Assessing investment in precision farming for reducing pesticide use in French viticulture

J-M LESCOT[(1)]*, S. ROUSSET[(1)], G. SOUVILLE[(1)]
(1) Cemagref, Agriculture and Rural Areas Dynamics Research Unit;
50, avenue de Verdun, Gazinet, 33612 Cestas cedex, France.
E-mail: jean-marie.lescot@cemagref.fr
*Corresponding author

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J-M Lescot[(1)]*, S. Rousset[(1)], G. Souville[(1)]
(1) Cemagref, Agriculture and Rural Areas Dynamics Research Unit;
50, avenue de Verdun, Gazinet, 33612 Cestas cedex, France.
E-mail: jean-marie.lescot@cemagref.fr
*Corresponding author

Abstract

The paper develops a mathematical programming model for assessing the impact of Environmental Policy instruments on French winegrowing farm's adoption of pesticides-saving technologies. We model choices with regards to investment in precision farming and plant protection practices, in a multi-periodic framework with sequential decision, integrating uncertainty on fungal disease pressure and imperfect information on equipment performance. We focus on recursive models maximizing a Utility function. These models are applied on a representative sample of 534 winegrowers from the French Farm Accountancy Data Network (FADN). As expected, both ecotaxes and green subsidies make precision farming equipment more profitable, but the investment rate remains however low and concentrated on basic systems. One explanation is grower's financial constraint in a context of market crisis and farm indebtedness. Shortcomings and further development of the models are discussed.

Key-words
Discrete Stochastic Programming - Precision Farming - Viticulture - Pesticides - Environmental Policy

1 Introduction

The European Pesticides Framework Directive (2009/128/EC) makes it mandatory for all Member States to establish national action plans, involving all the relevant stakeholders in the process and creating the necessary conditions for implementing integrated pest management that will become mandatory as of 2014. Moreover, protection of the environment could be enhanced by the use of precision farming technology aiming at reducing pesticides loss in the environment, such as low spray drift equipment, variable rate dosing, remote sensing and information technology (IT).

The advantages of new technologies in precision viticulture and particularly for spraying have been extensively studied in international agricultural engineering research (Arnó et al., 2009; Lamb et al., 2004; Llorens et al., 2010; Tisseire et al., 2007). For example, French engineering research teams have recently completed field-oriented studies on precision spraying within the AWARE (De Rudnicki et al. 2009, 2010; Ruelle and De Rudnicki 2009), OPTIDOSE (Davy and Heinzlé, 2009) and OPTIPULVE projects (Heinzlé and Florent, 2010).

In assessing sustainable farming technology, capital budgeting studies concentrate on farm size and profitability thresholds, whereas economics reveal how important are farmer individual characteristics, training, risk and uncertainty (Adrian et al., 2005; Greiner et al, 2009; Marra et al., 2003). Risk may be linked to the new technology as the new equipment may not have the expected maximum effectiveness, its performance being distributed around an average value. Uncertainty is mainly related to lack of farmers' information that could not make probabilities without references. Moreover, training plays a great role in adopting new technology as without skills farmer could not fully benefit from this new technology (Sunding and Zilberman, 2001; Zilberman et al., 1997).

Furthermore, plant protection management requires decision to be made at times when the outcomes or implication of application decisions will not be known (Rae, 1994). This problem can be then stated in term of Decision Theory involving specification of possible actions, states of nature probabilities and utility function to maximize considering the farmers rational decision making. Moreover, the methodology of economic optimization is the more relevant for analysis of investment and practices changes because of the possibility it offers decision makers to substitute alternative strategies (Hazell and Norton, 1986).

Mathematical programming models are widely used since they are able to capture the core decision-making processes and have the unique ability to link economic elements with ecological and biophysical elements (Buysse et al., 2007). We assume here that the farmer has got all the information needed for deciding to invest or not and that skills are immediate without any additional costs although real performance of the equipment is considered to be unknown before the purchase.

Many studies can be found in engineering literature on precision farming (PF) but only very few studies have examined the costs of investing in PF in comparison with the benefits expected (Godwin et al., 2003; Tozer 2009). No study has addressed so far the assessment of cost and benefits of PF applied to spraying equipment or has explored means for promoting such equipment. Few studies have questioned the winegrape sector (Fernandez-Cornejo, 1998; Ugaglia et al. 2008). The objective of this study is then first to propose a modelling framework for assessing farmers choice in PF equipment and plant protection strategies. We analyse then the effects of canonical Environmental Policy instruments such as taxes and green technology targeted subsidies for promoting the adoption of such equipments.

2 Model formulation

To assess investment decision in precision spraying equipment, we developed a Discrete Stochastic Programming (DSP) model (Aplan and Hauer, 1993; Birge and Louveaux, 1997). Stochastic models are appropriate when data evolve over time and decisions need to be made prior to observing the entire data stream.

Since Rae's seminal papers (Rae, 1971a, 1971b), DSP has been widely use in the field of agricultural economics, especially to model farmer's responses to climatic uncertainty (Cortignani, 2010; Jacquet and Pluvinage, 1997; Kingwell et al., 1993; Maatman et al., 2002).

