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► To cite this version:

Jean-Marie Lescot, M. Rouire, Matthieu Raynal, S. Rousset. Bio economic modeling of wine grape protection strategies for environmental policy assessment. Operational Research, 2014, 14 (2), pp.283-318. 10.1007/s12351-014-0152-y . hal-01094401

HAL Id: hal-01094401

<https://hal.science/hal-01094401>

Submitted on 12 Dec 2014

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Bio-economic modeling of wine grape protection strategies for environmental policy assessment

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Abstract. This research had two objectives. The first was to model the behaviour of wine producers, and the second was to assess the effectiveness of policies designed to reduce pesticide use in viticulture. We modeled the decisions of producers aiming to maximize their expected income while subject to a number of constraints and phytosanitary risks. We also examined the impacts of different protection strategies targeting downy mildew, the main grape disease in European Atlantic vineyards. The VINEPA model is a multi-periodic stochastic programming model based on panel-data of about one hundred representative winegrowing farms from the Farm Accountancy Data Network in the Bordeaux region. The response of vines to fungicide treatments against downy mildew was simulated through the Downy Mildew Potential System, an epidemiologic model initially developed for decision support, using data from multiple weather stations along with special plots of untreated vines, monitored weekly over a ten-year period. The VINEPA model accurately reproduced the current chemical protection strategies in the region. Simulations were then carried out for different types of taxes (*ad valorem* and volume based) at different rates. In addition, we analysed the effects of policies on spraying practices, along with their potential impact on investment in precision technology equipment.

Keywords: Stochastic programming, Wine grape growing, Downy mildew (*Plasmopara viticola*), Environmental policy, Bordeaux, VINEPA

Introduction

Pesticides are used extensively by winegrowers around the world. While the use of such substances has led to greater, more reliable production of grapes, it has also led to a reduction in biodiversity. There are growing levels of residue in surface and ground water, and risks to human health have been significantly increased, notably in terms of direct exposure, i.e. physical contact, and indirect exposure, through residue present in food and water. Among the other harmful side effects of pesticide use are atmospheric pollution and long-term damage to soil and micro-organisms. This continued application of chemicals in France, the most intensive in Europe in terms of mass of active substances per unit area (Eurostat, 2007), has also led to insects and fungi becoming increasingly resistant to treatment.

As an example of how extensively chemicals are used in French viticulture, vineyards account for only 3% of all farmland in mainland France, but represent 30% of total pesticide use. Eighty percent of that figure is used to treat downy (*Plasmopara viticola*) and powdery (*Erysiphe necator*) mildew.

In line with a number of other European countries, France is currently trialling a national pesticide reduction program, with the aim of halving pesticide use between 2008 and 2018 (Baschet and Pingault, 2009). However, reducing their use in viticulture is fraught with difficulties.

While vineyards produce many different grape varieties in a wide range of conditions, the main diseases affecting viticulture remain largely the same, e.g. downy mildew, powdery mildew, grey rot, and wood diseases. Downy mildew tends to reduce yield, while other diseases such as grey rot can cause “off” flavours. Winegrowers therefore need chemicals to maintain good yields, and ultimately to continue to make money.

While some pest-resistant grape types do exist, French PDO¹ wines can only be produced from certain varieties, making an immediate change more or less impossible (Aubertot et al., 2005).

Adopting environmentally friendly viticulture is not a straightforward process, and requires technical assistance. One such way of helping growers transition to “green” practices is through the use of decision support systems (Léger et al., 2010). However, such tools require large quantities of both local and regional data, such as that relating to weather conditions and pest epidemics. Another way to facilitate this reduction is through the use of precision farming technology, such as low spray drift equipment, variable rate dosing, remote sensing, and specialist software. This kind of advanced equipment minimises the quantities of pesticide released into the environment, thereby lessening human exposure and reducing costs (Arnó et al., 2009; Tisseire et al., 2007). Besides implementation costs, much of this advanced farming technology is only suitable for use on large areas of land, whereas vineyards can vary greatly in size and layout. While there are often very large plots in Bordeaux, vineyards and plots in areas such as Champagne and Burgundy may be much smaller, meaning that is neither economically nor practically viable for growers to buy such equipment. In some cases, costs mean that new machinery needs to be shared between several smaller vineyards.

¹ Protected Designation of Origin (PDO): quality wine and spirits with a protected origin, in accordance with Council Regulation 1234/2007.

The study detailed in this paper had two main goals. Firstly, we aimed to create a model to illustrate farmers' decision-making when protecting their crops against downy mildew. The second objective was to assess the effectiveness of certain economic instruments of agri-environmental policies in reducing pesticide use and encouraging the adoption of new crop protection technology.

Section 1 presents the biological and economic principles on which the study was based, our VINEPA model (Vineyard model for Environmental Policy Analysis), and the way in which it was created. Section 2 explains how we linked VINEPA to the Downy Mildew Potential System (DMPS), and in particular how we were able to reduce the vast quantities of data from the latter, using statistical analysis to represent biological risk. Section 3 details the different stochastic models we used. Section 4 shows the panel data from different vineyards. Section 5 presents the results generated by our model. Section 6 examines the effects of taxes in order to identify the possible trade-offs between the reduction of pesticide applications and farmer income.

1 Formulation of the model

Decision making in crop protection involves a certain amount of educated guesswork. Quite obviously, when a grower decides to implement certain measures, he or she has no way of knowing with absolute certainty what will be the result of that decision. The key question is therefore one of decision theory, involving the maximisation of a given criterion (income or utility), the identification of possible actions, and their associated state of nature probabilities. Optimisation techniques are particularly suitable to analysing changes to investment and farm practices, because they allow decision makers to compare a number of different strategies (Hazell and Norton, 1986). Falconer and Hodge (2000, 2001) used mathematical programming methods to evaluate the effects of incentives and taxes on pesticide use on British farmland, looking specifically at the complex effects of those policies on the environment and farmers' income. Apart from the few exceptions mentioned above, public policy instruments to reduce pesticide use are generally analysed using econometric methods, which have the advantage of being able to measure uncertainty from statistical inference, unlike Mathematical Programming, which requires sensitivity analysis.

In a recent paper, Skevas et al. (2012) analysed pesticide reduction policies by assessing the effectiveness of different economic instruments, applying their own simulation model to a data panel of Dutch cash crop farms. They found that even when taxes and penalties were calculated based on the toxicity of different pesticides, farmers were still unlikely to adopt less toxic products. In this particular simulation, quotas were found to achieve a greater reduction in pesticide use. Econometric approaches are however constrained by a need for data. When such data are not available, mathematical programming is a more effective way to analyse unprecedented policies, or policies for which projections cannot be made.

The first bio-economic model (to our knowledge) dealing with the protection of vineyards against downy mildew is that created by Leroy et al. (2010). Ugaglia (2011) developed an evolutionary model to show how integrated pest management could reduce fungicide use in French viticulture. Louchart et al (2000) created a farm-level programming model to analyse the choice between chemical and mechanical weeding. Stochastic models are most effective in cases where data develop over time, and decisions need to be made prior to observing the entire data stream.

Since the publication of Rae's seminal papers (Rae, 1971a, 1971b), Discrete Stochastic Programming or DSP has been widely used in the field of agricultural economics (Aplan and Hauer, 1993; Birge and Louveaux, 1997). One particular focus of this work has been farmers' response to climatic uncertainty (Cortignani, 2010; Kingwell et al., 1993; Maatman et al., 2002). The VINEPA model is the multi-periodic DSP model we created for this study. It is based on the assumption that wine producers maximise their income through a particular decision process. The first decision is when and how often to apply pesticides within a given growing season. The second is a longer-term choice as to whether or not they should invest in precision technology. Such investments will have a knock-on effect both on pesticide levels (because less will be used), and income (because of the cost of the new equipment). Investment can be either through direct cash payments or through borrowing, depending on the financial means of a given grower. In a previous version of the VINEPA model (Souville, 2010), only two general protection strategies were considered: systematic application (based on a pre-defined spraying calendar), and supervised control (based on disease monitoring). However, it is not possible to clearly differentiate these two strategies, and there is a lack of reliable data on their respective costs and benefits. In reality, most French winegrowers actually follow some kind of supervised control strategy (INRA, 2010).

