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OPTIMAL TREATMENT SCHEDULE IN INSECT PEST CONTROL IN VITICULTURE

Delphine Picart
Inra, UMR 1391 Ispa, Villenave d'Ornon, and Bordeaux Sciences Agro, UMR 1391 Ispa, Gradignan, France

Fabio Augusto Milner
School of Mathematical & Statistical Sciences, Arizona State University, Tempe, Arizona, USA

Denis Thiéry
Inra, UMR 1065, Save, Isvv, Villenave d'Ornon, and Bordeaux Sciences Agro, UMR 1065 Save, Gradignan, France

A model for the control of the European grapevine moth* Lobesia botrana *includes two control methods: insecticides and mating disruption. It yields the combination and schedule of application that minimize cost and losses due to the pest. A simulation is presented for an experimental situation.

***Keywords*:** age-structured population model; optimal control; population dynamics; viticulture

1. INTRODUCTION

Phytosanitary chemical products used in viticulture may have negative consequences on the environment and on human health (Tabashnik et al., 2003; Vassiliou, 2009). In Bordeaux, renowned châteaux are increasingly adopting the so-called "organic production," which consists of developing nonchemical devices to fight the pests. In 2007, 15,000 tons of pesticides were used in the French viticulture (Sinfort et al., 2009). Phytosanitary chemical products are also applied to reduce the pest population and fungal diseases such as the mildew and the powdery mildew (*Botrytis cinerea*).

In Europe, insecticide is spread two to five times per season, as soon as 100 bunches randomly harvested in a parcel contain 30 to 80 glomeruli, which are contracted inflorescences with short floral axes terminating each in a single flower (Les cahiers itinéraires de l'Institut technique de la vigne et du vin, 2003; Charmillot et al., 2006). To estimate the density of insects, wine makers use sexual and food traps.

The technique of mating disruption is used on 90,000 hectares in Europe (Kast, 2001; Vassiliou, 2009). It consists of diffusing a bio-synthetic molecule that is less

Address correspondence to Delphine Picart, Inra, UMR 1391 Ispa, F-33140 Villenave d'Ornon, France. E-mail: dpicart@bordeaux.inra.fr

damaging to the environment than insecticides. However, its cost is high and its efficiency low.

In the case of the grapevine moth *Lobesia botrana*, we shall determine the optimal combination of insecticide and mating disruption. We answer the question "How often and when should chemicals be spread to minimize harvest losses?"

2. MODEL

2.1. Efficiency of the Insecticide

The efficiency v of an insecticide or of an hormonal diffuser decays steadily after spreading:

$$v'(t) = -dv(t), \quad v(0) = v_0, \tag{1}$$

where d is the decay rate of the product efficiency in time and v_0 the maximal product efficiency (at the moment of application).

2.2. Population Control

In viticulture, most insecticides (neurotoxins, growth regulators, *Bacillus thuringiensis* toxin) used against the grape moth act on larvae (Oliva et al., 1999; Shelton et al., 2002; Thiéry, 2011). Their efficacy is maximal when applied at the egg stage. The mating disruption technique disturbs the mating of adult moths. The pheromone is to be spread at the beginning of the adult flight stage (Stockel et al., 1994; Thiéry and Delbac, 2011).

The age density of eggs at time t is $u^e(t)$, of larvae $u^l(t)$, and of adult female moths $u^f(t)$. The efficiency of mating disruption is $v_1(t)$, and the efficiency of pesticides is $v_2(t)$. Time t and age a are measured in days. The populations are governed by:

$$\begin{cases} \frac{\partial u^e}{\partial t}(t,a) + \frac{\partial u^e}{\partial a}(t,a) = -(\beta^e(a) + m^e(a) + v_2(t))u^e(t,a), \quad (t,a) \in \Omega^e, \quad \text{(eggs)} \\ \frac{\partial u^l}{\partial t}(t,a) + \frac{\partial u^l}{\partial a}(t,a) = -\beta^l(a)u^l(t,a) - m^l(a)u^l(t,a), \; (t,a) \in \Omega^l, \; \text{(larvae)} \\ \frac{\partial u^f}{\partial t}(t,a) + \frac{\partial u^f}{\partial a}(t,a) = -m^f(a)u^f(t,a), \quad (t,a) \in \Omega^f, \quad \text{(females)}, \end{cases} \tag{2}$$