Following Birge and Louveaux (1997), the problem is:

$$\min_x \; c^T x + Q(x)$$
$$s.c. \begin{cases} Ax = b \\ x \in X \end{cases}$$

c^T is the first stage objective, $Q(x)$ is the recourse function and x is the first-stage decision vector

Recourse function is usually approximated using the random variable named ξ: $Q(x) = \sum_{j \in \Omega} p^j Q(x, \xi^j)$

where p^j is the probability of event j, and $Q(x, \xi^j)$ is the recourse problem:

$$Q(x,\xi^j) = \min q(\xi^j) y$$
$$\text{s.c.} \begin{cases} w(\xi^j) y = h(\xi^j) - T(\xi^j) x \\ y \in Y \end{cases}$$

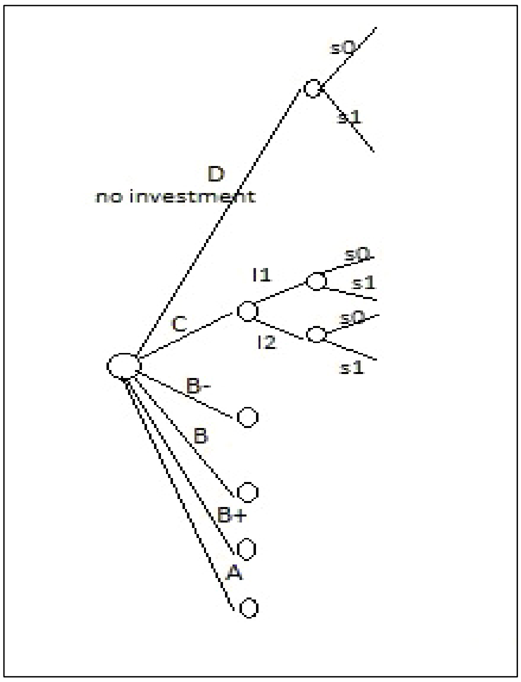
Where y is the second stage decision vector (vector of second stage variables corresponding to choice made after the random event), turning then to the deterministic equivalent program:

$$\min_x \; c^T x + \sum_j p^j \times q(\xi^j) y^j$$
$$s.c. \begin{cases} Ax = b \\ w(\xi^j) y^j + T(\xi^j) x = h(\xi^j) \\ x \in X, y^j \in Y \end{cases}$$

For vineyard plant protection (mainly fungal diseases), the farmer has to choose between different protection strategies or decision rules (Léger et al., 2007). Furthermore, he has the opportunity to invest in PF systems equipment allowing a better spraying and a reduction of pesticides application rate. We retained two levels of plant protection strategy (s_0, s_1) corresponding to the two main levels identified by the winegrowing experts consulted. Strategy s_0 represents systematic applications allowing permanent vineyard protection against pests and diseases, while s_1 corresponds to reasoned spraying applications following broad regional indicators and some field monitoring. We did not consider "integrated winegrape production" or organic farming. The first strategy was dropped because differences with s_1 concern mainly weed control and because of the difficulty to identify specific costs, practices such as leaf or cluster thinning being also used to address wine organoleptic quality. We dropped organic farming too because of the lack of reliable information and limited surveys on practices and production costs. We could stress that in 2006, when a national survey has been carried out, 90% of the vineyard was under strategy s_0 or s_1, s_1 being by far the dominant strategy (Agreste, 2006) with 76% of the plots.

For PF equipment, the grower has different options (See table 2 and Appendix 3). Investment can be made either with borrowing either cash, respectively named I_1 and I_2.

Decision maker has then to choose between 22 decision alternatives (Figure 1). Problem is then to find a model that allows foreseeing what will be the choice of the farmer for his plant protection strategy and how he will react to random parameters by choosing the objective function to maximize.



