement des Cépages Résistants* (OSCAR) to define specific parameters for the interaction between downy mildew populations and the resistance factors Rpv1 and Rpv3.

Addition of a fungicide protection module. The aim here was to model the effect of fungicide protection strategies on the dynamics of epidemics. This module considers contact fungicides that reduce pathogen infection rates. Starting from an application at the recommended rate that uniformly covers the leaves, this module simulates the decline in fungicide efficacy due to natural degradation and plant growth. Treatments are applied on the basis of a predefined schedule when disease severity exceeds a particular threshold. This module enables *landsepi* to calculates an environmental output variable for comparison of the scenarios tested according to the number of treatments applied per plot and per season.

Addition of an economic analysis module specific to vines. This module can be used to compare deployment strategies on the basis of economic criteria, through a cost-benefit analysis at three spatial scales: (i) each individual plot in the territory each year, (ii) each farm (considered as a group of plots) and (iii) the entire territory of the co-operative winery (defined as all the farms). The variables taken into account are (i) the product, which depends on the yield and valuation of the wine (i.e. its price, itself a function of the health of the plot, which may decrease if disease levels are too high), (ii) the cost of planting (a function of the cost of the cultivars deployed, resistant cultivars being 2.5 times more expensive at the moment), (iii) the cost of phytosanitary protection (production factors involved (inputs, labour, equipment and materials) and number of passes) and (iv) the annual net profit resulting from the difference between (i) and (ii)+(iii). A discounted cumulative net profit is calculated, corresponding to the sum of discounted annual net profits over 30 years at three levels (plot, farm, co-operative). The costs are standard costs, based on reference costs (Ugaglia, 2009). This function was parameterised for vines based on published data for the cost of production factors and expert opinion for the cost of resistant cultivars. This module was developed based on a function linking disease severity on leaves with yield losses (both quantitative and qualitative) (Savary et al., 2009).

2.2 Participatory workshops for the coconstruction of deployment strategies for the "Nous, les vignerons de Buzet" co-operative winery

This project focused on the Buzet Protected Designation of Origin (PDO) area, through a partnership with the "Nous, les vignerons de Buzet" co-operative winery. This PDO, established in 1973, is located in Lot-et-Garonne (47) around Buzet-sur-Baïse. Bounded by the Garonne to the north and east, and by the Landes forest to the west, its territory extends over 27 municipalities and includes approximately 3,800 plots actively used for wine production (Figure 2). The co-operative winery, founded in 1953, includes most of the producers of PDO wine in the area (160 producers in 2023), 1935 hectares under vines, and 95% of the output for this PDO. In 2020, production was about 13 million bottles. The co-operative lays down specifications that ensure a degree of uniformity in practices (95% of vineyards certified HVE (high environmental quality), AB (organic) or converting to organic practices since 2020), production costs and a common policy for product promotions. The co-operative also helps vinegrowers to renew the vines in their vineyards.

Collective scenarios for the deployment of mildew-resistant vine cultivars were coconstructed with teams from the co-operative winery, through four workshops organised on a monthly basis (January-June 2023) on the premises of the co-operative. The workshops were attended by the director of the co-operative, managers from the various departments of the co-operative (vineyard, marketing, research and innovation), researchers from the INRAE team (epidemiology, biomathematical modelling, plant pathology, IT development, economics) under the eye of an independent sociologist acting as an observer, and in the presence of an illustrator to facilitate graphic representation. The workshops were organised by the eco-design consultancy Think+, one of the co-operative's partners for the definition of its sustainable development strategy.

The theme of the first workshop was "Understanding the issues and sharing objectives". The *landsepi* model was presented and used as an educational tool to help the staff of the co-operative get to grips with the issue of the deployment of resistant cultivars and the need to manage the deployment of these cultivars at the territorial scale and, therefore, collectively, using the co-operative's plots as a basis for reflection. During the second workshop, facilitation approaches were used, with the teams from the co-operative winery, to identify a set of 12 exploratory deployment scenarios for simulation on the co-operative's land. These scenarios corresponded to the strategic objectives of the co-operative's stakeholders (e.g. replacing vines more than 30 years old with resistant cultivars, over a maximum of 5% of the surface area/farm, planting these cultivars in aquatic no-treatment zones, etc.). At the third workshop, the results obtained for the exploratory scenarios were presented, compared and discussed in terms of their ability to control downy mildew, promote the durability of resistance, reduce the number of fungicide treatments and increase the economic benefits to both the individual vineyards and the co-operative winery. This stage made it possible to eliminate certain scenarios and to refine others. Six preferred scenarios were identified for testing and were compared with the *status quo*, i.e. a scenario in which resistant varieties are not introduced and plots continue to be replanted with the susceptible cultivars traditionally grown in the PDO area. The fourth and final workshop provided an opportunity to discuss the six selected scenarios in greater depth, to improve their acceptability to stakeholders (vinegrowers, wineries), and to summarise the findings.