Because the latest version of our model is based on the choice of whether or not to spray a particular product to control downy mildew, it better represents growers' decision making, taking into account the type of fungicide (contact or systemic)², the active ingredient³ and the number of applications during the growing season (fig 1).

² Contact fungicides remaining on the outside of the plant can protect it from new infections for only a short period (7 days) because of new leaf growth and exposure to the environment (rain, ultraviolet light). Such fungicides are usually used for the first and late treatments, often copper (Fig 2). Systemic fungicides form a protective barrier on the plant, permeating into it and moving to both the top and bottom. They therefore play a protective role for both existing leaves and new shoots, guaranteeing efficient protection for a maximum of 14 days.

³ The number of active substances has been limited to the most used ingredients within the Bordeaux vineyard.

Fig 1. Sequence of fungicide applications against downy mildew in VINEPA (Growing season: April 20-August30)

The effects of downy mildew treatment on grape yields are simulated through an epidemiologic model called the Downy Mildew Potential System (DMPS), developed by a group of researchers for the French National Wine Institute. It includes data from weather stations (WS) and untreated wine plots over a ten-year period, monitored on a daily and weekly basis respectively (see §3). Using the results from the DMPS model, it is possible to define the relationships between reduced yield, number of treatments, and type of fungicide used. For other diseases, such as grape powdery mildew (*Erysiphe necator*), grey rot (*Botrytis cinerea*), and pests such as grapevine moths (*Cochylis*, *Eudemis* and *Eulia*) the VINEPA model uses standard values based on common practice in the Bordeaux wine region. Anti-moth treatment is taken to include two strategies: one application of a single-ingredient insecticide, and the use of pheromones for sexual confusion. For aerial spraying of pesticides, growers can choose to either use their existing equipment or invest in precision equipment⁴. For weeding, there are also two choices: chemical (two applications per season) with existing equipment and mechanical (vine-row management with two instances of weeding per season). Where mechanical weeding is chosen, the model only considers the cost per hectare of using machinery. The necessity of purchasing new equipment is not considered in this case, because this kind of machinery is generally already available to winegrowers.

The decision tree for crop protection is summarised in Fig 2.

Fig 2. Decision tree for vineyard protection. PT: Precision Technology (see below).

— Decision Making

The decision variables are as follows:

Technical variables

- Choice of the type of fungicide (p), contact (p_0) or systemic (p_1).

⁴ Herbicides were distinguished from other pesticides, as they are not applied with the same equipment as that used for spraying the canopy. Herbicides therefore are not concerned with reduction of the application rate.

- Number of treatments(n) : for each fungicide treatment against downy mildew, the grape yield response function derived from the DMPS model allows a calculation of the grape yield saved
- Choice of weeding type(w): mechanical or chemical.
- Choice of moth protection(m): by insecticide or by pheromones.

Financial variables

- Savings variable (s_t) : dependant on income, household consumption and the choice of whether or not to invest in precision farming. Savings are available at the beginning of the year.
- Choice of whether or not to invest in precision technologies at rate (i), and type of equipment (e)
- Type of financing(f). This choice is driven by the difference between the cost of credit and the potential interest to be gained from savings. The capacity to finance investment with equity capital is calculated each year based on savings from the previous year, minus minimum household costs.

Assuming that winegrowers will always strive for maximum profit, profit Y for a year t is defined as follows:

$$Y = P \times \bar{Y}_a(p, n) \times TY \times X + OPC - C(e, p, n) \times X - OC(w, m) \times X - R(e, f, i) - M(e, f, i) + s_t$$

Indices: α =states of nature, t = time period, e : equipment, n :number of treatments, w :weeding, m : protection against codling moths, f :mode of financing, i : borrowing rate

With

P :	Price used to value wine production (source: Farm Accountancy Data Network - FADN, average on the period 2003-2007) ⁵
$\bar{Y}_a(p, n)$:	Final yield rate depending on the states of nature and winegrowers' decisions as to the type and number of treatments p and n
TY :	Target yield for the vineyard, which is in France legally limited by PDO regulations (source: FADN, 2003-2007, average quantity of grapes produced over the last five years)
X :	Area in hectares (source: FADN, 2003-2007)
OPC :	Sum of other products, subsidies and expenses (source: FADN, 2003-2007)
$C(e, p, n)$:	Costs of fungicide treatments (downy mildew, powdery mildew and grey rot) depending on the number and the type of applications against downy mildew and the quantity of pesticides applied based on equipment efficiency ⁶
$OC(w, m)$:	Costs of chemical treatments other than fungicides (weeding, grapevine moths)
$R(e, f, i)$:	Annual repayments including interest if equipment is bought on finance and cost of equipment if bought in cash
$M(e)$:	Repair and maintenance costs related to equipment used, set at 10% of the purchase price
s_t :	Savings set at the beginning of the year and valued by a saving rate at the beginning of the following year

In the French wine industry, producers of less expensive entry-level wines, which account for the majority of Bordeaux wine estates, often have limited savings. It is therefore important to take into account the financial constraints of those producers. Consequently, financial constraints are included in the model using the following formula:

$$\text{Equipment payment } (e) < \text{available cash } (t)$$

These constraints are considered to be cash constraints when equipment is purchased using a grower's equity capital. Cash availability depends on a producer's average outgoings in a given year⁷.

Because investment is carried out over a long period, the VINEPA model uses a dynamic, multi-periodic approach to study the impact of different environmental policies. The decisions taken and the amount of money earned in a given year will inevitably have a knock-on effect on the initial data in the following year $t + 1$.

Because income needs to be re-assessed on an annual basis, it needs to be calculated based on a discount rate, which allows future values to be converted into present value, taking into account the preference for immediate satisfaction.

2 Modelling local epidemiological risk

⁵ The base price is computed from theoretical wine yield (hectolitres) and the gross value of production (euros) of different products (wine in bulk and bottle, fresh grapes, musts, and by-products, e.g. pomace and lee).

⁶ In assessing sustainable farming technology, capital budgeting studies concentrate on farm size and profitability thresholds, whereas economics highlights the importance of farmers' individual characteristics, level of expertise, risk and uncertainty (Adrian et al., 2005; Greiner et al, 2009; Marra et al., 2003). Risk may be linked to new technology, as new equipment may not have the expected maximum effectiveness. Its expected performance is considered to be distributed around an average value (see technical references) although real performance is actually unknown by the farmer. The performance of PT equipment is assumed to follow a distribution formalised in three classes, marked out by the first and third quartiles. Low and high levels of performance therefore have a probability of 25% and the average level a probability of 50%. This level of performance is considered to remain unchanged from one year to another during the simulation period. Although training plays a significant role in the adoption of new technology (Sunding and Zilberman, 2001), we consider that skills are immediate without any additional costs.

⁷ We set the outgoings at 18,000 EUR per family worker, based on the average wage of a qualified farm worker wage in 2006.

Downy and powdery mildew can completely destroy both grapes and leaves. Its severity depends on weather conditions and epidemiological pressure. There are no visible early warning signs, meaning that by the time the infection is visible, it is often too late to prevent it. The disease spreads exponentially, i.e. if an initial case is not treated promptly, the next case of infection will be even more severe. Because curative treatments are ineffective if applied more than 3 or 4 days after the initial contamination, growers tend to favour the use of preventive treatments, as they afford a much more reliable means of protection.

In order to achieve maximum effect, preventive fungicides need to be applied on a regular basis. For inland vineyards, this means at least 5 treatments per growing season. For properties situated close to the Atlantic coast or in the higher latitudes, daily applications of chemicals can be more than twice that number.