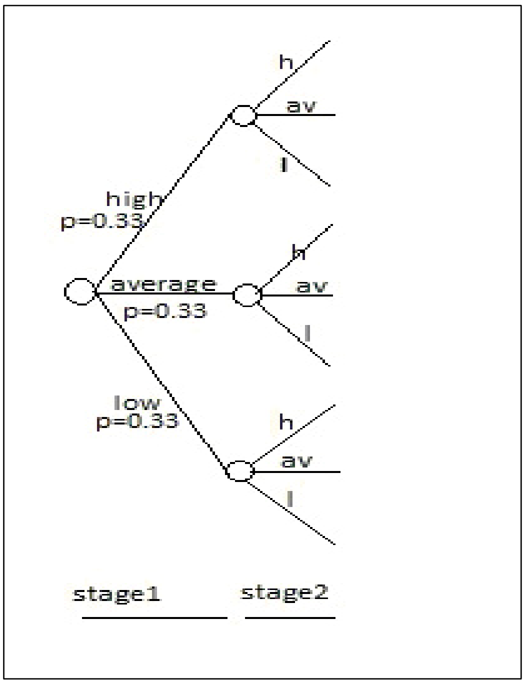


Figure 1 - Set of possible solutions for activity analysis

Figure 2 - scenarios pertaining to infection pressure

2.1 Random events

We decide to take interest in three random parameters: infection pressure (*ip*), farm cash balances (*Cb*) and equipment performance (*perf*). We name *sc_ip, sc_Cb, sc_perf*, the scenarios linked respectively to these three parameters. The disease pressure of the current year is the combination of the inoculum status of downy/powdery mildews and botrytis and of weather conditions. When a year with a low pressure occurs only little damage can be noticed on plots where no fungicide has been sprayed. Conversely, when pressure is high, the entire yield can be destroyed in the absence of applications. We limit the levels of pressure at three with high (h), average (av) and low (l) levels. Although probabilities may be conditional on the outcomes of the random pressure of previous stages, we assign equal probabilities to outcomes because of the present lack of reliable information on pressures for long time periods. The percentage of pesticides saving obtained with the new equipment is supposed to be unknown by the farmer when purchasing the equipment. We assume that the performance of the PF system follows a distribution that we formalize in three classes marked out by the first and third quartiles. Therefore low and high level have a probability of 25% and average level a probability of 50%. These references come from French engineering research institutes trials on precision spraying equipment and information technology (Davy and Heinzlé, 2009; De Rudnicki et al. 2009, 2010; Ruelle and De Rudnicki 2009; Heinzlé and Florent, 2010). Moreover, we consider that performance level remains the same between the years of the equipment use period. Third random parameter is related to the payoffs stream of the year (that we approximate by the turn-over) and includes all random events that do not relate to plant protection. This part can be connected to weather conditions (hail, sunshine …), to others factors influencing the quality of the grapes or to market conditions (fluctuation of wine prices, etc.).

For taking into account all random events, we distinguish scenarios pertaining to the infection pressure and scenarios pertaining to the income balance. Scenarios for the probabilistic analysis are detailed in figure 2 for infection pressure and are similar for the income balance. Number of scenarios increase exponentially with the number of years.

If r represents the events and n the number of years, we have then:

$1 + r + r^2 + r^3 + ... + r^n = \frac{r^{n+1} - 1}{r - 1}$ scenarios. We note Y_{sc} the income linked with a random event *sc=(sc_Cb, sc_ip, perf).*

2.2 Expected income model

First modelling aims at maximizing the sum of the expected payoffs of the farmer on several years. We use then the Expected value of random events equivalent to the expected value of the farm income as the recourse problem is a simple linear function. For the value function, we use the Audsley and Wheeler (1978) procedure to calculate the annual cost of PF equipment using actual cash flows (Audsley and Wheeler, 1978; Musser et al., 1988). We decide to differentiate the number of years the equipment is owned/used and the term of the loan if the equipment is purchased by borrowing (Ford and Musser 1994). In order to better represent financial capacity of farms for investing in PF, we added additional constraints representing credit rationing. For deciding if the farm can get a loan or not, we consider last farm income minus minimal household consumption and liabilities. Thus only positive revenue could have access to loan or buy cash saving then on loan cost, interests and commissions. Details of the model are given in Appendix 1.

2.3 Utility Function

For assessing the number of farms that should have always interest in investing in PF equipment and /or apply the strategy s_1 whatever the state of nature, we model the worst and best of cases maximizing the Income variable allowing then to bound the problem. All the random events do not have to be calculated. We choose the worst and the best solution for each income, infection pressure or equipment performance. For the worst of cases it comes down/amounts to maximize income Y such that $Y \le Y_{sc} \quad \forall sc$ *with sc: scenario and f*or the best of cases by maximizing the income variable such that $\underset{sc}{Max}\{Y_{sc}\}$. This non linear form can be written in the following:

$$Y \le Y_{sc} + B_{sc} \times M \quad \forall sc$$

$$\sum B_{sc} = card(sc) - 1$$

With M an upper bound on the difference between the minimum and the maximum incomes.

$$B_{sc} \in \{0,1\}$$

Farmer's preferences among alternative farm plans are based on the expected income *E[Y]* and associated income variance *V[Y]* (Hazell and Norton, 1986). When the utility function is of the exponential form $1 - e^{-\beta Y}$ and Y normally distributed then

$$E[U(Y)] = E[Y] - \frac{1}{2} \cdot \beta V[Y]$$

Because of a scale problem with the variance, we focus on the deviation standard and calculate it on all the final scenarios on N years. We use then the following Utility function:

$$Max \quad Y - \sqrt{\sum_{sc} \sigma_{sc}{}^2 \times p_{sc}}$$

$$\begin{cases} (...) \\ Y = E[Y_{sc}] \\ StdDev_{sc} = Y - Y_{sc} \quad \forall sc \end{cases}$$

With p_{sc}= probability of scenario

Calculation of the objective function is very long as we have for the 3 infection pressure levels, 243 scenarios on five years and 3125 scenarios for five levels of cash balance leading to 243*3125*3 = 2,278,125 scenarios.