where $\Omega^k = [0, T] \times [0, L^k]$, $k = e, l, f$, and the boundary conditions are

$$\begin{cases} u^e(t,0) = (1 - v_1(t)) \int_0^{L^f} \beta^f(a)u^f(t,a)\, da \quad \text{(eggs)} \\ u^l(t,0) = \int_0^{L^e} \beta^e(a)u^e(t,a)\, da \quad \text{(larvae)} \\ u^f(t,0) = \int_0^{L^l} \beta^l(a)u^l(t,a)\, da, \quad \text{(females)} \end{cases} \tag{3}$$

for $t \in [0, T]$, with initial conditions

$$u^k(0,a) = u_0^k(a), \quad a \in [0, L^k], \qquad k = e, l, f. \tag{4}$$

The function β^e represents the transition rate between egg and larva; the function β^l represents the transition rate between larva and female adult. The function β^f represents the age-specific fertility. These rates follow Gaussian distributions, truncated to appropriate age intervals $[0, L^k]$ $(k = e, l, f)$:

$$\beta^k(a) = b_1^k \exp\left(-\left(\frac{a - b_2^k}{b_3^k}\right)^2\right), \tag{5}$$

where b_1^k, $k = e, l, f$, are positive constants, meaning that the growth of an egg cohort or a larval cohort is normally distributed in age with truncation, as is the egg-laying of a female cohort. The means are b_2^k and the standard deviations are b_3^k, $k = e, l, f$.

The age-specific mortality functions m^k, $k = e, l, f$, are

$$m^k(a) = \frac{c}{L^k - a}, \quad a \in [0, L^k], \tag{6}$$

where L^k represents the maximal age in stage k.

The first Eq. (3) describes the birth dynamic under mating disruption, the second Eq. (3) describes the hatching dynamic, and the third Eq. (3) describes the adult flight dynamic.

The control function v_i, $i = 1, 2$, is solution of Eq. (1) with decay rate d_i. Mating disruption is represented as a reduction in the total number of new laid eggs in the first Eq. (1). When the insecticide targets newly hatched larvae, the control modifies the egg dynamic in the first Eq. (2).

2.3. Optimal Treatment Schedules

To minimize harvest losses, we find the optimal control schedule $0 \le t_1 < t_2 <, \ldots, < t_N < T$ of N insecticide applications:

$$\begin{cases} \min\limits_{0 \le t_1 < t_2 < \ldots < t_N < T} \mathcal{J}(t_1, \ldots, t_N), \\ \text{where} \\ \mathcal{J}(t_1, \ldots, t_N) = \mu \int_0^T \int_0^{L^l} u^l(t, a)\, da\, dt + \alpha N, \\ P^f(t) = \int_0^{L^f} u^f(t, a)\, da \ge 0, \\ \text{and } u^l \text{ and } u^f \text{ are the functions defined in Eq.(2) to (4).} \end{cases} \tag{7}$$

The dates of application are represented by t_i, the loss due to larva-induced damage per unit area per time unit is represented by μ, and the cost of an insecticide application is represented by α. $\mathcal{J}(t_1, \ldots, t_N)$ represents harvest losses in euros per hectare. The last relation in Eq. (7) states that treatment begins after adults are caught by traps.

We solve Eq. (7) using the program BCONF in the commercial package Absoft.

2.4. Application

We use field data providing the daily total number of male moths captured in traps from April 1 to May 31 (left panel of Figure A1 and Table A1 in the

Appendix). We assume that the total number of females is the same as the total number of males to initialize the boundary conditions in Eq. (4):

$$\begin{cases} u^f(t,0) = q^f(t), \\ u^e(t,0) = u^l(t,0) = 0, \end{cases} \tag{8}$$

where $t \in [0, 61]$ spans the two months of trapping and q^f represents the daily inflow of female moths. The initial conditions are

$$u^k(0,a) = 0, \quad k = e, l, f. \tag{9}$$

Because the proportion p of moths captured by the traps is unknown, we assign it a value in a plausible range in the simulations. Subsequent insect generations are simulated using Eq. (2) to (4) through a numerical method based on finite volumes (Picart and Ainseba, 2011).