Mildew contamination is usually triggered by periods of heavy rain. However, wet conditions do not automatically lead to infection. In order for mildew to take hold, there needs to be a large quantity of mature *inoculum*, or spores.

2.1 Downy Mildew Potential System

The Downy Mildew Potential System (DMPS) is an epidemiological model to predict the probability that vines will be infected with downy mildew. Initially developed by researchers from SESMA (Strzyk, 1994; Raynal, 1994, 2010), it has been in use with the French Vine and Wine Institute (IFV) since the early 90s. Since 2001, the weekly probability of infection has been published on the official website of the French winegrower's union. The predictions made by the DMPS model are continuously compared with statistics gained through weekly monitoring of a number of "test sites" where vines are purposely left unprotected against disease. This allows researchers to verify the reliability of the advice being given to growers.

Downy mildew can affect vines at varying levels of severity. This is reflected in the diagrams displayed in Figure 3, which are based on DMPS simulations for the Bordeaux area over the last five years. The infection shown is at "bunch close" stage during the last ten days of July. As can be seen, the level of infection predicted by the model is consistent with that actually encountered after incubation (ten to fifteen days).

Weather stations (WS) were used in the model to represent the conditions where certain vineyards are located. For our study, simulations were carried out for 26 different WS sites spread across the Bordeaux wine region (Figure 5), over a period of 12 years (2001 to 2011).

Figure 3. Onset of downy mildew at the "bunch close" stage (20th of July) from 2008 to 2012 (upper line of the table). To be compared with the severity of infection observed on test sites in early August (end of ripening phase) i.e. after the incubation period for infections occurring around 20th of July (lower line).

The model assumes that the biological cycle of downy mildew will change with local weather conditions. Because of this, simulations are calibrated based on historical weather data. This ensures that the model is being applied to an area of homogenous meteorological characteristics.

Figure 4. Progressive severity of onset of downy mildew (Blanquefort WS) in 2000. Red bars show the effectiveness of one instance of treatment, calculated on the date of application. Also shown are the effectiveness of individual treatments (as part of a treatment plan), and the level of damage still present at harvest time (20th September).

For each simulated year, the DMPS model provides certain information, such as the extent of damage caused by each case of rain-induced infection. This is shown in Figure 4 as the theoretical consequences of infection. The success rate required for a treatment to be considered effective is set at 95%.

The efficiency of a treatment plan — which can be applied either partially or totally — can then be evaluated based on length of spraying period, effectiveness of a given treatment, and the length of time for which vines remain protected. Effectiveness is calculated based on the amount of damage prevented for each case of infection, as estimated by the model.

Based on these settings, the model can estimate to what extent infection will be reduced if the vines are sprayed in a certain way. The sum of these estimations provides an indication of the total amount of grapes saved from infection.

Fig. 5 - Location of the winegrowing farms (FADN) with location of meteorological WS

2.2 Analysing the results of the epidemiological model

Since we had such a large quantity of DMPS information to deal with (data from 26 WS over a period of 12 years) it was necessary to carry out a preliminary analysis (Rouire, 2012). The risk of reduced yield caused by downy mildew depends on the location of a vineyard (in relation to a given WS), the year, and the number of treatments applied.

Because these three factors are difficult to analyse simultaneously, we decided to analyse two factors, while fixing the third criterion, i.e. different locations and levels of infection prevented by treatment for a particular year (fixed factor). For a given year, comparing WS with the level of infection prevented allows the “epidemiological profile” of stations in a given area to be identified. It also means that WS with similar characteristics can be grouped together.

Where the fixed factor is that of the WS, it is possible to evaluate the effectiveness of different treatments from one year to the next. We used different variance analyses (ANOVA)⁸ to identify the effects of the three factors affecting yield.

To find out whether or not the interaction between the “WS” and “treatment” variables has any effect on yield, we used a repeated two way-ANOVA analysis. Applying the Fischer test to our results, it was possible to deduce that yield losses vary significantly depending on the WS. We also used the Contrast Method to compare WS, which showed that this variation was not significant for all stations, and that those not significantly different could be grouped together using classification. For the year factor, yields were calculated sequentially several times for the same WS at different times (every year).

Because the condition of independent factors is not verified, we used a two-factor ANOVA for the “treatments” and “year” factors. Fisher test showed that years, treatments, and the interaction between the two have a direct effect on yield levels. On this basis, we concluded that epidemic pressure varies significantly depending on the year, irrespective of the WS being studied. Because of that, it was not possible to calculate average values. We therefore decided to simplify the construction of each simulation by identifying groups of years with a similar epidemiological profile.

Using the R software (Hudson, F et al. 2010), we carried out a series of factor analyses to identify the structure of the relationships between variables (Principal Component Analysis), classify those variables, and group together similar years and WS (Joining Tree Clustering).

Clustering was first applied to WS for each year. While some WS have similar characteristics year on year (often relating to their geographical location, but not always), many groups of stations are completely different from one another. Because of this, it was impossible to conclude that the vineyards located in these areas would have similar yields from one year to the next. Clustering was therefore not effective when applied to WS.

Following this, we decided to create clusters of years, allowing us to identify time periods with similar epidemiological characteristics. These groups of years were the same for all WS: group1: 2007 alone, group2 (2000, 2008, and 2009) and group 3 (2001, 2002, 2003, 2004, 2005, 2006, 2010, and 2011). These groups were then inputted into the model with their corresponding probabilities of occurrence (Fig. 6).

Fig 6. Analysing data from the DMPS model. Dendrogram for gathering years (Hierarchical clustering).

⁸ Multiple ANOVA on 3 factors was not possible because of the limited number of observations by crossing the modalities of the 3 factors (1 yield measurement per crossing).

3 The Discrete Stochastic Model

3.1 Scenarios

The main challenge faced by a grower in dealing with downy mildew is to choose when and how many times to spray their vines, depending on the risk of infection in a given year. In our model, this is represented by a random parameter (downy mildew infection), the only such parameter taken into account.

The data from the DMPS model provided us with a theoretical level of yield achieved, based on the number of treatments applied on particular dates over a 12-year period. We assumed that the probability of a given year having a given set of characteristics is 1/12, thus leaving us twelve possible scenarios of epidemic pressure.

The disadvantage of a scenario-based approach is that the VINEPA model grows exponentially with the number of random events and number of years simulated. For example, a simulation over a period of five years will generate 248,832 scenarios (12^5). To simplify the model, we used the data analysis mentioned above to reduce the number of simulated scenarios, grouping together years with similar epidemiological profiles. There were three groups, with probabilities of 1/12, 3/12 and 8/12 respectively. This allowed us to reduce the number of scenarios down to 243 (3^5).

3.2 Implemented models

To analyse the effects of economic instruments of public policy on winegrowers, it is necessary to model their behaviour. The question of how best to do this is a complex one. The difficulty lies in the uncertain environment in which winegrowers work, which in turn affects their decisions relating to pesticide use.

Stochastic programming models take advantage of the fact that probability distributions governing the data are known or can be estimated.

While problems of deterministic optimisation are formulated using known parameters, real-world situations can present a variety of unknown elements. One example of this is the fact that it is impossible to predict with complete accuracy the effect fungicide spraying will have on the onset of downy mildew.

When the parameters are known only within certain bounds, robust optimisation is one approach to tackling such problems (see "worst case" below). The objective of this kind of approach is to find a solution which is possible for all data, and optimised as far as possible.

In the scenarios we worked on, the DMPS model provided the effectiveness of individual treatments for a given year. For this reason, we did not consider the second decision-making phase (recourse decision), because once a particular treatment has been applied, the effects of subsequent sprayings are intrinsically linked to those of the initial application, making remedial action impossible.

The objective of the VINEPA model is to maximise the total income of a winegrower over several years. Several approaches were used to manage uncertainty and winegrower preference. We used GAMS to program a number of different versions of the VINEPA model, not all of them linear. They were then solved using three different solvers: Dicopt, Conopt3, and Cplex.