2.4 Financial constraints

The economic situation of grapegrowers seriously limits new investments. Since the early 2000's, the French wine chain has been facing a market crisis. Expert's reports assert that this crisis is structural rather than conjunctural, pointing a declining domestic market, the growing competition from USA and the Southern hemisphere in export markets, and a slow adaptation of French growers (Hannin et al., 2010; Heijbroek, 2007). Many growers only stay in business with off-farm income or by using European partial vine pulling subsidies. FADN data shows that 14% of growers had a negative average operating profit over the 2002-2006 period, 51% had at least one year with negative operating profit during that five years period. Contrary to previous crisis that where specific to Southern France, the new crisis has been affecting nearly all French regions, even iconic places like Bordeaux or Burgundy. Financial constraints are another problem for growers. They are explained by credit rationing coming from asymmetric information between small enterprises and their lenders (Maurel and Viviani, 2010). They are often important in agriculture (Barry and Robison, 2001). When capital markets do not operate perfectly, that is when banks base their lending decisions on available collateral or financial ratios rather than projected profitability, farmers are likely to face credit constraints and their investment will be sensitive to cash flow (Benjamin and Phimister, 2002). In their crop allocation or technological choice, farmers may therefore prefer regular incomes over irregular ones (Bocquého and Jacquet, 2010). Empirical studies show that French banks do use financial ratios such as debt to equity ratio for credit access to winegrape growers (Cadot, 2008). Following farm decision literature, we implemented cash balance and liquidity constraints (Bocquého and Jacquet, 2010; Louhichi et al. 2004; Ridier and Jacquet, 2002).

2.5 Multi-period modelling

In the Expected income model, decision is made on a one year-basis. In order to model the evolution of the equipment with time, we developed a recursive and a dynamic multi period model. In the new models we take into account the variation of the levels of subsidies and the variable costs which were constant in the first models. Only the recursive model and its outcomes are presented further. It founded out indeed that the dynamic model needed much longer time for resolution than the recursive model and outcomes were similar.

We repeat each year and during n consecutive years, the farmer decision formalized by the Expected income model presented. In order to know which decision will be made the year n, we should consider factors of the preceding year such as the farm cash balance, disease pressure and investment or not in PF equipment and the percentage of recycling Plant Protection Product (PPP). Financial constraints change as well throughout the years because of the cash balance changes (see 2.5). For resolution we chose to enumerate the set of solutions that changes as the years go by depending of the choices that have been made previously.

We use the following algorithm:

Loop for N years

> *Computation of* $capBor_e$ *and* $capCash_e$
>
> *Solution of models (expected income, Worst, Best, Mean-Std deviation)*
>
> *Computation of To (turn over) and predY (preceding farm revenue)*
>
> *Change of sets of possible solutions*

End of loop

Models have been developed with GAMS and solver CPLEX10. GAMS (General Algebraic Modelling System) is a modelling system for mathematical programming problems (Brooke et al, 1988) consisting of a language compiler and a set of integrated solvers.

3 Data

For simulations, we used different data on winegrowing farms and plant protection practices. Source and description of data are detailed in table 1. Farm economic and financial information comes from the Panel Data of the French Farm Accountancy Data Network (FADN)[1]. In our sample of 534 winegrowers followed between 2002 and 2006, there is a strong inter-firm and interregional heterogeneity. For example, the size of vineyard goes from 0.8 to 148.8 hectares (mean: 20.8; σ: 17.4). The average 5 years turn-over goes from 7,270 to 1,993,337 € (mean: 208,747; σ: 215,279).

Data on pesticides could not be used as FADN does not report physical information and even don't differentiate expenditures by active substance or Plant Protection Products category (herbicides, fungicides, insecticides). Therefore, real application rate and commercial products are extracted from the Winegrape cultural practices survey conducted by the Ministry for Agriculture and Fisheries on 5216 vine plots in 2006. We aggregated information at the local scale, with 23 wine places such as *Médoc*, *Libournais*, *Côtes* and *Entre-deux-mers* in the Bordeaux region. Within these areas, growers face similar pests and climatic environment and have comparable production systems (grape varietals, vine density, yield, trellising system …). We calculated the average application rate by area, allowing then to apply different kind of taxes on pesticides, either on commercial products either on active substances. We also used the Input costs in Viticulture and Oenology data base[2]. We discriminate the herbicides from the other pesticides, as herbicides are applied with different equipment than those used for canopy spraying and therefore not concerned with application rate reduction. The simulated average pesticides cost is 414 €.ha-1 (82 € for herbicides and 331 € for fungicides and insecticides), ranging from 129 to 825 €.ha-1.

Table 1: Data description.

