Managing pest resistance to *Bt* crops with dynamic refuge size adjustments

Marion Desquilbet [1] Markus Herrmann[2]
markus.herrmann@ecn.ulaval.ca

[1] Toulouse School of Economics (INRA, GREMAQ)

[2] Department of Economics (CREATE), Université Laval, Québec

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Context and goal

- Effectiveness of pesticides / pest-toxic crop varieties may be lost over time (⇐ selection pressure)
- Natural resource economics: pesticides / pest-toxic varieties: affect two interdependent "biological resources":
  - Level of the pest population (detrimental resource)
  - Susceptibility of this population to pesticides / pest-toxic crop varieties (beneficial resource)
- Goal of this paper: contribute to the theory of the optimal use of pest-toxic varieties over time

Context

- Literature:
  - Seminal paper: Hueth & Regev (1974) (dynamic externalities of pesticide use)
  - Early contributions 1970s-1980s (chemical pesticides)
  - New scrutiny: advent of pest-toxic GM *Bt* crops and refuge regulation
- Refuges:
  - First mandatory large-scale system for pest resistance management
  - All farmers growing a *Bt* crop must allocate a given percentage of their area to a non-GM, non-insect-toxic variety
  - **Principle**: resistant insect emerging from *Bt* crops is likely to mate with one of the much larger population of susceptible pests emerging from refuge fields

Literature

- Laxminarayan and Simpson (2002), Qiao *et al.* (2008, 2009)
    - Biological model: rather inconsistent with the lifecycle of insects, first two models written for haploid pests, continuous time not best-fitted (high selection if zero refuge)
- Grimshud and Huffaker (2006)
    - Ad-hoc specification of relative speed of resistance
- Secchi *et al.* (2006), Hurley *et al.* (2001)
    - No analysis of overcost of *Bt* and fitness cost, or constant refuge

Our approach

- Stylized bio-economic model of *Bt* crops & refuges, compatible with population biology literature (and with Hurley et al. 2001, who have constant refuge)
- Identify analytically inter-temporal effects on pest population / susceptibility
- Draw a clear picture the optimal, time-variant refuge and an exhaustive dynamic comparative exercise with simulations
- Discussion of previous stylized analytical models

Assumptions

- Pest population: $N = N_{rr} + N_{ss} + N_{rs}$
- Alleles: $N_r + N_s = 2N$

  $N_r = 2N_{rr} + N_{rs} \qquad N_s = 2N_{ss} + N_{rs}$
- Proportions: $p_r + p_s = 1 \qquad p_r = N_r/(2N) \qquad p_s = N_s/(2N)$
- Lifecycle:
  - Stage 1: adult migration, reproduction, density dependence

$$N_1 = [1 + g(1 - N/K)]N$$

$$N_{rr,1} = {p_r}^2 N_1 \quad N_{rs,1} = 2p_r p_s N_1 \quad N_{ss,1} = {p_s}^2 N_1$$

  - Stage 2: genotype-induced mortality

$$N_{rr,2} = (1 - c)N_{rr,1} \quad N_{rs,2} = \phi N_{rs,1} \quad N_{ss,2} = \phi N_{ss,1}$$

Biological model: allele numbers

$$
\begin{aligned}
N_r' &= N_r\left[1+g\left(1-\frac{N_r+N_s}{2K}\right)\right]\frac{(1-c)N_r+\phi N_s}{N_r+N_s}\\
N_s' &= N_s\left[1+g\left(1-\frac{N_r+N_s}{2K}\right)\right]\phi
\end{aligned}
$$

- Logistic regeneration / density dependence of pest population
- Impact of random mating on the genotypic composition
- Fitness of the aggregate of susceptible alleles

Bio-economic model

- Laws of motion:

$$
\begin{aligned}
N' &= f_N(N, p_r, \phi) = \left[(1-c){p_r}^2 + \phi(1-{p_r}^2)\right]\left[1 + g\left(1 - \frac{N}{K}\right)\right] N \\
{p_r}' &= f_r(p_r, \phi) = \frac{(1-c){p_r}^2 + \phi p_r(1-p_r)}{(1-c){p_r}^2 + \phi(1-{p_r}^2)}
\end{aligned}
$$