3. Results

3.1 The coexistence in the same area of cultivars with monogenic and polygenic resistance jeopardises the durability of resistance

The grapevine downy mildew resistance genes Rpv1 and Rpv3 can be deployed i) together in the same cultivar ("PY" pyramiding strategy), ii) in different cultivars each carrying a single resistance gene, grown on the same plot ("MI" mixture strategy), iii) in single resistance-gene cultivars grown on different plots ("MO" mosaic strategy), or iv-v) in hybrid strategies combining pyramiding with mixtures or mosaics, ("PY+MI" and "PY+MO" strategies). We used the *landsepi* model described by Zaffaroni et al (2024a) to compare the control over pathogen evolution and epidemics provided by the three strategies: PY, PY+MI and PY+MO. The strategies were deployed in a simplified landscape consisting of 400 square plots of 1 ha each. Assuming a low probability of mutations toward virulence, we found that the evolutionary and epidemiological control over the pathogen provided by the pyramiding strategy was compromised as soon as cultivars with monogenic resistance are simultaneously present in the landscape (PY+MI and PY+MO hybrid strategies), even at low proportions (Figure 3A). Furthermore, the efficacy of the pyramiding strategy relative to hybrid strategies depending on whether the adapted strains are subject to a fitness cost on all the varieties considered (both susceptible and resistant) or only those on which their virulence genes are not required, particularly when these costs are high (Figure 3A, situation $\theta=0.5$ and a=0 *versus* $\theta=0.5$ and a=0.5). The pyramiding strategy outperforms the hybrid strategies if a high fitness cost is paid only for unnecessary virulences, whereas these strategies have similar performances if a fitness cost is paid for all varieties. We also found that the difference in performance between the three strategies was much smaller if the probability of mutations toward virulence was high (Figure 3B). However, the performance of the pyramiding strategy remained equal to, or even substantially better than that of the hybrid strategies in all the conditions considered, i.e. all the combinations of parameters tested in our simulations (Zaffaroni et al., 2024b).

Much of the advantage of the pyramiding strategy derives from the need for the pathogen to accumulate two mutations to bypass the two resistance factors present in the resistant cultivar. The acquisition of these mutations may occur simultaneously or sequentially. For simultaneous acquisition, assuming independence between mutations, the probability of acquiring both the virulence mutations is equal to the square of the probability of phenotypic mutation to virulence. This squaring makes the event "a strain adapted to the pyramided cultivar (thereafter “superpathogen”) appears in the pathogen population during a growing season" almost certain for a high probability of phenotypic mutation (of the order of 10^{-4}) but highly improbable for a low probability of phenotypic mutation (of the order of 10^{-8}). These differences translate into a strong advantage of pyramiding over hybrid strategies (Figure 3A) or, conversely, into performances that are similar but always superior for pyramiding alone (Figure 3B). This dichotomy highlights the importance of using dedicated studies to determine the probabilities of mutation towards virulence, which remains largely unknown. A recent study suggested that such events are quite frequent for Rpv3 (Paineau et al., 2024). However, it is not possible to transpose this result to other resistances, as Rpv3 resistance was already deployed in certain hybrid grapes grown in Europe before the Second World War. Resistances should be studied case-by-case, particularly for Rpv1 in our case study.

At low mutation probabilities, the simultaneous acquisition of virulence mutations is highly unlikely. The more probable sequential acquisition scenario greatly favours the pyramiding strategy over hybrid strategies (Figure 3A). Sequential acquisition requires the establishment of strains with single virulence (i.e. possessing only one of the mutations) within pathogen populations. This situation is strongly favoured by the deployment of varieties with single-gene resistance, as these varieties constitute an evolutionary springboard, promoting the emergence of the superpathogen. However, there is an exception to this rule in situations in which the pathogen adaptation leads to a fitness cost for the pathogen on all cultivars, not just those on which its virulence factors are not required. In this case, pathogen adaptation is slowed down by the time required for the establishment of single mutants that are subject to fitness costs on all hosts present in the landscape. In this situation, hybrid strategies, particularly those combining pyramiding with mixtures (PY+MI) provide levels of control over pathogen evolution and epidemics equivalent to those provided by the pyramiding strategy. This result highlights the need to perform experiments to estimate the fitness costs of downy mildew strains on all cultivars, both susceptible and resistant, available to wine growers.

3.2 Exploring deployment strategies in the Buzet vine-growing region through participatory workshops

The six scenarios that emerged from the workshops are the first result of this participatory research (Table 1). All six scenarios are based on the deployment of resistant cultivars (RC) in which Rpv1 and Rpv3 are pyramided. Initially, all the plots in the two zones of the vineyard considered ("the heart of the vineyard" and "low-density vines", Figure 2) were cultivated with susceptible cultivars (SC) of known ages. The scenarios involved replanting the plots with a SC or RC over the 30 years of the simulation considered, according to several criteria: replacement of vines in plots over 30 years old, compliance with VIFA regulations[1], vine replacement in sensitive areas, etc. In scenario S1, all the plots are planted with a RC as soon as they reach the age of 30 years, whereas in scenario S2 replanting occurs on 3.3% of the oldest plots each year. Scenarios S3 and S4 include constraints on the maximum percentage of land per farm planted with RC, 5% in scenario S3 (in line with VIFA regulations), and 20% in scenario S4 (assuming a relaxation of regulations). Finally, stakeholders focused on the location of the plots planted with RC in scenarios S5 and S6: aquatic (i.e. near watercourses or elements of the hydrographic network) or periurban (i.e. located close to human dwelling) no-treatment zones (NTZ). These zones are subject to a ban on phytosanitary treatments with synthetic products, with the exception of biocontrol products and products authorised for organic farming. The six scenarios differed in the percentage of land under RC at the end of the 30 years simulated. In four of the scenarios, less than 19% of the land was replanted with RC (S3, S4, S5, S6), whereas over 95% of the land was replanted with RC in the other two (S1 and S2). Only scenario S2 corresponds to a gradual introduction of RC. In the other five scenarios, the age structure of the plot results in a rapid introduction of RC from early on in the simulation. A status quo scenario, S0, in which only SC are planted, was also simulated to serve as a point of comparison.