Data type	Scale	Source	Data base description
Farm economic and financial data	Individual. Panel Data of 534 French wine grape farms over a 5 years period.	Farm Accountancy Data Network. Quality wine, Wine other than quality. French Ministry of Agriculture (Agreste, 2002-2006).	Vine and other crops area, production, turn over, labour, costs, land and buildings, stocks, circulating capital, debts, grants and subsidies.
Fungicides application	Local. 2006 survey of 5216 vine plots in the main winegrowing regions.	Winegrape cultural practices survey. French Ministry of Agriculture (Agreste, 2006).	Vine density, yield, cultural practices, use of herbicides, fungicides and insecticides (Frequency, date of application, PPE name and dose)
PPP prices	National. Reported prices.	Input costs in Viticulture and Oenology 35th edition and following (Bonet et al., 2006).	Plant Protection Products, unit costs, active substance., official application rate

To assess investment, we considered five precision spraying systems named A, B+, B, B- and C. (Table 2). Appendix 3 provides a brief description of these PF systems. Choice D refers to the no-investment in PF, the farmer keeping his equipment used presently. The systems are taken from commercially available packages and costs data come from Cemagref Montpellier. Because of the range of market purchase prices for this PF equipment, the median of the price range was used. Fungicides savings data comes from field trials recently conducted by the French Institute of Vine (Davy and Heinzlé, 2009; Heinzlé and Florent, 2010) and Cemagref Montpellier (De Rudnicki et al. 2009, 2010; Ruelle and De Rudnicki 2009).

[1] FADN http://ec.europa.eu/agriculture/rica/index_en.cfm.

[2] The data file has been compiled by INRA Montpellier during a previous study (Mezière and al., 2009) and kindly provided to us.

Table 2: Technical references for Precision spraying systems.

System*	Purchasing price (€)	Fungicides savings (%)		
		Low	Med	High
C: basic	3500	5%	10%	20%
B-: tunnel sprayer	10000	5%	15%	30%
B: tactical control	20000	10%	24%	41%
B+: spatial control	35000	15%	32%	51%
A: embedded control	67500	28%	44%	61%

* See details in Appendix 3.
Sources: Costs data: Cemagref Montpellier. Fungicides savings: field trials of French Institute of Vine and Cemagref Montpellier.

Excepted for Plant Protection Products, information on plant protection strategies is scarce particularly on incidental expenses with strategy s_1. With a reasoning strategy for application, farmers reduce application rates, especially the years with low fungal diseases pressure. Neither this information on reduction rate nor probabilities values for the infection pressure is available to date. We consider nevertheless constant additional expenses of 100 €.ha^{-1} for strategy s_1 corresponding to information procurement, training and extension services. Similarly, we chose to adjust the application rates depending of the level of downy/powdery mildews and botrytis (Table 3).

Table 3: Pesticides rate adjustment according to fungal diseases pressure.

Strategy	s_0	s_0	s_0	s_1	s_1	s_1
Diseases pressure	Low	Med	High	Low	Med	High
Application rate (1=ref.)	1.2	1.2	1.2	0.8	1	1.2

Comparison of models

Results concerning strategies from the Expected income, Worst of cases and Best of cases models are presented in table 4. From the sample used in this study, analysis has been extrapolated to all the vineyard farms of France using the weighting provided by the FADN. As we could expect, with worst and best of cases functions, optimal strategies are respectively s_1 and s_0 for all the farms. With the average and Mean-Standard deviation functions, all the farms except one chose the s_1 strategy. This result underestimates very likely the reality of farms plant protection strategies. From the Winegrape cultural practices survey (Agreste, 2006), we know indeed that s_0 strategy which is mainly represented in the Champagne region represents though 14% of the group of farms.

Table 4: Models outcomes on the strategy choice.

model	Expected income		Worst (safety first)	Best (optimistic)	Mean-STD Utility	
strategy	S_0	S_1	S_0	S_1	S_0	S_1
sample	1	533	534	534	1	533
population	64	24026	24090	24090	64	24026
percentage	0,3	99,7	100	100	0,3	99,7

Table 5: Models outcomes on the investment decision.

model	Expected income		Worst (safety first)		Best (optimistic)			Mean-STD Utility	
strategy	D	C	D	C	D	C	B-	D	C
sample	473	61	523	11	422	107	5	476	58
population	22064	2026	23752	338	20153	3789	149	22166	1924
percentage	91,6	8,4	98,6	1,4	83,7	15,7	0,6	92	8

4 Assessment of Environmental Policy instruments

To foster reduction of the use of pesticides amongst vineyard growers, we intend to study the impact of canonical Environmental Policy instruments based on ecotaxes and "green" subsidies. Models are used to first assess the effect of taxes which by increasing pesticides application costs make then investment in PF equipment economically more interesting. Since 1996, Denmark has a differentiated levy on pesticides (Hoevenagel et al., 1999). The percentage of tax is nowadays 54% of the retail price for insecticides, and 54% for herbicides and fungicides. The non-point source pollution tax set by the French Water Law and collected on pesticides sellers by regional Water agencies since 2008 is based on four categories of actives substances, depending of the environmental impact: in 2010, the levy is 5.1 €.Kg^{-1} for category I (Toxic, very toxic, carcinogenic, mutagenic or toxic for reproduction), 2.0 € for category II (Harmful for the environment), 0.9 € for category III (Mineral substances harmful for the environment) and 0.0 for category IV (Other active substances). Only results with the French water law tax are presented here.