Theoretical work on risk management defines risk as the uncertainty of events (weather, epidemics or prices). The consequences of those risks (production levels and income) are therefore uncertain. A set of values for uncertain events can be called a state of nature that has a corresponding probability of occurrence.

The Expected value model

The first and easiest way to solve the winegrowers' problem is to replace random parameters by their expected value. The expected value function then becomes the maximisation of expected profit, given different states of nature. Our model (as presented in appendix 1) provides the optimal solution that a grower would adopt if his sole aim was to maximise his expected revenue.

If (Ω, F, P) is a discrete probability space where $\omega \in \Omega$ are events (scenarios), $f_t^\omega(x_t, x_{t-1}, y_t, y_{t-1})$ is the objective function associated with the completion of the event ω and $p(\omega)$ is the probability associated with this event. Considering our multi-period MINLP model, the corresponding expected value model is constructed as follows:

$$\begin{aligned} \text{Max } Z &= E \left[\sum_t f_t^\omega(x_t, x_{t-1}, y_t, y_{t-1}) \right] \\ &= \sum_{\omega \in \Omega} p(\omega) \sum_t f_t^\omega(x_t, x_{t-1}, y_t, y_{t-1}) \end{aligned}$$

Subject to constraints (1) to (13) cf. appendix 1

If the expectation of random data is considered, the optimal solution generated may not be the best for certain scenarios. However, this kind of model provides a good overview of the best average solution, not necessarily the one that would be chosen by the growers themselves.

Worst and best case scenarios

We carried out simulations for worst and best case scenarios, allowing us to set upper and lower limits of income. Modeling the problem for worst case scenarios is a very pessimistic approach. However, it provides information about the number of growers who will invest in the most pessimistic way, and what their treatment strategy will be if nature (e.g.

epidemiologic events) does her worst by selecting the state of nature that minimizes their income. In essence, the best (optimum) decision is the one whose worst outcome is at least as good as the worst outcome of any other decisions. The pessimistic model is one of the most important tools in robust decision making and particularly robust optimisation, where it is referred to as the “Maximin Criterion”.

The optimum solution for this model is that which provides maximum benefit to the grower in cases where pest epidemiologic pressure is at its very worst.

The problem is simply written by:

$$\begin{aligned} & \text{Max} \sum_t f_t^{\omega_p}(x_t, x_{t-1}, y_t, y_{t-1}) \\ & \sum_t f_t^{\omega_p}(x_t, x_{t-1}, y_t, y_{t-1}) \leq \sum_t f_t^{\omega}(x_t, x_{t-1}, y_t, y_{t-1}) \quad \forall \omega \in \Omega \end{aligned}$$

where ω_p is the worst scenario.

The optimum solution provides is therefore the lower limit of the objective function of the overall problem.

Modeling for the best case scenario will find the decision that generates a highest level of winegrower income that is at least as good as the best income for any other decision.

That is:

$$\begin{aligned} & \text{Max} \sum_t f_t^{\omega_b}(x_t, x_{t-1}, y_t, y_{t-1}) \\ & \sum_t f_t^{\omega_b}(x_t, x_{t-1}, y_t, y_{t-1}) \geq \sum_t f_t^{\omega}(x_t, x_{t-1}, y_t, y_{t-1}) \quad \forall \omega \in \Omega \end{aligned}$$

where ω_b is the best scenario.

“Wait and See” approach

The “Wait-and-See” approach assumes that the decision maker already has information on the realisation of the random variables before making a decision.

Consequently, for each scenario, it is possible to find an optimal solution, as it would be if the parameters were distributed in a deterministic way, and the expected values of the solutions were being calculated.

This approach provides information about what would be the optimum decisions for winegrowers to make if they had a perfect knowledge of epidemic pressure. Clearly, this would never be the case in reality, however effective any decision-making tools used.

Mean-Standard deviation model

Economic theory tells us that winegrowers are generally risk averse, preferring lower income and greater security over a higher level of expected income with less security. Many studies have confirmed this hypothesis (OECD, 2009), with a number of methods being developed to take this behaviour into account when modeling risk. These different approaches are discussed in detail in Apland and Hauer (1993). They aim to describe as accurately as possible the attitude of farmers dealing with random events.

Of all these approaches, the concept of the utility function is the most common. It implies that a risk-averse agent will prefer a guaranteed level of income rather than being subject to a lottery. From the expected profit $E[Y]$ presented in the appendix 1 for the deterministic model, an alternative and allegedly better decision criterion to that of the expected monetary value is the maximization of the expected utility, i.e. expectation of $U(Y)$.

The most straightforward approach is the mean-variance (*EV*) analysis. It is the most appropriate when the probability distribution of outcomes is normal, since the mean and variance completely describe such distribution. Where this is not the case, (*EV*) analysis is still appropriate when the decision maker utility function is a quadratic. This model makes it possible to translate the preference for a lower but more secure income.

Because computed values of variance are often very high, and not measured in the same units as the random variable Y , we used standard deviation instead of variance.

We used the mean-standard deviation model (Hazell and Norton, 1986; McCarl and Spreen, 1997) to translate the growers' preference for lower but safer income. It is based on the *EV* model where $E[U(Y)] = E[Y] - \frac{1}{2}\beta V[Y]$ (Freund, 1956) and where β is a risk-aversion parameter.

The objective function therefore becomes:

$$\text{Max } Z = E(Y) - \varphi \sigma_Y$$

where $E(Y)$ is the expected income, φ a risk aversion coefficient and σ_Y the standard deviation of Y .

Expectation of revenue is calculated from the aforementioned expected value model while the standard deviation depends on different scenarios. If Y_ω denotes the income obtained over the whole planning horizon for scenario ω , then:

$$\sigma_Y = \sqrt{\sum_{\omega \in \Omega} p(\omega) \times (E(Y) - Y_\omega)^2}$$

4 Data

VINEPA uses panel data drawn for 105 wine estates representative of the Bordeaux region, drawn from the Farm Accountancy Data Network (FADN), which provides structural, economic, and financial information (Agreste 2003-2007). Figure 6 gives an overview of all the other data used and how they were obtained.

The data relating specifically to Bordeaux show large disparities in cash flow, profit, and grape valuation prices (Appendix 2, Table 1) between different *appellations* (winemaking areas). There are also similar disparities between individual wine estates within those areas. Many growers exhibited negative cash flow figures, which is indicative of the current financial crisis affecting wine production. Because of the variable nature of the data, we decided to apply the model to each individual property.

Since the FADN neither includes agricultural practices nor differentiates pesticide expenditure by active ingredient or by categories of pesticides (herbicides, fungicides, insecticides), we had to look elsewhere for our pesticide-related data. As a result, information on empirical application rates, active ingredients and commercial products used by farmers was extracted from survey on winegrowing practices conducted in 2006 by the Ministry for Agriculture on 5,216 vineyard plots (670 plots in Bordeaux) (Agreste, 2006, 2010).

Yield levels in Bordeaux viticulture are subject to certain restrictions. While the PDO regulations impose an arbitrary upper limit, the growers themselves may artificially limit production in order to ensure a quality end product. In view of this, the target yield used by our model was the average quantity and price of wine produced over a five-year period (2003-2007). Wine farms were grouped together at local scale by sub-regions of Bordeaux such as Médoc, Pomerol-Saint-Emilion, Graves, etc. In the small number of cases where the data available for a given *appellation* was limited (only a handful of estates), we merged neighbouring groups together. This was a logical choice, because these areas shared common production systems (grape cultivars, vine density, yield, trellising systems, etc.). They were also subject to similar pest problems and weather conditions. It therefore made sense to calculate average application rates by area.

The database used for recommended application rates and the cost of inputs was compiled by Bonet et al. (2006) from INRA Montpellier. The sources and descriptions of data are detailed in Appendix 2, Table 3.