Like epidemiological control (data not shown), the number of fungicide treatments applied per growing season is strongly influenced by the proportion of RC in the landscape (Figure 4A). Scenarios S1 and S2, in which almost all the plots are replanted with RC after 30 years, provided the best results (83% decrease in the mean number of treatments for S1 and 51% decrease for S2). The differences between the two zones were minor, and we will not, therefore, comment on them below. The best performance in scenario S1 resulted from a massive initial introduction of RC (over 65% of the plots replanted with RC in the first year, versus only 50% of the plots after 15 years in scenario S2). Conversely, the smaller areas replanted with RC in scenarios S3 to S6 resulted in lower treatment sparing, with 39% less fungicide use for S4 and

[1] There is also a regulatory framework for the planting of disease-resistant vine cultivars, particularly for PDO wines. Resistant cultivars can now be included in PDO specifications on an experimental basis as cultivars of interest for adaptation purposes (termed VIFA in French). Under the procedure, PDO status can be maintained subject to the following conditions: (i) no more than 5% of the area under vines should be replanted, and (ii) no more than 10% of the output of a structure incorporated into blends of wines with PDO status. The observation period for experiments is set at a minimum of 10 years, after which the cultivars may be definitively included in the specifications, withdrawn from the specifications, or the observation period extended by 5 years (at the discretion of the PDO).

5% less for S6. Beyond these trends, differences were also observed in inter-simulation variability, as shown by the size of the 80% confidence intervals (Figure 4A). This variability, which was much greater in scenarios S1 and S2, can be explained by the occurrence of resistance breakdowns, abolishing the benefits of RC over large swathes of the landscape. This results in highly bimodal distributions of epidemiological control and numbers of treatments applied. Furthermore, unlike mean treatment-sparing values, which are not dependent on the fitness cost of virulence in the pathogen, confidence intervals are decreased by high virulence costs (0.25). In practice, the existence of high fitness cost of virulence would, therefore, ensure the treatment-sparing achieved in scenarios S1 and S2.

The effects of the scenarios on evolutionary control — i.e. the durability of the RC deployed — operate in the background. Scenario S1 provides the best evolutionary control (as estimated by the probability of a superpathogen establishment) because it is associated with a massive deployment of RC, from the first few years of simulation onwards (probability of establishment between 0.14 and 0.25, depending on the fitness cost). This level of control is much better than that obtained with the progressive deployment used in S2 (probability of establishment between 0.12 and 0.4), in which the coexistence of SC and RC in the landscape for many years favours the emergence of the superpathogen on SC. The durability of resistance results from a balance between several mechanisms: (i) the probability of superpathogen appearing by mutation (which increases with the proportion of the landscape under SC), (ii) its ability to maintain itself on SC in competition with wild-type strains (which decreases with increasing virulence costs), and (iii) its probability of dispersing from a SC to a RC (maximal in landscapes with a 1:1 ratio of SC and RC). Our results also show that resistance durability, and the other output variables considered, are modulated by the particular characteristics of the landscape considered. Indeed, similar proportions of RC (scenarios S3, S5 and S6) can lead to differences in resistance durability linked to the specific configuration of the landscapes in the Buzet area. For example, RC were, by chance, allocated to a larger number of small plots in scenario S3, and a smaller number of large plots in scenarios S5 and S6. These differences in configuration modify the distance of contact between the perimeters of plots planted with SC and plots planted with RC, thereby modifying the likelihood of exchanges of infectious propagules (*i.e.* spores) between cultivars.

Finally, from an economic point of view, the deployment of RC leads to an increase in net profits over the S0 scenario, with large differences between scenarios (Figure 4B). These differences largely reflect the treatment sparing achieved as a function of the area under RC (Figure 4A). Scenario S1 results in the largest increase in net profit (36% more than for the base scenario, S0). Scenarios S2 and S4 increased net profit by 10% and 9%, respectively. The other three scenarios increased net profit by less than 5%. The confidence intervals for net profits are also of particular interest. As for fungicide treatments, the confidence intervals were wide for scenarios S1 and S2, which were the most promising scenarios overall when all criteria were taken into account. Once again, this difference is a consequence of the resistance genes being overcome. Two processes have an impact on the economic results. Firstly, resistance breakdown abolishes the advantage of RC as a means of decreasing the cost of plant protection. Secondly, the extra cost of purchasing these cultivars may not be offset by the savings in treatment costs if the resistance is overcome rapidly after planting. This situation occurs, in particular, with scenario S2 (progressive planting of RC). This scenario is the only one for which the 80% confidence interval includes negative values for variations in net profit, i.e. situations involving economic losses relative to the *status quo*.

4. Discussions and conclusions

The modelling approach used here is based on solid mathematical foundations and on knowledge of the epidemiology and evolution of plant pathogens acquired over the last four decades (Rimbaud et al., 2021ab). Modelling is free from the logistical, financial and legal constraints associated with experimentation in agricultural systems, and can therefore be used to compare a range of strategies for deploying resistant cultivars without the risk of disastrous epidemics or of the resistance genes concerned being overcome. Furthermore, by simplifying a complex reality, models can often be generalised to several comparable situations. However, the results of any experiment (whether a simulation, as here, or carried out in the real world) must be interpreted in the light of the underlying assumptions and presupposed simplifications. For example, the *landsepi* model does not take into account the effects of environmental variables (particularly meteorological variables) despite their known effects on the short-term dynamics of epidemics. We focus here solely on the interactions between epidemiological, evolutionary and economic aspects in the long term, with the aim of comparing deployment strategies on a level playing field. We assume that the weather conditions would have affected all strategies in the same way and would not, therefore, change our conclusions. This may therefore be considered valid only if this assumption holds true. More generally, modelling can integrate the epidemiological and evolutionary mechanisms occurring at nested spatial and temporal scales (plants, plots, landscape-territory), but it cannot do everything. Experimentation and observation are equally vital for informing, calibrating and testing models. For example, our results for the coexistence of cultivars with monogenic and polygenic resistance in the landscape clearly highlight the need for experimental studies to specify the values of certain parameters (probability of mutations toward virulence, fitness costs) with a very strong influence on the probable outcome of such combinations of cultivars.