- Susceptibility may be renewable:

$$
\Delta p_r \equiv {p_r}' - p_r = \frac{(1-p_r){p_r}^2(1-c-\phi)}{(1-c){p_r}^2 + \phi(1-{p_r}^2)}
$$

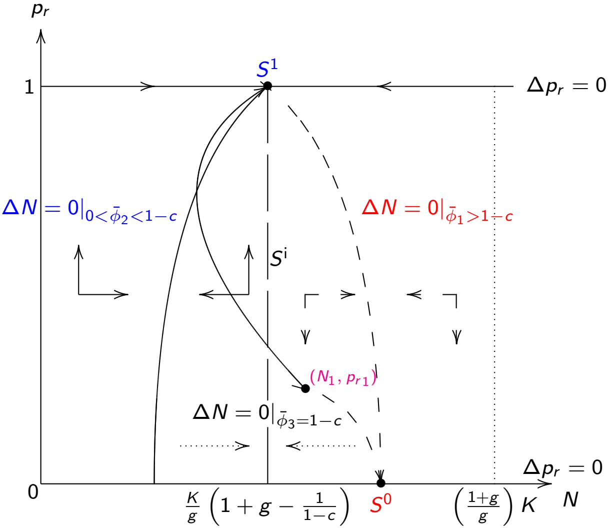


Figure: The phase diagram

- Per-period cost function:

$$C(N, p_r, \phi) = \alpha f_N(N, p_r, \phi) + c_s(1-\phi)$$

- Intertemporal objective:

$$V(N_1, p_{r1}) = \min_{0 \leq \phi \leq 1} \sum_{0}^{T} \delta^t C(N, p_r, \phi)$$

subject to $T < \infty$ and the laws of motion of the state variables.

Optimal control problem (discrete time)

$$L = \sum_{t=0}^{T} \delta^t \{ -C(N_t, p_{r\,t}, \phi_t) + \delta\lambda_{t+1} \left[f_N(N_t, p_{r\,t}, \phi_t) - N_{t+1} \right]$$

$$+\delta\mu_{t+1} \left[f_r(p_{r\,t}, \phi_t) - p_{r\,t+1} \right] \}$$

- Necessary conditions for an optimum:

$$\frac{\partial L}{\partial \phi_t} \leq 0,\ \phi_t \geq 0 \quad \text{and} \quad \frac{\partial L}{\partial \phi_t}\phi_t = 0$$

$$\text{or} \qquad \frac{\partial L}{\partial \phi_t} \geq 0,\ \phi_t \leq 1 \quad \text{and} \quad \frac{\partial L}{\partial \phi_t}(1 - \phi_t) = 0$$

$$\frac{\partial L}{\partial N_t} = 0 \qquad \frac{\partial L}{\partial p_{r\,t}} = 0$$

$$\frac{\partial L}{\partial [\delta\lambda_{t+1}]} = 0 \qquad \frac{\partial L}{\partial [\delta\mu_{t+1}]} = 0$$

Interior solution

$$c_s - \delta\mu_{t+1}\frac{(1-c)(1-p_r){p_r}^2}{[\phi + p_r^2(1-c-\phi)]^2}$$
$$= \left(1 + g\left(1 - \frac{N}{K}\right)\right) N(1-{p_r}^2)(\alpha - \delta\lambda_{t+1})$$

- Left-hand side: social (marginal) cost of using *Bt* seeds: additional cost of *Bt* seeds + shadow cost of building up resistance
- Right-hand side: social (marginal) benefit of avoided pest damage

Optimal solution in the last period

- Shadow values: $\mu_{T+1} = \lambda_{T+1} = 0$
- No overcost of *Bt* seeds ($c_s = 0$): no refuge in last period (as long as $p_r < 1$)
- Overcost of *Bt* seeds ($c_s > 0$): in last period, extreme control:
  - no refuge if low p_r / high N
  - only refuge if high p_r / low N