Computation with data from input costs and winegrape survey shows that the actual tax pressure on French winegrowers is low, 4% on average, or 18 €.ha^{-1} for a PPP spending of 432 €.ha^{-1}. To change behaviour, tax should be much higher. In the DSP simulation, we set up six different levels of Water law tax: t0: no tax; t1: actual tax; t2: t1*3; t3: t1*10; t4: t1*30; t5: t1*100..

Subsidy to investment in pesticides saving technology is another incentive to encourage PPP reduction. Since 2007, a French governmental program supports 40% of investment cost, with a ceiling of 30000 € by farm. We simulate six different levels of support: sb0 (no subsidy), sb1 (40% of investment cost, with 30000 € ceiling), sb2 (60%), sb3 (80%), sb4 (40% with 60000€ ceiling), sb5 (40% with 100000 € ceiling).

Effects of taxes and green investment subsidies with the Mean-STD Utility model are presented in Appendix 2 and summarized in figures 3 and 4. More results could be found in Souville (2010). Without public incentive, only the basic system C is profitable for a significant number of winegrowers, more than 10% of the sample (Figure 3, t0). As expected, the number of farms investing in PF technology increases with the level of taxes. Nevertheless, amongst the five systems appraised, the basic system C remains by large the most widely adopted. The other systems remain generally too expensive for winegrowers, even with a relatively hard tax pressure (note that the B- system is never chosen).

There is a serious concern about the social acceptability of higher taxes. Last, we can notice from tax t5, the reversal of the trend because of increasing financial constraints: the highest the level of taxes is, the most active they are; however, if fiscal pressure raises too much, shortage of profits constraints investment.

With green investment subsidies (Figure 4), there is no more taking on farmer's income and therefore no activation of credit access constraint. We see that increasing the rate of subvention (sb2, sb3) is more effective that the subsidy base (sb4, sb5). However such program is supported by public founding and leads to a suboptimal level of PPP use (Baumol and Oates, 1988). A tax scheme with compensation would be another more efficient instrument.

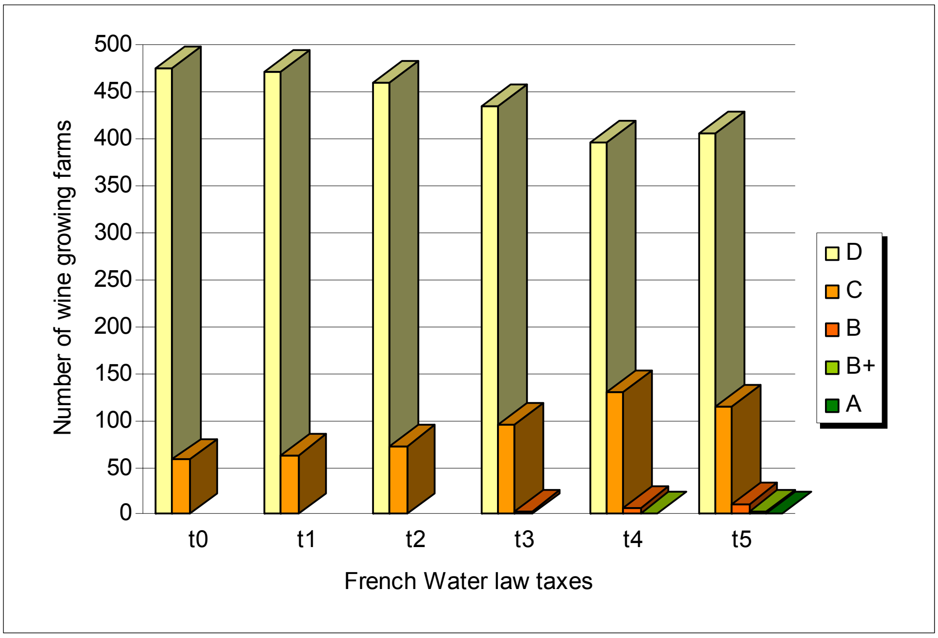


Figure 3. Results of an increase in French Water law tax (differentiation by toxicity). *Legend: t0: no tax; t1: actual tax; t2: t1x3; t3: t1x10; t4: t1x30; t5: t1x100.*