The parameters in Eq. (2) to (6) are based on Thiéry (2008) and Picart (2009): $b_1^f = 19.34$, $b_2^f = 3.5$, $b_3^f = 0.35$, $L^f = 10$ in Eq. (5) for an average fertility of 12 eggs per female per day; $c = 0.05$, $L^e = L^f = 10$, and $L^l = 50$ in Eq. (6) for an average larval mortality of 10% per day, and an average egg and female moth mortality of 6% per day; $b_1^e = b_1^l = 16.1$, $b_2^e = 7.5$, $b_2^l = 40$, $b_3^e = b_3^l = 0.35$, $L^e = 10$, and $L^l = 50$ in Eq. (5).

Ugaglia (2007) evaluated the cost of producing wine in the Médoc at 10,000€ per hectare. In our case study, $\mu = 9.18$€ per 10,000 larvae, so that the harvest loss due to the pest is $\mu \int_0^{182} \int_0^{50} u^l(t,a)\, da\, dt = 1{,}000.93$€ per hectare, that is 10% of the cost.

According to the *Institut français de la vigne et du vin*, mating disruption has an average cost of 210€ per hectare. It reduces the size of the first generation of larvae by 40%–60% when infestation is not too strong (Les cahiers itinéraires de l'Institut technique de la vigne et du vin, 2003). We take $N = 1$ and $\alpha = 210$€ in Eq. (7), and $d = 1/182$, and $v_0 = 0.42$ in Eq. (1) to have a 60% reduction of the larva population for the whole season.

The *bacillus thuringiensis* toxin in 2003 cost between 22 and 28€ per hectare. It remains active for 10–12 days. Therefore we use $d = 1/10$, $v_0 = 1$, and $\alpha = 22$ in Eq. (1). A growth regulator costs between 40 and 67€ per hectare, remaining active for 3 weeks. Therefore we use $d = 1/21$, $v_0 = 1$, and $\alpha = 67$ in Eq. (1).

3. RESULTS

We determine the optimal schedule for three control procedures: mating-disruption, insecticide, and mating disruption combined with insecticide. We compute harvest losses and the efficiency of the control (percentage of larvae killed during the entire season). We determine the optimal total number of insecticide applications and their schedule.

3.1. Mating Disruption

Table 1 shows that the best date to install the diffusers is when the first adult moths appear. This control reduces losses by approximately 37%.

Table 1. Mating disruption diffusers: optimal treatment dates, efficiency, and losses (in € per hectare)

	Treatment date	Efficiency (%)	Loss per ha (€)
Early use	May 23	60.6	603.5
Late use	June 10	52.0	682.0

For a late application, the best date is June 10, just before the onset of the second insect generation, with resulting losses per hectare 13% higher.

3.2. Insecticides

Table 2 presents the optimal schedule from Eq. (7) for 1 to 5 applications of the cheaper ovicide (22€ per hectare), with a 10-day effective action (for example with the *Bacillus thuringiensis* toxin). Four applications are optimal: three during the first insect generation (April 23, May 3, and May 27) and one at the beginning of the second insect generation (June 18), resulting in a reduction of harvest losses of more than 56%.

Tables 3 and 4 show that the optimal number of larvicide applications is two for growth regulators and five for Bt-based products. Their use reduces losses by 79%–85%. For both products, the optimal treatment dates are during the first adult flight, except for the fourth and the fifth applications, which should be conducted during the egg-hatching of the second generation. The efficiency of the two procedures is between 92% and 96%.