Technical specifications for precision equipment

The costs and benefits of new technologies in precision viticulture (particularly for pesticide spraying) have been extensively looked into. They have also been the topic of a number of field studies such as the AWARE (Ruelle and De Rudnicki 2009), OPTIDOSE (Davy and Heinzlé, 2009) and OPTIPULVE projects (Heinzlé et al., 2010). When evaluating investment choices, the model considers five possible types of precision spraying equipment, referred to as B, C-, C, C+ and D. Lescot et al. (2011) provides further information on precision technology equipment.

These categories are based on machinery that has been commercially available since the late 2000s. The price used for the model is the median market price. Data on pesticide savings come from field trials recently conducted by Irstea Montpellier and the French Institute of Wine.

VR Equipment	Purchasing price (€)	Average fungicide savings (%)		
		Low (p=0,25)	Medium (p=0,5)	High (p=0,25)
B :Basic	3500	5%	10%	20%
C-: Tunnel sprayer	10000	5%	15%	30%
C : Tactical control	20000	10%	24%	41%
C+: Spatial control	35000	15%	32%	51%
D : Embedded control	67500	28%	44%	61%

Compared to farm revenues and total costs, pesticide expenditure is comparatively low (700 €/ha on average) with almost half dedicated to preventing downy mildew (appendix table 2). Chemicals to protect vines against downy and powdery mildews are often sprayed at the same time (2 or 3 applications) resulting on average in 10.3 runs and 16.7 applications⁹ within the Bordeaux region.

⁹ Application of different products: 1 run with 2 different products = 2 applications

Fig.7 – Data description and sources

5 Results

Distributions of the variable representing the number of applications against downy mildew are presented for the different models in Figure 8 A-D. The VINEPA model outcomes with 9 to 10 applications accurately reflect the chemical protection strategies observed in 2006 and 2010 (Agreste, 2006, 2010) on Bordeaux plots receiving an average of 8 to 9 treatments (Fig 8A).

It is important to note the bimodality of the distribution of the variable number of treatments, giving a strong indication that the distribution of the variable is not normal. This bimodality can be interpreted in two ways. It can either be seen as representing two distinct attitudes towards downy mildew protection, or as the result of a simple overlap in distribution between contact and preventive treatments.

For the worst case scenario, the distribution has only one mode and is also symmetrical, in contrast to the best case scenario, where the distribution is multimodal with three “peaks”. In addition to indication that the distribution of the variable in population is not normal, this distribution (Fig 8D) could reveal more obviously the diverse attitude of farmers towards risk in comparison to the other models (Fig 8A-C).

Fig 8. Model outcomes showing the number of pesticide applications to protect grapevines against Downy mildew (standard spraying equipment) Fig A-D clockwise

6 Environmental policy

Different environmental policies could potentially encourage reduced use of pesticides in agriculture. The instruments that could be used in doing this can be divided into six groups: regulation, information-persuasion-awareness, technological and institutional change, bilateral arrangements, market-based instruments, and private law instruments. The VINEPA model was developed to examine market-based incentives, such as taxes and targeted subsidies. It illustrates the extent to which those incentives effectively promote both a less widespread use of pesticides, and changes in farming technology, i.e. shifting from current standard equipment to more environmentally-friendly machinery. Because of space constraints, the results included in this paper are confined to taxes and their effects on management practices, i.e. reduced pesticide use, changes in the types of pesticide applied, and the use of precision equipment.

6.1 Taxes on pesticides

The main aim of pesticide taxes is to reduce their use. Most previous *ex ante* analyses of the regulation of pesticides have concluded that they are effective in doing so. However the design of a tax (e.g. whether it is *ad valorem* or volume-based) may play a role in determining that effectiveness. For *ad valorem* taxes, charges can be calculated based on retail price or the price of active ingredients. Some taxes may be specific to a given type of ingredient, while others may also take into account particular environmental risks. In 1996, as part of a pesticide action plan, Denmark introduced an ambitious *ad valorem* tax on pesticides (PAN, 2005). The tax, based on maximum retail price, was different depending on the type of chemical. Herbicides and fungicides were taxed at 34%, while a 54% rate was applied to insecticides. While the action plan as a whole led to a general decrease in the use of pesticides, the role of taxation alone in achieving this result remains unclear (Hoevenagel et al., 1999). Today, Denmark is restructuring its tax system so that those pesticides posing the greatest risk to human and environmental health will be subject to the highest taxes, whilst less harmful plant protection products will be taxed at a lower rate.

In France, pesticides are taxed based on active ingredients and their respective toxicity classifications¹⁰. This tax was first devised in 2006 as part of the National Water Law (Loi n°2006-1772). It has been levied on pesticide retailers since 2008. In 2010, category 1 pesticides were taxed at 5.10 € per KG, category 2 at 2 € per KG, category 3 at 0.90 € per KG. Category 4 pesticides were exempt from the tax.

The impact of taxation on pesticide use in treating downy mildew is subject to a number of factors. The potential impact of a tax depends heavily on the substitution¹¹ or complementary¹² effect between the pesticides used. Taxes are applied based on specific active ingredients, and not on individual commercial products. Therefore, taxing one ingredient may have the unintended effect of increasing the price of a product where that particular ingredient is combined with another, less harmful one.

In our model, the effects of taxation are considered only in terms of substitution, i.e. to what extent farmers will change from using one ingredient to another, rather than a change in the commercial product they spray.

The main effects expected from taxes are the following:

¹⁰ There are four categories according to the Law: category I (toxic, very toxic, carcinogenic, mutagenic or toxic for reproduction), category II (Harmful for the environment), category III (Mineral substances harmful for the environment) and category IV (other active substances).

¹¹ In the case of substitution, a higher tax on one active ingredient will make other active ingredients relatively cheaper and more attractive. This will have a positive impact on the effects of a differentiated tax.

¹² There is complementarity when the use of one pesticide has a clear connection with the use of another pesticide (particularly pesticides including two or more active ingredients like contact + systemic fungicides usually applied against downy mildew). In this case, tax on active ingredients may have little impact.

- changes in the number of treatments applied depending of the type of action (contact and systemic),
- change in the use of active ingredients,
- change in pesticide costs depending on the change in the use of pesticides and the rate of the tax,
- change in total costs (depending on the pesticide costs and the cost-share of pesticides),
- change in revenues and gross margin,
- change in spraying equipment (from present standard to precision technology).

The two aforementioned types of taxes (*ad valorem* and volume-based) at different rates were assessed in terms of their potential impact on pesticide use and on the adoption of precision equipment to spray fungicides and insecticides. For the *ad valorem* tax type, we experimented with two different tax rates (50% and 100% of the retail price), for all ingredients, irrespective of toxicity. For the volume-based tax type, we tested different tax rates (from 3 to 16 times the present level). Table 1 gives an overview of the scenarios generated and their respective tax rates.

Table 1. Taxes and rates assessed with the VINEPA model

Toxicity classes	Ad valorem tax		Volume based tax (French Water Law) per kg or litre of active ingredient							
	Uniform	Differentiated	x1	x 2	x 4	x 6	x 8	x 11	x 16	
4	50% 100%	0%	0,00 €	0,0 €	0,0 €	0,0 €	0,0 €	0,0 €	0,0 €	
3	50% 100%	10%	0,90 €	1,8 €	3,6 €	5,4 €	7,2 €	9,9 €	14,4 €	
2	50% 100%	20%	2,00 €	4,0 €	8,0 €	12,0 €	16,0 €	22,0 €	32,0 €	
1	50% 100%	50%	5,10 €	10,2 €	20,4 €	30,6 €	40,8 €	56,1 €	81,6 €	

x1: Present (baseline)

Impacts on pesticides use and spraying applications

In the first series of scenarios, we consider that farmers use their standard spraying equipment and do not have access to precision technology. Increasing the level of taxes results in a slight reduction in fungicide applications (about one treatment per year), highlighting the inelasticity of demand in relation to prices. The only way for demand to be reduced through taxation is by a drastic hike in the amount being levied. Outcomes by tax type and rate are shown below (tables 2A-B, 3A-B).