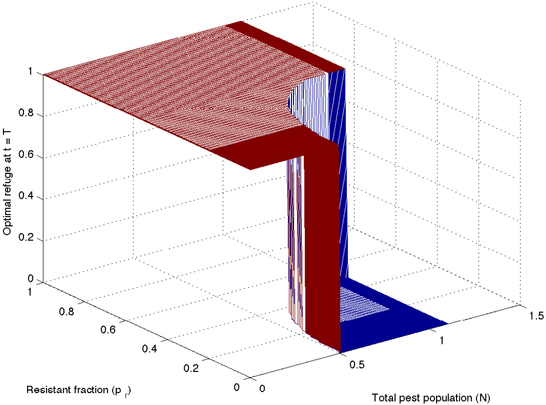
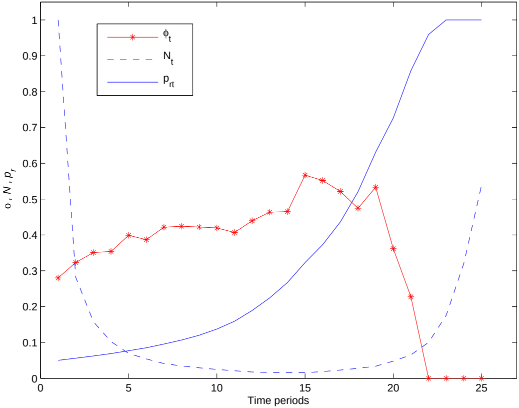
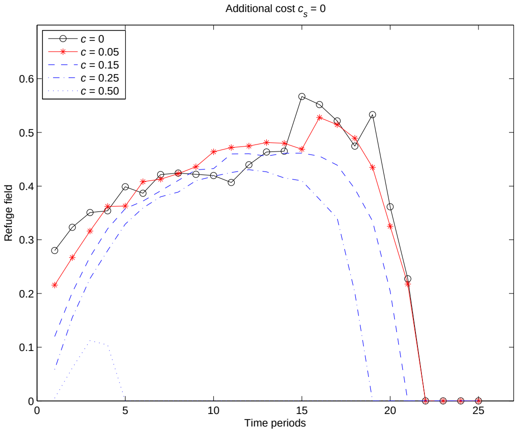


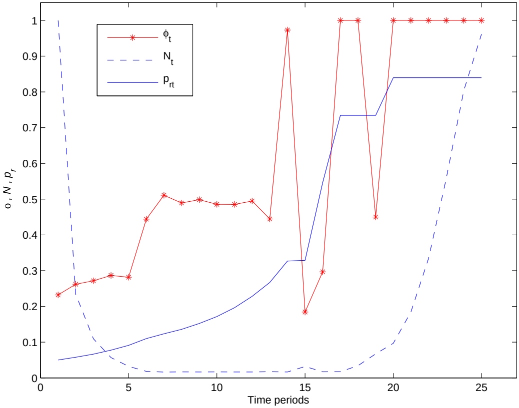
Figure: Optimal refuge policy at $t = T$ (ϕ_T)



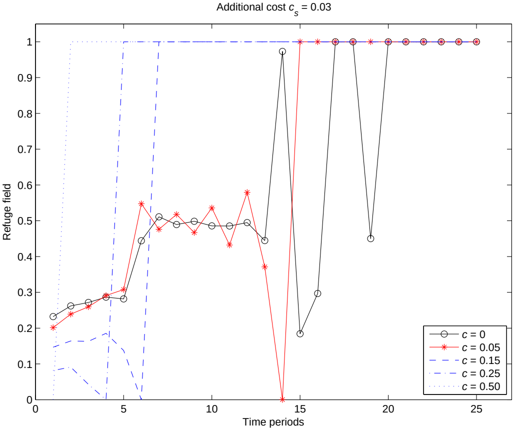
- Evolution of $(N_t, p_{r\,t}, \phi_t)$ with $c_s = c = 0$
- Susceptibility of pest population = non-renewable resource
- No refuge in last period