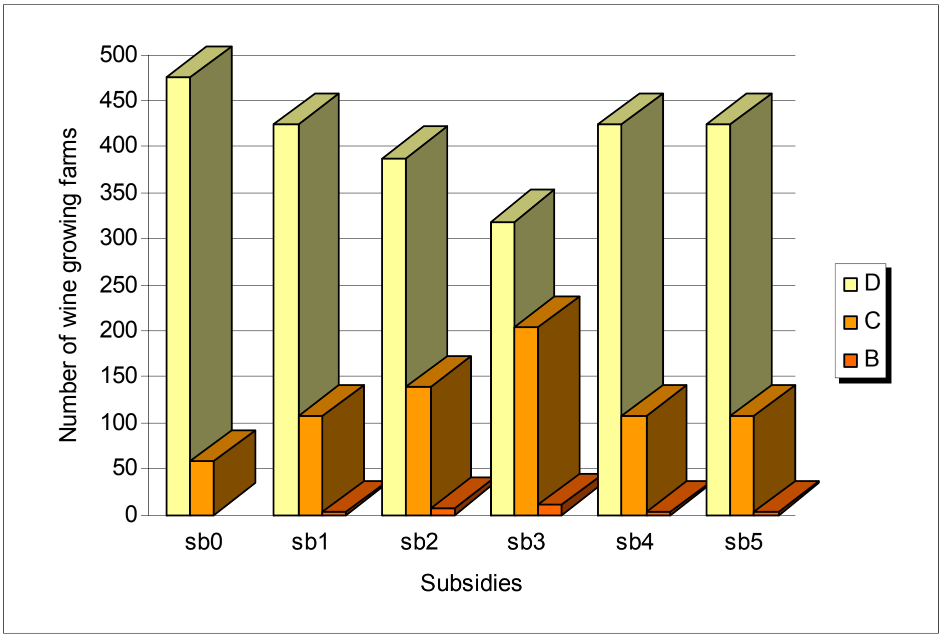


Figure 4. Results of a green investment subsidy. *Legend: sb0 (no support), sb1 (40% of investment cost, with 30000 € ceiling), sb2 (60%), sb3 (80%), sb4 (40% with 60000€ ceiling), sb5 (40% with 100000 € ceiling).*

5 Conclusion

In order to assess the potential adoption of pesticides-saving technologies by French winegrowing farms, we elaborated a Discrete Stochastic Programming model and conducted microsimulations on FADN and plant protection practices data. The main result is that only the basic precision spraying systems available will be adopted by a significant number of winegrowers, even with strong governmental incentives. French farms are generally too small for high-tech systems that need larger vine acreage to spread investment costs. These systems are probably more suitable for agricultural subcontractors or for larger US, Australian or South African estates. Moreover, with taxes on pesticides, liquidity constraints on farms are increased; however, the cash balance and credit constraints could be further formulated more smoothly than it is presently. Another way of modelling improvement is to better represent bio-economic relationships; levels of fungal disease pressure used in DSP modelling are extremely simplified with three levels with same probabilities whatever the geographic area; furthermore these events are translated by a determinist modulation of quantities. These limits to models developed so far will be anyhow further overcome with additional epidemiologic data. The next step of the work will be then to integrate chronological series on fungus disease pressure and grape yield response with data from regional fields network.

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Appendix 1. Expected Income Model

$$MAX \quad Y = \sum_{n=1}^{N1} (To - area \times \sum_{s} (B_s - rec_e \times Bi_{s,e}) \times coefR_s \times Cpp) \times w^n$$

$$+ \sum_{n=1}^{N1} (-area \times B_s \times vCs_s - B_s \times fCs_s - Crep_e \times I_e) \times w^n$$

$$- I2_e \times \sum_{n=1}^{N2} R_e \times w^n - I1_e \times Cpur_e$$

$$\begin{cases} \sum_s B_s = 1 \quad \ldots\ldots & (1) \\ \sum_e I_e \leq 1 \quad \ldots\ldots & (2) \\ I1_e + I2_e = I_e \quad \ldots\ldots \ \forall e & (3) \\ Bi_{s,e} \leq B_s \quad \ldots\ldots \ \forall e, s & (4) \\ Bi_{s,e} \leq I_e \quad \ldots\ldots \ \forall e, s & (5) \\ B_s, Bi_{s,e}, I_e, I1_e, I2_e \in \{0,1\} \end{cases}$$

Index

s: strategies, e : type of equipment, n : years

Variables

B_s*= 1 if strategy s is chosen*
= 0 else.
$I1_e$ *or* $I2_e$ *equal 1 if farmer invests in equipment e.* $I1_e$*= 1 if equipment is bought without borrowing* $I2_e$*=1 if investment with borrowing*
I_e *: Sum of* $I1_e$ *and* $I2_e$

$$BI_{s,e} = B_s \times I_e$$

Constraints

(1) Only one strategy is chosen.
(2) Only one investment maximum could be made
(3) Enables calculation of variable I_e*.*
(4) and (5) enable multiplication between B_s *and* I_e *.*

Data

area — *the size of the farm.*
Cpp — *the costs of Plant Protection Products used with strategy 1 for a year with average infection pressure.*
vCs_s *,* fCs_s — *correspond to the sum of other costs related to one strategy (like e.g. observation costs,) with respectively one element varying according to the concerned area and another constant element .*
$Crep_e$ — *repair and maintenance costs for equipment e*
$Cpur_e$ — *initial purchase cost for equipment e*
R_e — *reimbursement cost of the loan made for purchasing equipment e.*

$$R_e = \frac{Cpur_e \times i \times (1+i)^N}{(1+i)^N - 1}$$

$w = \frac{1+g}{1+r}$ — *Discount rate where g is the inflation rate and r is the interest rate*

Random data

To the turnover of the farm for year *n*

rec_s the percentage of PPP savings (or loss avoided)

$coefR_s$ the percentage of the reference Plant Protection Product which is applied according to the strategy

Additional Constraints (6) and (7)

If equipment is bought with a loan (6)

$$I2_e \leq capBor_e \qquad \forall e \quad (6)$$

$$capBor_e = \begin{cases} 0 \text{ if } predY\text{-}minHc\text{-}R_e < 0 \\ 1 \text{ else} \end{cases}$$

With

predY last farm income minus minimum Household consumption and liabilities (minHc). Thus only positive revenue could have access to loan or buy cash saving then on loan cost, interests and commissions.