Ad-valorem tax

Limit models

In these two cases, there is a decrease in the number of spraying applications, whatever the type of fungicide, as can be seen in table 2A. This reduction is more significant for the best case scenario, showing that there is significant room for pesticide reduction in those scenarios. That reduction is much more significant at the highest tax rate (100%), with a 36% reduction (from 6.2 to 3.9 treatments). In the worst case scenario, the shift ranges from 9.2 to 8.1, representing a 12% decrease.

Where a 50% tax rate is applied, pesticide use is slightly less reduced, with a 6% reduction in the worst case scenario, and a 19% drop in the best case scenario.

Approximate models

For the approximate models, reductions are similar to those achieved in the worst case scenario, with a reduction ranging from -7 to -9% for a 50% tax rate, and a reduction of treatments from -15 to -17% when a 100% rate is applied. There is no shift between types of fungicide.

"Wait and See"

The relative decrease in the number of treatments (-11% for a 50% tax rate and -20% for a 100% tax rate) is slightly higher than the reduction achieved with other models (except the best case scenario).

Table 2A: Average number of applications with different rates for an *ad valorem* tax (precision technology not considered)

Uniform ad valorem Tax - Standard technology												
	Utility function	no tax			tax rate 50%				tax rate 100%			
		p0	p1	total	p0	p1	total	variation	p0	p1	total	variation
Worst of cases		2,8	6,4	9,2	2,4	6,3	8,7	-0,06	2,0	6,1	8,1	-0,12
Best of cases		2,2	3,9	6,2	1,7	3,2	5,0	-0,19	1,4	2,5	3,9	-0,36
Approximate models	E(Y)	2,4	6,5	8,8	1,9	6,2	8,0	-0,09	1,5	5,8	7,3	-0,17
	E[U(Y)]	2,6	6,5	9,1	2,2	6,3	8,5	-0,07	1,7	6,0	7,8	-0,15
Wait and See model		2,6	5,0	7,5	2,2	4,5	6,7	-0,11	1,9	4,1	6,0	-0,20

E(Y): Expected value model, E[U(Y)]: Mean standard deviation model

Volume based tax

Limit models

In these cases, there is no real change in spraying practices. There is a slight reduction at the highest tax rate simulated set at 16 times the present level (reduction from -4% to -9% depending on the model considered). The lowest reductions

can be seen in the best case model, where preference is progressively given to contact fungicides as the tax rate rises, particularly Metiram–Zn (a fungicide in toxicity class 4, and therefore tax exempt).

Approximate models

Results are similar to those of the limit models, with only a small decrease for the highest rates. The gradual reduction ranges from -1% to -9%. When the results for the two formulations of the approximate model are compared, it can be seen that including risk in the objective function results in a slightly higher number of sprays (+0.3 on average).

“Wait and see”

There is a similar very small reduction in spraying (ranging from -1% to -4%) following an increase in tax. The progressive shift from systemic to contact fungicides is similar to that found in the best case model. This change is not observed for the other models.

Table 2B. Average number of applications with different rates for a volume based tax (precision technology not considered)

Volume based tax (French Water Law) - Standard technology												
	Utility function	present			x 2				x 4			
		p0	p1	total	p0	p1	total	variation	p0	p1	total	variation
Worst of cases		2,8	6,4	9,2	2,8	6,3	9,1	-0,01	2,7	6,3	9,0	-0,01
Best of cases		2,3	3,7	6,1	2,5	3,5	6,0	-0,01	3,0	3,2	6,1	0,01
Approximate models	E(Y)	2,4	6,4	8,7	2,4	6,3	8,7	-0,01	2,3	6,2	8,5	-0,02
	E[U(Y)]	2,6	6,5	9,1	2,6	6,4	9,0	-0,01	2,5	6,4	8,9	-0,02
Wait and See model		2,6	4,8	7,4	2,7	4,7	7,4	-0,01	2,9	4,5	7,5	0,00
	Utility function	present			x 8				x 11			
		p0	p1	total	p0	p1	total	variation	p0	p1	total	variation
Worst of cases		2,8	6,4	9,2	2,6	6,3	8,9	-0,03	2,6	6,2	8,8	-0,04
Best of cases		2,3	3,7	6,1	3,3	2,8	6,1	0,01	3,3	2,7	6,0	-0,02
Approximate models	E(Y)	2,4	6,4	8,7	2,2	6,2	8,4	-0,04	2,2	6,1	8,2	-0,06
	E[U(Y)]	2,6	6,5	9,1	2,4	6,3	8,7	-0,04	2,2	6,3	8,5	-0,07
Wait and See model		2,6	4,8	7,4	3,0	4,3	7,4	-0,01	3,1	4,2	7,3	-0,02

6.2 Potential impact on the adoption of precision viticulture equipment

In the previous results, potential investment in fixed-capital was not considered, with pesticide treatments being applied by constant standard spraying technology. However, since the late 2000s, precision farming technologies initially developed for arable crop and horticulture, have been adapted for winegrowing and slowly introduced in the European farm machinery market. By introducing equipment choice, increasing taxes are supposed to promote the adoption of precision technology (PT), in addition to triggering a reduction in treatment frequency.

The results generated by our model show that almost half of the wine estates studies could conceivably invest in some basic precision equipment. Some properties even have the capacity to invest in more advanced equipment. The number of farms investing in PT depends on the model used (Appendix 3, Fig.1 & 2). In the best case model, farmers are less willing to invest in PT than in other, more uncertain situations. When we compare the number of treatments with the opportunity to invest or not, we note that investment in PT does not result in less applications. This however does not imply an increase in the total quantities applied, as PT allows less pesticide to be used at each application. Model outcomes relating to practices are summarized in Tables 3A and 3B. Depending on the model used, the following results are obtained:

Ad-valorem tax

Limit models

Where the tax rate is set at 50%, over half of all growers opt for equipment in categories B and C, i.e. the least expensive. Of this proportion, most choose category B machinery, which is the most basic. Where a 100% tax rate is introduced, winegrowers are more likely to invest in more advanced equipment, such as that in categories C and C+. In the worst case scenario, a larger number of farms adopt precision technology, but preference is still given to the most basic equipment.

When farmers have the opportunity to invest in precision technology, increased taxation results in a similar reduction in treatments applied. This reduction is however lower than for the cases when farmers do not have access to precision technology. Reductions achieved at the highest tax rate range from 9% (worst case scenario) to 32% (best case scenario). These results can be explained by the amount of pesticide saved through the use of such equipment.

Approximate models

The same effect is observed with the approximate models for the 50% and 100% tax rates, with reductions of 13% (expected value model) and 15% (mean-standard deviation model) for the highest rate of 100%.

“Wait and see”

A comparable reduction in the number of spraying applications is achieved with a higher tax rate. When the opportunity to invest in precision technology is given to farmers, reductions in the number of treatments following taxation are more limited, when compared with other cases where only standard equipment is considered.

Table 3A. Average number of applications with different rates for an Ad valorem Tax when precision technology opportunity is considered

Uniform ad valorem Tax - Precision Technology												
	Utility function	no tax			tax rate 50%				tax rate 100%			
		p0	p1	total	p0	p1	total	variation	p0	p1	total	variation
Worst of cases		2,8	6,4	9,2	2,5	6,3	8,8	-0,05	2,1	6,2	8,4	-0,09
Best of cases		2,3	4,0	6,3	1,8	3,4	5,2	-0,17	1,5	2,7	4,3	-0,32
Approximate models	E(Y)	2,4	6,5	8,9	1,9	6,2	8,1	-0,09	1,6	5,9	7,6	-0,15
	E[U(Y)]	2,7	6,6	9,2	2,3	6,4	8,6	-0,06	1,8	6,2	8,0	-0,13
Wait and See model		2,6	5,0	7,6	2,3	6,4	8,6	0,14	2,0	4,3	6,3	-0,17

E(Y): Expected value model, E[U(Y)]: Mean standard deviation model

Volume based tax

Trends are similar to the outcomes of the *ad valorem* tax, with a slight decrease or even no change of the number of applications. The biggest reduction is obtained with the approximate models (-7%). For the best case and the “wait and see” models, increasing tax has no effect on spraying practices. We can suppose that these models express the lowest possible number of spaying applications that guarantee effective protection from downy mildew. Consequently, increasing the tax rate does not impact the number of treatments.