Table 2. Optimal schedule of ovicide spread, efficiency, and losses

Total number of applications	Optimal dates	Efficiency (in %)	Loss per ha (in €)
1	April 23	40.0	665.8
2	April 23, June 22	61.0	524.2
3	April 23, June 22, June 22, July 16	75.1	449.5
4	April 23, May 3, May 27, June 19	83.2	435.6
5	April 23, May 3, May 27, June 19, June 30	89.3	441.4

Table 3. Optimal schedule of larvicide spread, efficiency, and losses: growth regulator

Total number of applications	Optimal dates	Efficiency (in %)	Loss per ha (in €)
1	April 29	69.5	371.6
2	April 28, May 22	92.3	211.0
3	April 29, May 22, June 18	97.2	228.7
4	April 29, May 22, June 18, July 6	99.0	277.9

Table 4. Bt toxin: optimal schedule of larvicide spread, efficiency, and losses

Total number of applications	Optimal dates	Efficiency (in %)	Loss per ha (in €)
1	April 30	45.9	562.8
2	April 30, May 13	69.5	349.2
3	April 30, May 13, May 31	86.6	199.2
4	April 30, May 13, May 31, June 18	93.0	157.5
5	April 30, May 13, May 31, June 18, July 11	96.0	149.0
6	April 30, May 13, May 31, June 18, July 11, August 16	97.9	150.3

3.3. Optimal Use of Mating Disruption and Bt-Based Larvicides

Table 5 shows that, under mating disruption, four applications of Bt-based larvicide are optimal: three during the first generation and one at the beginning of the second generation. Losses are reduced by over two-thirds compared with the dynamic without control. The efficiency of this control procedure is about 97%.

3.4. Pest Control in Practice

3.4.1. Population control by larvicide. The cheaper and most efficient procedure consists in five applications of a Bt-based larvicide. It costs 75% less than mating-disruption alone, 65% less than ovicides, and 54% less than the combination of ovicides and mating disruption. The latter however is 1% more efficient in reducing the pest population size.

At a comparable efficiency between 92% and 93%, a cheaper solution consists in four applications of a larvicide with a 10-day active period. Its resulting costs and losses are 25% less than with two applications of a larvicide with a 3 week active period (Tables 3 and 4). This latter solution is more environment friendly; it allows the reduction of the amount of larvicide by at least a half.

The ovicide only is an expensive treatment: for a reduction of 83% of the larval population, four applications are necessary, whereas a comparable larval reduction

Table 5. Mating-disruption: optimal schedule of larvicide spread, efficiency and losses

Total number of applications	Optimal dates	Efficiency (in %)	Loss per ha (in €)
1	April 30	77.0	459.7
2	April 30, May 13	86.7	386.6
3	April 30, May 13, May 31	94.9	326.9
4	April 30, May 13, May 31 June 18	97.1	326.5
5	April 30, May 13, May 31, June 18, July 11	98.4	335.3

is reached with at most three applications of larvicide or two applications of larvicide combined with mating disruption. In this case the loss is 327€ per hectare, against 436€ for the ovicide-only treatment.

The use of mating disruption alone leads to the worst losses (Tables 1 to 5). Combined with larvicide, mating disruption reduces both the amount of chemicals applied and the total number of surviving insects. With three larvicide treatments, the larval population is reduced by 34% more than with mating disruption alone, and the financial loss is reduced by 46%.

3.4.2. Control only the first insect generation. The best period to apply the controls is from the appearance of first adult moths to the moment when three quarters of the adults of the next generation have come into existence. At least 60% of insecticide applications are scheduled during the first insect generation and have the effect of reducing the larval population size by 74.5%–94.9%. Later application of the control is less efficient to control the pest, as shown in Table 1.

3.4.3. No treatment at some specific dates. Tables 3 and 4 show that treatment dates for larvicide applications should be spaced out to avoid the overlap of protection periods. For example, the optimal application schedule of a larvicide with an active period of 10 days is to treat every 19 days on average. This rule does not apply to ovicides whose life (longer than 21 days) exceeds the average length (20 days) of 2 consecutive applications.

3.4.4. Rely on the first catches in the traps to plan the first treatment. The first application of insecticide should be scheduled during the first 10 days of catches, that is, just before the first peak of female moth presence in the vineyard (Table 6 and Figure A1). The date of the first application depends on the control method. The application should begin on the second day of trap catches for ovicides, on the eighth or ninth for larvicides. The first application of ovicide corresponds to the first day of egg-laying; the first application of larvicide corresponds to the first hatchings of these eggs.