If equipment is bought cash (7)

$$I1_e \leq capCash_e \qquad \forall \text{e} \quad (7)$$

$$capCash_e = \begin{cases} 0 \text{ if } CB - Cpur_e < 0 \\ 1 \text{ else} \end{cases}$$

CB: Cash Balance = To- Cpp –Cs (other costs of the strategy)

Appendix 2. Details of model outcomes for taxes and subsidies

Table A1. Model outcomes with the Mean-STD model and French Water law taxes

Taxes		D	C	B	B+	A	s0	s1
t0	**sample**	**476**	**58**				**1**	**533**
t0	population	22166	1924				64	24026
t0	*percentage*	*92*	*8*				*0,3*	*99,7*
t1	**sample**	**472**	**62**				**1**	**533**
t1	population	22041	2049				64	24026
t1	*percentage*	*91,5*	*8,5*				*0,3*	*99,7*
t2	**sample**	**461**	**73**				**1**	**533**
t2	population	21673	2418				64	24026
t2	*percentage*	*90*	*10*				*0,3*	*99,7*
t3	**sample**	**436**	**95**	**3**				**534**
t3	population	20691	3322	77				24090
t3	percentage	85,9	13,8	0,3				100
t4	**sample**	**396**	**131**	**6**	**1**			**534**
t4	population	18972	4888	198	32			24090
t4	*percentage*	*78,8*	*20,3*	*0,8*	*0,1*			*100*
t5	**sample**	**406**	**114**	**10**	**3**	**1**		**534**
t5	population	19473	4131	370	84	32		24090
t5	*percentage*	*80,8*	*17,1*	*1,5*	*0,3*	*0,1*		*100*

Table A2. Model outcomes with the Mean-STD model and Green investment subsidies

Subsidies		D	C	B	s0	s1
sb0	**sample**	**476**	**58**		**1**	**533**
sb0	population	22166	1924		64	24026
sb0	percentage	92	8		0,3	99,7
sb1	**sample**	**425**	**107**	**2**	**1**	**533**
sb1	population	20260	3785	45	64	24026
sb1	percentage	84,1	15,7	0,2	0,3	99,7
sb2	**sample**	**388**	**139**	**7**	**1**	**533**
sb2	population	18780	5098	212	64	24026
sb2	percentage	78	21,2	0,9	0,3	99,7
sb3	**sample**	**319**	**204**	**11**	**1**	**533**
sb3	population	15953	7799	338	64	24026
sb3	percentage	66,2	32,4	1,4	0,3	99,7
sb4	**sample**	**425**	**107**	**2**	**1**	**533**
sb4	population	20260	3785	45	64	24026
sb4	percentage	84,1	15,7	0,2	0,3	99,7
sb5	**sample**	**425**	**107**	**2**	**1**	**533**
sb5	population	20260	3785	45	64	24026
sb5	percentage	84,1	15,7	0,2	0,3	99,7

Appendix 3. Technical references for Precision spraying systems

		D		C		B-		B		B+		A	
		No precision	Price (€)	Basic	Price (€)	Tunnel sprayer	Price (€)	Tactical control	Price (€)	Spatial control	Price (€)	Embedded control	Price (€)
Equipment	Sprayer	Pneumatic 4 rows 7 km/h	10000	Pneumatic 4 rows 7 km/h	10000	Side/side 4 rows 5 km/h	15000	Side/side 4 rows 5 km/h	20000	Side/side 4 rows 5 km/h	30000	Side/side 5 rows 7 km/h	40000
	Pesticides injection	No		No		Yes		Yes		Yes		Direct injection 3 tanks	15000
	Equipment		10000		10000		15000		20000		30000		55000
Information Technology	Meteorological station	No		Fixed	500	On traceability system	1000	On traceability system	1000	On traceability system	1000	Fixed + mobile	2000
	Recommendation map	No		No		No		No		No		Yes	500
	LAI/NDVI measurement	No		No		No		Pocket Sensor	3000	Pocket Sensor	3000	On-machine sensor	5000
	Canopy geometry measurement	No		No		No		Pocket Sensor	1000	Pocket Sensor	1000	On-machine sensor	5000
	Record keeping / Traceability	Manual		Basic	3000	Basic	3000	Basic	3000	Traceability on tractor	5000	Traceability on harvest machine	5000
	Data processing software	No		No		Plot	1000	Plot	2000	GIS	5000	GIS	5000
	IT (€)		0		3500		5000		10000		15000		22500
Spray System	Purchase price (€)		10000		13500		20000		30000		45000		77500
	Δ with No PF		0		3500		10000		20000		35000		67500
Fungicides savings (%)	Low-Med-High	0		5 10 20		5 15 30		10 24 41		15 32 51		28 44 61	

Sources: Cemagref Montpellier and French Institute of Vine.