Table 3B. Average number of applications with different rates for a Volume based Tax when precision technology opportunity is considered

Volume based tax (French Water Law) - Precision Technology																
	Utility function	Present			x 2				x 4				x 6			
		p0	p1	total	p0	p1	total	variation	p0	p1	total	variation	p0	p1	total	variation
Worst of cases		2,8	6,4	9,2	2,8	6,3	9,2	-0,01	2,8	6,3	9,1	-0,01	2,8	6,3	9,1	-0,02
Best of cases		2,4	3,8	6,2	2,5	3,6	6,1	-0,02	3,0	3,3	6,3	0,02	3,2	3,1	6,3	0,02
Approximate models	E(Y)	2,4	6,4	8,8	2,4	6,3	8,8	-0,01	2,4	6,3	8,7	-0,01	2,4	6,3	8,6	-0,02
	E[U(Y)]	2,6	6,5	9,1	2,6	6,4	9,0	-0,01	2,6	6,4	9,0	-0,01	2,5	6,4	8,9	-0,02
Wait and See model		2,6	4,9	7,5	2,7	4,8	7,5	-0,01	2,9	4,6	7,5	0,00	3,0	4,5	7,5	0,00
	Utility function	Present			x 8				x 11				x 16			
		p0	p1	total	p0	p1	total	variation	p0	p1	total	variation	p0	p1	total	variation
Worst of cases		2,8	6,4	9,2	2,7	6,3	9,0	-0,02	2,7	6,2	8,9	-0,03	2,5	6,2	8,7	-0,05
Best of cases		2,4	3,8	6,2	3,2	3,0	6,2	0,01	3,3	2,9	6,2	0,00	3,6	2,6	6,2	0,00
Approximate models	E(Y)	2,4	6,4	8,8	2,3	6,2	8,5	-0,04	2,3	6,1	8,4	-0,05	2,1	6,1	8,2	-0,07
	E[U(Y)]	2,6	6,5	9,1	2,5	6,3	8,8	-0,03	2,4	6,3	8,7	-0,04	2,2	6,2	8,5	-0,07
Wait and See model		2,6	4,9	7,5	3,0	4,5	7,5	-0,01	3,1	4,4	7,4	-0,01	3,2	4,2	7,4	-0,02

E(Y): Expected value model, E[U(Y)]: Mean standard deviation model

7 Conclusion

When modeling winegrowers’ behaviour, we made the standard assumption that producers always aim to maximise their profits, and will consequently use pesticides as long as marginal costs are less than the marginal benefits obtained. While our study did not take into account irrational over-use of pesticides, we examined the issue of risk, and farmers’ preferences relating to that risk.

The outcomes of our simulations show that fungicide use is more or less completely unaffected by increases in the price of pesticide. This confirms the findings of a number of previous econometric studies, which demonstrate the low price elasticity of demand relating to agricultural pesticides (Hoevenagel, 1999).

With this in mind, it would be logical to assume that pesticide taxes will only have a short term effect on the reduction of pesticide applications to protect vines from mildew, while at the same time generating high tax revenue for the governments who impose them. While generating additional public money is not the primary objective of such taxes, such surplus funds can be earmarked for further agricultural investment, such as subsidising farmers who wish to purchase precision technology, thus reducing the financial burden of fixed capital expenditure.

Our results are in line with previous studies showing that there are few viable ways of reducing pesticide use in viticulture without compromising yield. This means that growers are restricted in the extent to which they can change their agricultural practices.

In the short run, the only way of effectively altering winegrowers' behaviour is through greater taxation, but such increases may prove politically sensitive.

As would be logically expected, there are less pesticide applications in the best case scenario, when epidemic pressure is perceived as low, and the weather conditions are the least conducive to the spread of infection. Obviously, these conditions do not occur every single year.

A clear representation of random events (such as those simulated in the "wait and see" model, is extremely useful in reducing pesticide use. It shows that the introduction of decision-making tools could lead to a real decrease in the number of pesticide treatments applied to vineyards. While the introduction of precision technology does not by itself lead to a reduction in the number of treatments, the savings achieved by investing in such equipment could help to reduce spray drift, therefore limiting the unwanted side effect of pesticides being transferred into the natural environment.

Acknowledgements

The authors acknowledge the financial support provided by the Aquitaine Regional Council (Environment and Vine and Wine Quality, collaborative project n°20101202001, Institute of Vine and Wines Sciences - ISVV). We would like to thank Geneviève Souville and Maria Aránzazu Simó Ramiro for their excellent research assistance. We also thank the French Ministry of Agriculture for allowing us to access data from FADN and wine grape cultural practice survey, and INRA UMR SYSTEM for providing us the database on pesticide costs and recommended application rates. The authors are responsible for any remaining errors. The article in no way reflects the opinions of the Aquitaine Regional Council.

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Appendix 1

The VINEPA model (expected value model)

$$\begin{aligned} \text{Max } E(\pi) = & \sum_{n=0}^N w^n \times \\ & \left(\begin{aligned} & \sum_a \left(\text{Pr}(a) \times \left(rdtT0_a + \sum_{t=1}^{20} (ita_{a,t} \times y_{n,t,p_0} + (ita_{a,t} + ita_{a,t+1}) \times y_{n,t,p_1}) \right) \right) \times (v \times Y \times area - varCost) \\ & + opc \\ & - area \times \left(\left(1 - \sum_e x_{n,e} Eco_e \right) \times \left(\sum_p productPrice_p \times z_{n,p} + fongiPrice \right) + \sum_p fuelPrice_p \times z_{n,p} \right) \\ & - area \times \left(\max \left(0, 6 - \sum_p z_{n,p} \right) \times COidiumFuel + CBotrytisFuel \right) \\ & - area \times ((1 - r_n) \times cdc + r_n \times cdm + (1 - t_n) \times chc + t_n \times ccs) \\ & + s_{n-1} \times i \\ & + \sum_e x_{n,e} \times maintenanceCost_e \\ & - \sum_e ((x1_{n,e} - x1_{n-1,e}) \times Cmat_e + x2_{n,e} \times R_e) \end{aligned} \right) \end{aligned} \quad (1)$$

$$\sum_p y_{n,t,p} \leq 1 \quad \forall n, t \quad (2)$$

$$y_{n,t,p1} + \sum_p y_{n,t+1,p} \leq 1 \quad \forall n, t \quad (3)$$

$$y_{n,t,p1} = 0 \quad \forall n, \forall t \in [t16, t20] \quad (4)$$

$$x1_{n,e} \geq x1_{n-1,e} \quad \forall n, e \quad (5)$$

$$x2_{n,e} \geq x2_{n-1,e} \quad \forall n, e \quad (6)$$

$$\sum_e (x1_{n,e} + x2_{n,e}) \leq 1 \quad \forall n \quad (7)$$

$$x1_{n,e} + x2_{n,e} = x_{n,e} \quad \forall n, e \quad (8)$$

$$z_{n,p} = \sum_t y_{n,p,t} \quad \forall n, p \quad (9)$$

$$s_n \leq \max(0, s_{n-1} \times (1 + i) + \pi_{n-1} - minCons - \sum_e (x1_{n,e} - x1_{n-1,e}) \times Cmat_e) \quad \forall n \quad (10)$$

$$x1_{n,e} \leq x1_{n-1,e} + \max(0, 1 + s_{n-1} \times (1 + i) + \pi_{n-1} - minCons - Cmat_e) \quad \forall n \quad (11)$$

$$x_{n,e}, x1_{n,e}, x2_{n,e}, y_{n,t,p}, r_n, t_n \in \{0,1\} \quad \forall n, t, p, e \quad (12)$$

$$z_{n,p} \in [0,20] \quad \forall n, t \quad (13)$$

$$s_n \geq 0 \quad \forall t$$

$n = 0, \dots, N$	Years included in the planning period, where $t = 0$ is the present and $t = N$ is the terminal period,
$t = 1, \dots, 20$	Weeks included in a crop year,
$a \in \{gp1, gp2, gp3\}$	Levels of disease pressure
$p \in \{p0, p1\}$	Type of treatment which can be chosen by the winegrower, where p_0 is a contact treatment and p_1 a systemic treatment,
$e \in \{B, C^-, C, C^+, D\}$	Different PT equipments