The primary objective of this work, which was linked to the "Territorial levers" theme of the call for projects, was to enable the teams of a collective organisation, an agent for change at the scale of a vine-growing region, to tackle the issue of disease-resistant cultivars, their deployment and the durability of their resistance. The co-operative winery was already interested in varietal innovation at the start of the project, but the participatory workshops provided mutually beneficial opportunities for exchanges between professionals in the field, to improve our understanding of the factors influencing the durability of varietal resistance, and enabling researchers, to clarify — or even modify — their working hypotheses. The discussions that took place at these four workshops are illustrated, together with a number of elements of biology, in a comic strip destined for a lay audience (Plantin et al., 2024). The possibility of running live simulations (via a web interface) of the deployment of resistant cultivars on the actual plots of the Buzet vine-growing area greatly helped to facilitate dialogue. Similarly, the involvement of an agency specialising in the running of participatory workshops enabled each of the participants to focus on the fundamental aspects of their activities. During the workshops, the teams from the "Nous, les vignerons de Buzet" co-operative winery took part in several phases (in particular an ideation phase in which they were required to be very creative in the definition of scenarios) with the aim of developing more realistic deployment scenarios, some of which were at odds with PDO rules. One of the advantages of modelling is that it allows us to go beyond the limits of existing growing systems and imagine more radical scenarios. In this respect, the objective of this study was achieved.

The workshops led to the identification of two scenarios for the deployment of resistant cultivars that the co-operative winery considered to be the most likely in the short term — scenarios S5 and S6 — in which RC were planted within the NTZ. However, the implementation of these scenarios would require the INAO to approve a request from the co-operative winery to include the resistant red varieties Artaban and Vidoc in the Buzet PDO specifications, to support the planting efforts of the vine-growers. In the end, the co-operative winery adjusted its choice of scenarios and the reasoning behind its innovation strategy in the light of the discussions and results provided by the model. It demonstrated its capacity, as a collective organisation, to serve its members, by prioritising scenarios ensuring the durability of resistance genes and epidemic control, thereby meeting the long-term socio-economic needs of its members. The collective deployment RC at the level of the co-operative winery — initially founded as a production-based organisation pooling means and resources, but also a collective organisation forming a community around this project — could therefore ensure the sustainable management of resistance genes.

The prioritisation of these two scenarios by the stakeholders incorporated a range of considerations extending well beyond the specific question of the durability of resistance addressed by modelling. In particular, discussions focused on obstacles and levers for the adoption of these scenarios by vine-growers and consumers. As far as vine-growers are concerned, the levers that can be mobilised are (i) a reduction of the use of pesticides (demonstrated in all our simulations) and pesticide residues in wines, (ii) improvements in working conditions and (iii) the enthusiasm of certain vine-growers for innovation. Conversely, the obstacles and reasonable doubts that remain concern (i) the adaptation of resistant cultivars to climate change, (ii) a fear of having to revert to the usual treatment strategies if resistance is overcome, (iii) the availability of resistant plants, (iv) the re-emergence of diseases traditionally controlled by phytosanitary treatments (black rot) and (v) regulatory constraints linked to VIFAs, which limit planting possibilities and, therefore, possibilities for treatment sparing. However, these constraints are modulated by the ability of the PDO authorities to adapt their rules over time. Demand also plays an important role in the acceptability of resistant cultivars. Consumer interest in, and willingness to pay for, new wines with a better environmental and health performance will be decisive in the choices of vine-growers (Fuentes Espinoza et al., 2018). The co-operative winery is already communicating about innovative products, particularly to local consumers, and is promoting local consumption in its shop. However, several obstacles raise questions about the feasibility of differentiating wines produced from these grape varieties and about the information to be provided to consumers about RC: (i) there is a risk that consumers will confuse resistant cultivars (obtained through a traditional selection process based on crosses) with genetically modified organisms, (ii) there is a risk of losing traditional consumers, (iii) it may prove difficult to benefit from the first mover advantage (i.e. the economic advantage gained by players who adopt a technology before others), if many other organisations embark on this approach and (iv) it may be difficult to promote these new wines in the face of the proliferation of labels.

Finally, the conclusions reached in the Buzet area are probably transposable to other vine-growing areas, and even to the management of other pathogens with epidemic cycles similar to that of downy mildew in vines. This is the case, for example, for phoma stem canker on oilseed rape, caused by the fungus *Leptosphaeria maculans*, which has a life cycle characterised by clonal reproduction during the growing season of oilseed rape, interspersed with sexual reproduction events during the period between successive crops. Like downy mildew on grapevine, phoma stem canker is at the heart of the issues surrounding the reduction of phytosanitary treatments and the preservation of resistance genes. Our results are therefore likely to be of interest to specialists in the oilseed rape and other sectors.

This project has raised the profile of resistance genes as common goods and demonstrated their value through a participatory approach to the deployment of resistant cultivars at the landscape and territorial levels. However, this is only the first step, and it demonstrates the need to implement participatory and multidisciplinary approaches (such as living laboratories) to promote the joint management of plant health, with an appropriate contribution of the human and social sciences.