Table 6. Optimal application dates and time elapsed since capturing the first moths in traps

Control procedure	Application dates	Days from first moths trapped
Ovicide	April 23	2
	May 3	12
	May 27	36
	June 18	–
Larvicide with growth regulator	April 29	8
	May 22	31
Larvicide with Bt toxin	April 30	9
	May 13	22
	May 30	61 (last)
	June 17	–
	July 10	–

4. CONCLUSION

We presented a model for controlling the infection by *Lobesia botrana*, affecting vineyards by insecticides and mating disruption.

By simulations, we found that insecticides are more efficient than mating disruption, as it is the case in real experiments (Charmillot et al., 2006).

We determined the optimal strategy to control the crop pest and the timetable of its application. The optimality criterion combines the decrease of the pest population over the entire crop season (equivalently, the smallest losses caused by the surviving larvae) and the cost of the control application. In the case of the European grapevine moth, we determined the optimal application schedules for various phytosanitary products. Inputs are the mortality and fertility rates of the pest population, the mean growth rate at each of its developmental stages, and its initial distribution.

We found that controls are the most efficient when applied from the appearance of the first adult moths until the last appearance of second-generation adult moths.

The optimal total number of applications of a phytosanitary product depends on its action mode, targeting eggs or larvae, its action period, lasting from a few days to several weeks, and its cost. The optimal control of a European grapevine moth population, as in Figure A1 in the Appendix, is to apply the cheapest larvicide (22€ per hectare), with an active period of 10 days, five times.

The time elapsed between two applications of insecticide should be longer than the period during which the insecticide is effective, except for the first two applications of an ovicide (Table 2). The optimal timing of the first application depends on the first catches. It is the second day for an ovicide and the second day plus the mean growth time of eggs for a larvicide. These correspond to the first egg-laying by adult female moths and to the mean time of egg-hatching. Applications of insecticide should rely on the date of the first moth catches of moths.

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5. APPENDIX

Table A1. Daily total number of male moths trapped in the vineyard of a well known château from the Sauternes denomination. Data were collected and are supplied by the research unit Save of the Institut national de la recherche agronomique (French national research Institute of agronomy)

	April										May		
Day of the month	1-20	21	22	23	24	25	26	27	28	29	30	1	2	3
Moths trapped	0	39	37	37	38	38	18	15	61	17	13	45	83	12
							May							
Day of the month	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Moths trapped	0	0	59	0	0	77	34	6	0	12	0	0	30	7
Day of the month	18	19		21	22	23	24	25	26	27	28	29	30	31
Moths trapped	13	0	0	0	0	4	2	25	16	35	0	0	69	0

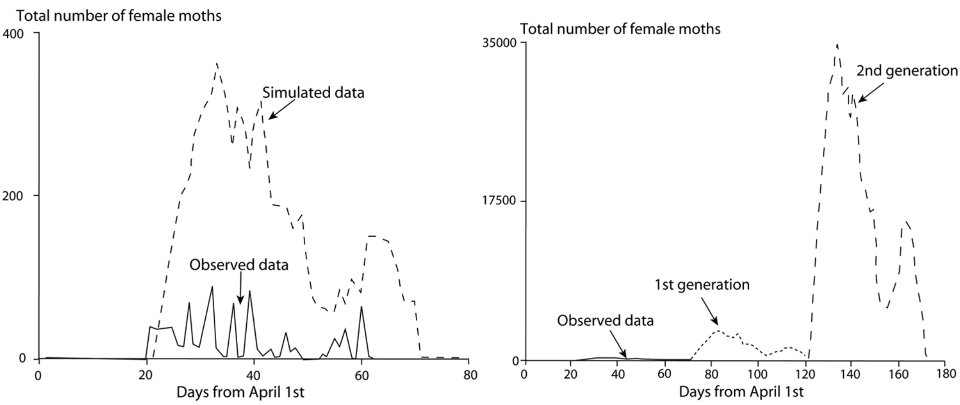

Figure A1. Left: daily total number of moths trapped (solid line) and simulated moth population size (dash-dotted line); right: simulated second generation (dashed line) and third generation (dash-dotted line) moth population size.