Parameters

w	Discount rate,
$\Pr(a)$	Probability for level of disease pressure a ,
$rdtT0_a$	Percentage of the objective yield obtained if any treatment are realized for the level of disease pressure a ,
$ita_{a,t}$	Percentage of the objective yield earned if a contact treatment is realized in the week t for the level of disease pressure a ,
v	Production value,
Y	Objective yield of the winegrower,
$area$	Size in hectare of the winegrowing farm,
$varCost$	Variable costs which depend on income,
opc	Sum of other products, subsidies and expenses,
Eco_e	Percentage of plant protection products savings (or losses avoided) ,
$productPrice_p$	Cost per hectare of the p treatment products (Copper at the end of the period),
$fuelPrice_p$	Cost per hectare of the fuel used for the p treatment,
$fongiPrice$	Cost per hectare of the other fungicide products (Powdery mildew, Grey rot),
$COidiumFuel$	Cost per hectare of the fuel used for the Powdery mildew treatments,
$CBotrytisFuel$	Cost per hectare of the fuel used for the Grey rot treatment,
cdc	Cost per hectare of a chemical weeding program,
cdm	Cost per hectare of a mechanical weeding program,
chc	Cost per hectare of an insecticide program,
ccs	Cost per hectare of a sexual confusion program,
i	Saving rate,
$maintenanceCost_e$	Repair and maintenance costs for equipment e ,

$minCons$	Household consumption of the year,
$Cmat_e$	Initial purchase cost for equipment e ,
$R_e = \frac{Cmat_e \times tx \times (1+tx)^N}{(1+tx)^N - 1}$	Reimbursement cost of the loan made for purchasing equipment e .

Decision variables

$x_{n,e}, x1_{n,e}, x2_{n,e}$	Binary investment variables: $x_{n,e} = 1$ if the winegrower invests in the equipment e the year n or if he has already invested in this equipment a previous year and 0 otherwise, $x1_{n,e} = 1$ if the winegrower purchase the equipment e without borrowing the year n (or a previous year), 0 otherwise and $x2_{n,e} = 1$ if the equipment e is bought with a loan.
$y_{n,t,p}$	Binary treatment decision variables: $y_{n,t,p} = 1$ if the winegrower realizes a p treatment in the t week of the year n .
$z_{n,p}$	Number of p treatments realized the year n .
r_n	Binary variables: $r_n = 1$ if the winegrower doesn't use any herbicide (mechanical weeding) the year n and 0 otherwise.
t_n	Binary variables: $t_n = 1$ if the protection against moths is carried out by sexual confusion the year n and 0 if it is by insecticides.
s_n	Savings realized the year n .

Appendix 2

Table 1. FADN data (averages by sub-region with standard deviation in italic characters)

area (ha)	Sales (average 2003-2007)	Net profit before tax	Family work units	Target yield (HI)	Average valuation price (€/HI)	Appellations vineyard
17,2 7,0	296633 276118	24894 16800	1,6 0,6	56,3 7,9	93,4 84,2	Bergerac
19,4 10,5	238809 235141	17624 36560	1,6 0,6	65,4 7,8	142,6 82,2	Blayais-Bourgeais
27,3 20,8	136936 110967	-58074 138953	1,8 0,6	64,6 2,8	140,1 72,8	Bordeaux (generic)
31,1 16,9	197794 206146	18998 40529	1,6 0,7	64,6 5,1	113,4 49,6	Entre Deux Mers
11,4 5,8	189205 97584	22259 30157	1,5 0,7	56,7 14,2	215,1 126,6	Entre Deux Mers (sweet)
20,7 8,5	224977 102689	12686 35402	1,8 0,7	51,1 10,5	265,9 120,6	Graves
30,3 19,1	267406 190719	33474 95542	1,5 0,5	64,4 2,8	178,0 63,2	Médoc
17,7 10,7	729932 1141696	189257 167436	1,7 0,8	64,6 12,4	775,5 631,5	Médoc Cru
28,7 16,3	115758 83478	182086 156593	1,5 0,9	58,7 5,4	474,6 351,9	Pomerol St Emilion
23,6 26,2	410200 590374	14559 28338	1,5 0,6	49,6 17,3	268,5 187,0	Sauternais

Table 2. Pesticide average practices and related pesticides costs within the Bordeaux region.

Target	Number of treatments		Total
Chemical weeding	2	1 in spring (pre emergence) 1 in summer (post emergence)	165 €
Powdery Mildew	6		115 €
Grey Rot	1		103 €
Downy Mildew	9	alternatly contact and systemic	275 € (contact) 365 € (systemic)
Grapevine Moths (insecticide)	1		15 €

Table 3 Characteristics of the main active ingredients used in Bordeaux.

Type	Target	Mode of Action	Reference Product	Active Ingredient	Concentration	Dose (g of AI per ha)	Toxicity Class	EIQ	EIQ_Field
Fungicides	DM	Contact	POLYRAM DF	Metiram-Zn	0,8	2800	4	40,6	101,4
	DM	Contact	BOUILLIE BORDELAISE RSR	Copper sulfate+lime	0,2	2400	3	67,7	144,9
	DM	Systemic	OCARINA	Improvalicarb	0,042	126	4	23,7	2,7
	DM	Systemic	OCARINA	Copper_Oxychloride	0,203	609	3	33,2*	18*
	DM	Systemic	ARTIMON	Fosetyl-Al	0,35	1400	4	12,0	15,0
	DM	Systemic	ARTIMON	Mancozeb	0,35	1400	2	25,7	32,1
	DM	Systemic	MIKAL FLASH	Fosetyl-Al	0,5	2000	4	12,0	21,4
	DM	Systemic	MIKAL FLASH	Folpel	0,25	1000	2	31,7	28,3
	PM		KUMULAN	Sulfur_micronise	0,8	10000	3	32,7	291,4
	PM		CORAIL	Tebuconazole	0,25	100	2	40,3	34,5
	PM		STROBY DF	Kresoxim-methyl	0,5	100	2	15,1	1,3
	GR		SCALA	Pyrimethanil	0,4	1000	2	12,7	10,8
Insecticides	GM		DURSBAN 2 RAK1/RAK2	Chlorpyrifos-ethyl Acetate_de_Z9_E	0,23	285	2 0	26,9 0,0	6,5 0,0
Herbicides	Weeds		ROUNDUP Ultra_max	Glyphosate	0,45	180	2	15,3	11,8
			KATANA	Flazasulfuron	0,25	50	2	18,5	0,8
			PLEDGE	Flumioxazine	0,5	600	1	24,0	12,3
DM: Downy Mildew; PM: Powdery Mildew; GR: Grey Rot; GM: Grapevine Moths EIQ: Environmental Impact Quotient*									

EIQ: A method to measure the environmental impact of pesticides, the EIQ calculates a pesticide's risk to farm workers, consumers, and terrestrial organisms based on a ranking methodology. The ranks are manipulated in equations to arrive at a final EIQ score. To account for different formulations of the same active ingredient and different use patterns, a simple equation called the EIQ Field Use Rating was developed, EIP Field Use Rating = EIQ Score * Application Rate

Appendix 3

Fig. 1 Effects of an increasing volume based tax rate on investments in precision technology

Fig. 2 Effects of ad valorem tax rates on investments in precision technology