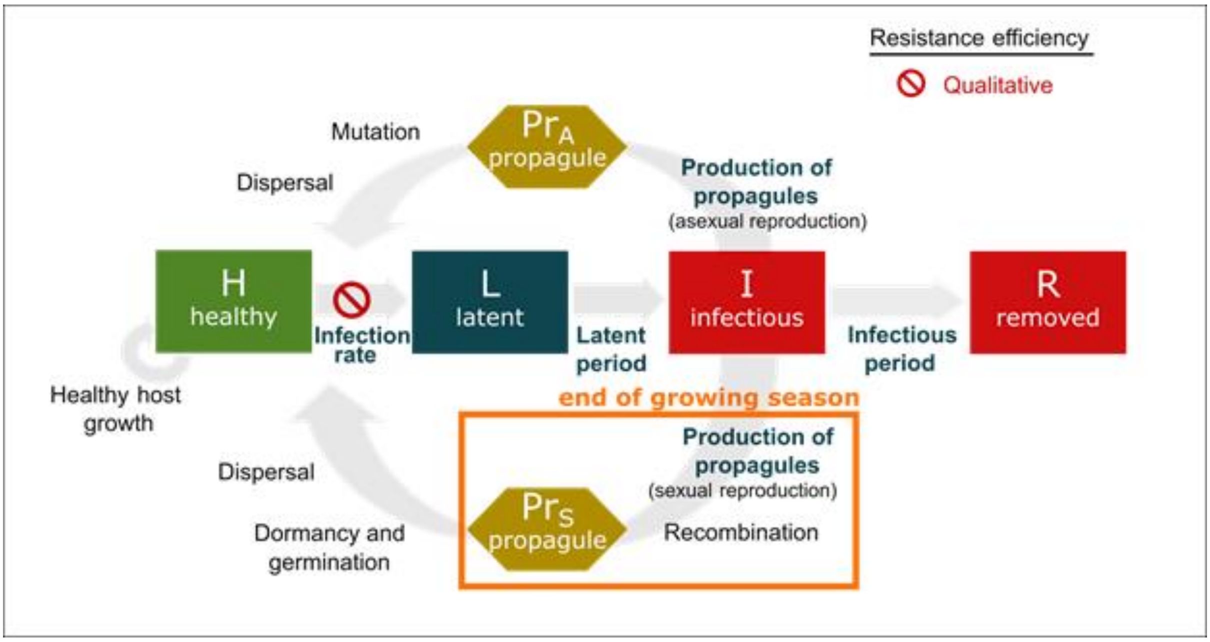

Figure 1: Addition of the sexual reproduction cycle of pathogens to the architecture of the *landsepi* model. During the growing season, healthy hosts can be infected by propagules generated by asexual reproduction. After a latent period, infectious hosts begin to produce new asexual propagules, which can mutate and then disperse in the landscape. At the end of the infectious period, infected hosts become epidemiologically inactive. At the end of the growing season, new infectious propagules are produced, this time by sexual reproduction. The spores thus formed remain dormant in the soil and germinate during subsequent growing seasons, initiating new epidemics.

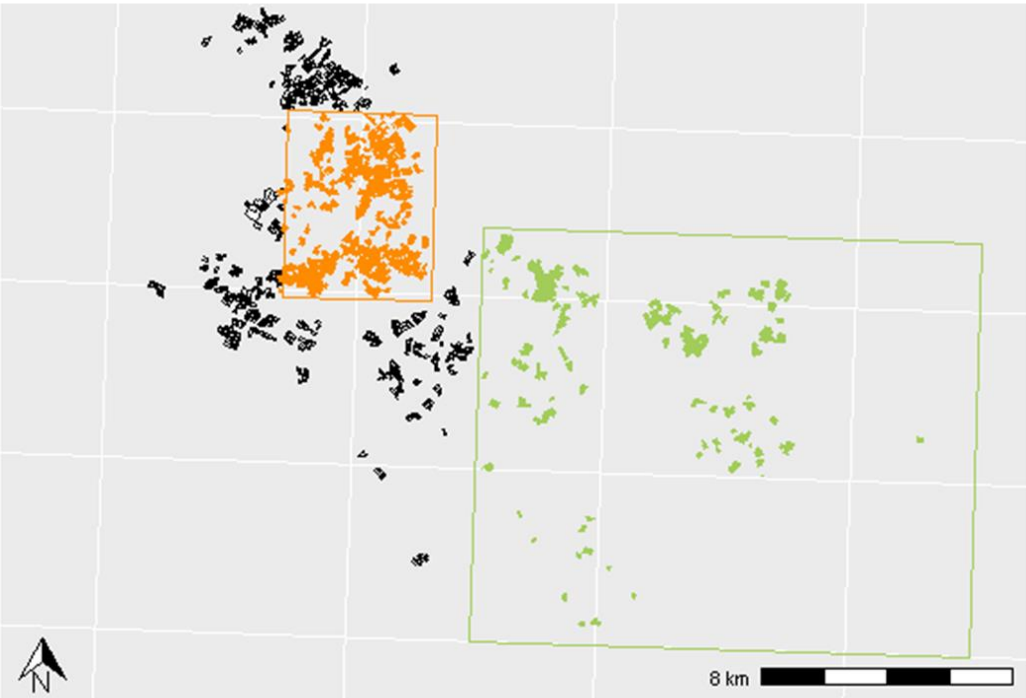

Figure 2: Map of the plots of the Buzet protected designation of origin vineyard. Two landscapes were considered within this area as a basis for the simulations. The "heart of the vineyard" landscape corresponds to the central zone of the area (in orange). It comprises 1,422 plots (mean surface area, 0.46 ha) managed by 57 vine-growers. The "low-density vineyard" landscape corresponds to a peripheral zone (in green). It comprises 709 plots (mean surface area, 0.56 ha) managed by 36 vine-growers.

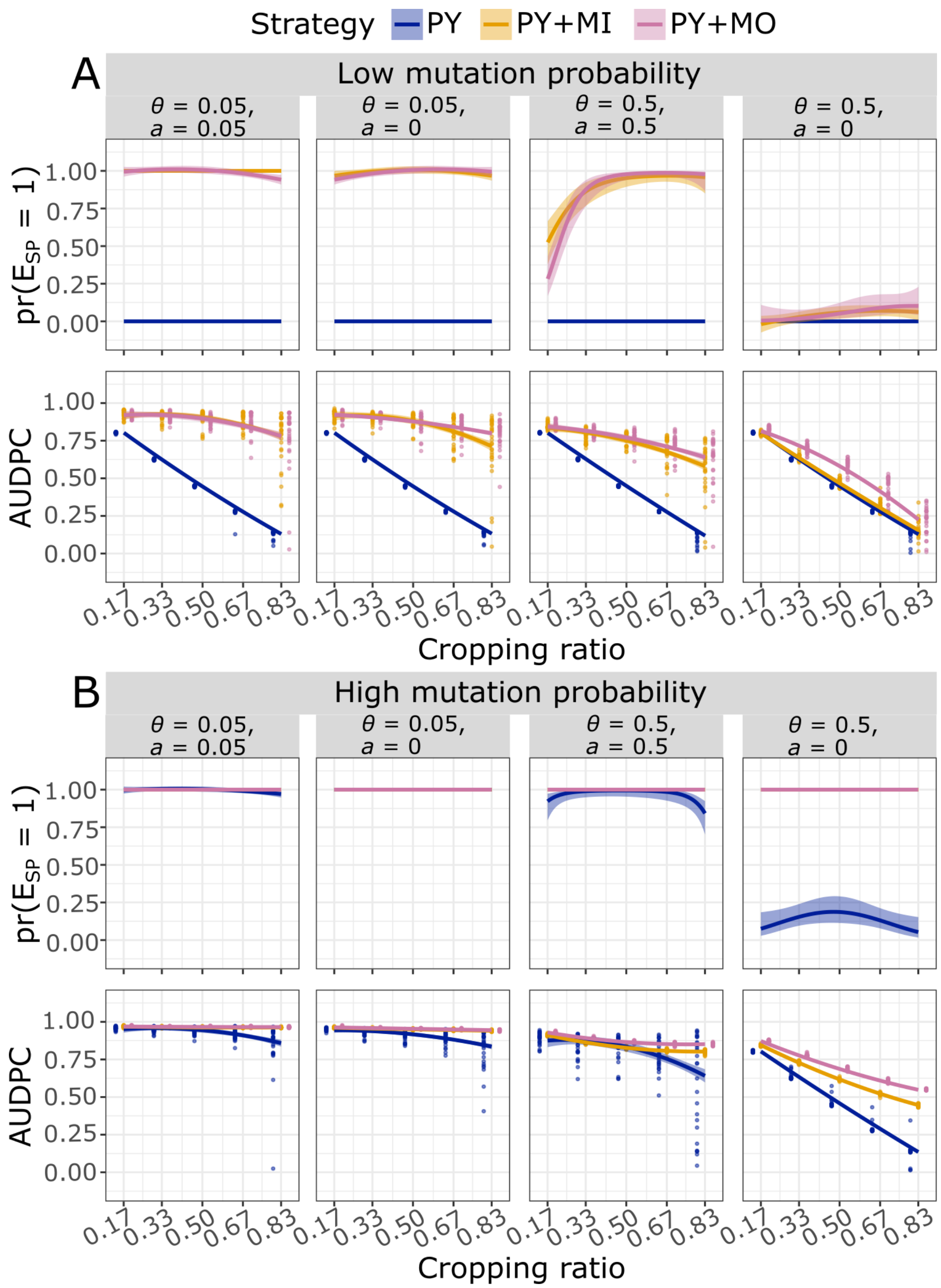

Figure 3: Effects of mutation rates, fitness costs of virulence and the proportion of resistant cultivars on the performance of pyramiding (PY) and hybrid (PY+MI and PY+MO) strategies . In panel (A) the probability of mutation is low, and in panel (B) the probability of mutation is high. The first row in each panel pr(E_{SP}=1) shows the probability of strains adapted to the pyramided variety ('superpathogens') becoming established and in the second row, the AUDPC (area under the curve of the proportion of hosts infected) indicates the relative intensity of the epidemic. The graphs in each row show the effects of the proportion of resistant cultivars in the landscape ('cropping ratio') on the variable considered as a function of the fitness cost — intermediate (θ = 0.05) or high (θ = 0.5) — paid for unnecessary virulence only (a = 0.05 and a = 0.5, respectively), or paid on all cultivars (a = 0), for the three strategies considered. The curves were produced by fitting second-order (first row) or polynomial (second row) logistic regressions to the simulation results; the envelopes delimit the 5th and 95th percentiles.

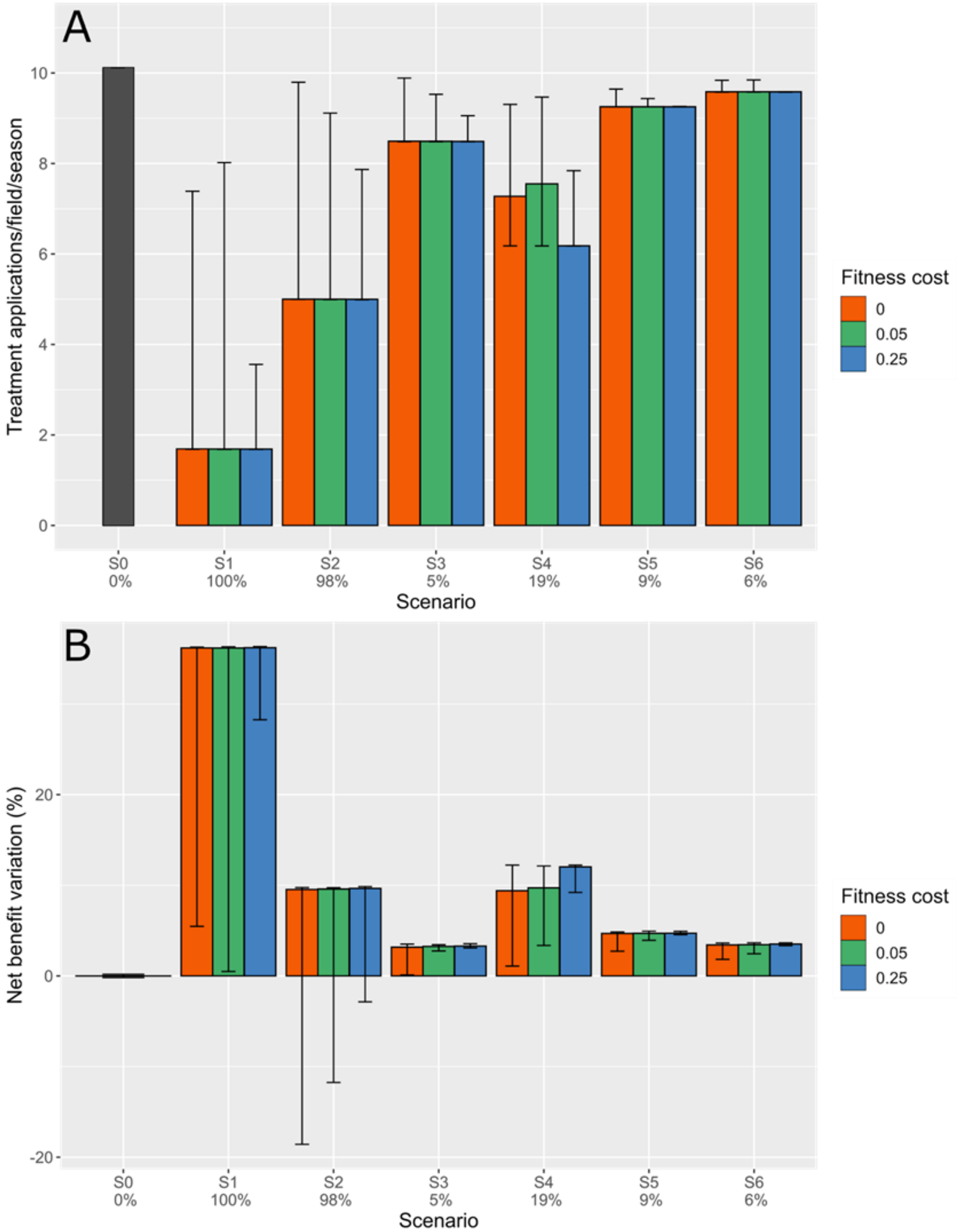

Figure 4: Environmental and economic impacts of the six deployment scenarios selected at the end of the workshops. A: Number of treatments per plot and per growing season for the 6 scenarios. The simulations were carried out in the "heart of the vineyard" landscape of the co-operative's territory, under three assumptions about the fitness cost of the adaptation of downy mildew strains to resistance factors ("fitness cost"). The histograms show the median number of treatments calculated over 50 replicates, and the intervals show the 10% and 90% quantiles. B: As for panel A, for the variation in net profit calculated relative to the reference scenario S0 (replanting with susceptible cultivars only). The percentage of the area planted with RC after 30 years in the "heart of the vineyard" landscape is indicated below the name of each scenario.

Table 1: Summary of scenarios coconstructed with teams from the "Nous, les vignerons de Buzet" co-operative winery. The scenarios are defined on the basis of rules governing the choice of plots to be replanted with resistant (RC) or susceptible (SC) cultivars. The percentage of the area planted with RC and SC after 30 years is indicated. The scenarios concern the "heart of the vineyard" (HoV) and "low-density vineyard" (LDV) landscapes.

Scenario	Planting rules	% planted after 30 years			
		HoV		LDV	
		SC	RC	SC	RC
S0	*Status quo:* SC planted in plots over 30 years old	100	0	100	0
S1	RC planted in plots over 30 years old	0	100	0	100
S2	RC planted in 3.3% of the oldest plots every year	0	98	0	96
S3	RC planted on plots over 30 years old, covering up to 5% of the total area of the farms, otherwise SC	95	5	96	4
S4	RC planted on plots over 30 years old, covering up to 20% of the total area of the farms, otherwise SC	81	19	81	19
S5	RC planted only on plots classified as NTZ (aquatic), and SC planted on plots more than 30 years old.	91	9	95	5
S6	RC planted only on plots classified as NTZ (periurban), and SC planted on plots more than 30 years old.	94	6	96	4

Ethics

The authors declare that the experiments were performed in accordance with the national regulations applicable.

Declaration on the availability of data and models

The data supporting the results presented in this article are available on request from the authors.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.

Not relevant

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Declaration of interest

The authors declare that they do not work for, advise, own shares in, or receive funds from any organisation that could benefit from this article, and declare no affiliation other than those listed at the beginning of the article.

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References

Agreste, 2021. Survey of phytosanitary practices in viticulture in 2019: IFT and number of treatments. www.agreste.agriculture.gouv.fr

Agreste, 2019. Arable cropping practices 2017: IFT and number of treatments. www.agreste.agriculture.gouv.fr

Fouillet E., Delière L., Chartier N., Munier-Jolain N., Cortel S., Rapidel B., & Merot A. (2022). Reducing pesticide use in vineyards. Evidence from the analysis of the French DEPHY network. *European Journal of Agronomy*, *136*, 126503.

Fuentes Espinoza A., Hubert A., Raineau Y., Franc C., Giraud-Héraud E. (2018). Resistant grape varieties and market acceptance: an evaluation based on experimental economics. *OENO One*, *52*(3). https://doi.org/10.20870/oeno-one.2018.52.3.2316

Gilligan C.A., 2008. Sustainable agriculture and plant diseases: an epidemiological perspective. Philosophical Transactions of the Royal Society B-Biological Sciences 363, 741-759. https://doi.org/10.1098/rstb.2007.2181

Hannachi M, Coléno F., Bousset L., Delourme R., ChevreA-M., Balesdent MH., Rouxel T., Pinochet X., Leflon M., Multeau C., Garmendia-Auckenthaler L. (2021). Towards managing resistance genes as common goods. In: L'immunité des plantes. Pour des cultures résistantes aux maladies. Editions Quae

OSCAR, 2023. Observatoire nationale du déploiement des Cépages Résistants - synthèse 2022, 13p.

Ostrom E. 1990. Governing the commons: The Evolution of Institutions for Collective Action. Cambridge: Cambridge University Press, 1990. Pp. 280

Paineau M., Mazet I. D., Wiedemann-Merdinoglu S., Delmotte F., Fabre F. (2022). The characterization of pathotypes in grapevine downy mildew provides insights into the breakdown of Rpv3, Rpv10 and Rpv12 factors in grapevines. Phytopathology, 112 (11), 2329-2340, https://dx.doi.org/10.1094/PHYTO-11-21-0458-R

Paineau M., Minio A., Mestre P., Fabre F., Mazet I.D., Couture C., Legeai F., Dumartinet T., Cantu D. and Delmotte F. (2024), Multiple deletions of candidate effector genes lead to the breakdown of partial grapevine resistance to downy mildew. New Phytol. https://doi.org/10.1111/nph.19861

Plantin L., Miclot A.S., Papaïx J., Rey J-F., Rimbaud, L., Zaffaroni M., Alonso Ugaglia A., Fabre F 2024. Les résistantes: Vines like no other. 2024. https://hal.inrae.fr/hal-04604456

REX Consortium. Heterogeneity of selection and the evolution of resistance. Trends Ecol Evol. 2013 Feb;28(2):110-8. doi: 10.1016/j.tree.2012.09.001

Rimbaud L., Fabre F., Papaïx J., Moury B., Lannou C., Barrett L., Thrall P. (2021a). Models of plant resistance deployment. Annual Review of Phytopathology, 59, 125-152, https://dx.doi.org/10.1146/annurev-phyto-020620-122134

Rimbaud L., Papaïx J., Fabre F. (2021b). Stratégies paysagères pour déployer efficacement et durablement la résistance : modèles et prédictions. In: L'immunité des plantes. Pour des cultures résistantes aux maladies. Editions Quae. https://hal.inrae.fr/hal-03131097

Rimbaud L., Papaïx J., Barrett L. G., Burdon J. J., & Thrall P. H. (2018b). Mosaics, mixtures, rotations or pyramiding: What is the optimal strategy to deploy major gene resistance? Evolutionary Applications, 11(10), 1791-1810.

Rimbaud L., Papaïx J., Rey J.-F., Barrett L. G., & Thrall P. H. (2018a). Assessing the durability and efficiency of landscape-based strategies to deploy plant resistance to pathogens. PLoS Computational Biology, 14(4), e1006067.

Savary S., Delbac L., Rochas A., Taisant G., Willocquet L., 2009. Analysis of Nonlinear Relationships in Dual Epidemics, and Its Application to the Management of Grapevine Downy and Powdery Mildews. Phytopathology 99, 930-942. https://doi.org/10.1094/PHYTO-99-8-0930

Ugaglia A., 2009. Pratiques de comptabilité analytique en viticulture : des coûts de production au coût des pratiques environnementales, La Revue du Financier, n°176, mars-avril 2009.

Zaffaroni M., Rimbaud L., Rey J-F., Papaïx J., Fabre F. 2024a. Effects of pathogen reproduction system on the evolutionary and epidemiological control provided by deployment strategies for two major resistance genes in agricultural landscapes. Evolutionary Applications, 17 (1), pp.e13627. https://dx.doi.org/10.1111/eva.13627

Zaffaroni M., Papaïx J., Rimbaud L., Geffersa A., Rey JF., Fabre F., 2024b. Combining single-gene-resistant and pyramided cultivars in agricultural landscape compromises the benefits of pyramiding in most, but not all, productions situation. To be published in Phytopathology, https://doi.org/10.1094/PHYTO-02-24-0075-R

Zhan J., Thrall P. H., Papaïx J., Xie L., & Burdon J. J. (2015). Playing on a Pathogen's weakness: Using evolution to guide sustainable plant disease control strategies. Annual Review of Phytopathology, 53, 19-43.