- Comparative dynamics wrt c when $c_s = 0$
- Susceptibility of pest population becomes renewable resource
- No refuge in last period • Reduces optimal refuge size
- No refuge: happens earlier



- Evolution of $(N_t, {p_r}_t, \phi_t)$ with $c_s > 0$ and $c = 0$
- First phase: refuge increases
- Second phase: refuge back and forth
- Third phase: no *Bt*



- Comparative dynamics of the refuge policy $c_s > 0$
- Benefits of having *RR* pests rather than others (increased mortality due to fitness cost of resistance)
- Optimal solution: always complete exhaustion of pest susceptibility when $c > 0$

- Time-variant versus constant refuge

	c	0	0.05	0.15	0.25	0.5
$c_s = 0$	$V(p_{r1}, N_1; \phi_t)$	0.0768	0.0452	0.0153	0.0055	4.2×10^{-4}
	$V(p_{r1}, N_1; \bar{\phi})$	0.0822	0.0552	0.0242	0.0102	4.7×10^{-4}
	$\bar{\phi}$	0.4050	0.3550	0.2450	0.1350	0.005
	$(\Delta V / V(.; \phi_t))$	(7%)	(22%)	(58%)	(85%)	(12%)
$c_s = 0.03$	$V(p_{r1}, N_1; \phi_t)$	0.3485	0.2956	0.2157	0.1399	0.0309
	$V(p_{r1}, N_1; \bar{\phi})$	0.3888	0.3786	0.3737	0.3730	0.3724
	$\bar{\phi}$	0.4550	0.4350	0.4250	0.4250	0.4250
	$(\Delta V / V(.; \phi_t))$	(11%)	(28%)	(73%)	(166%)	(1105%)

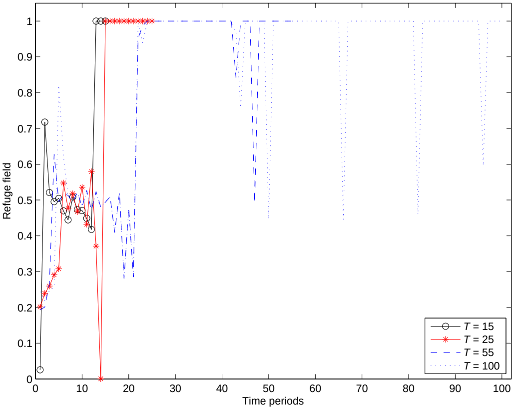


Figure: Comparative dynamics of refuge policy and time horizon (T)

T	15	25	55	100
$V(p_{r1}, N_1; \phi_t)$	0.1972	0.2956	0.6969	0.8901
$V(p_{r1}, N_1; \bar{\phi})$	0.2730	0.3786	0.8137	1.0673
$\bar{\phi}$	0.40	0.4350	0.55	0.5750
$(\Delta V / V(; \phi_t))$	(38%)	(28%)	(17%)	(20%)
ρ	0	0.03	0.15	0.25
$V(p_{r1}, N_1; \phi_t)$	0.4636	0.2956	0.1391	0.0581
$V(p_{r1}, N_1; \bar{\phi})$	0.5115	0.3786	0.1755	0.1251
$\bar{\phi}$	0.445	0.4350	0.395	0.36
$(\Delta V / V(; \phi_t))$	(10%)	(28%)	(26%)	(115%)

Table: Comparative dynamics on the time horizon and the discount rate ($c_s = 0.03$ and $c = 0.05$)

Conclusion

- Beware of what biological model you use
- Optimal adjustment of refuge size:
  - No overcost of *Bt* seeds: more and more, then less and less refuge
  - Overcost of *Bt* seeds: more and more, then back and forth, then only refuge
- Possible extensions?
  - Cross-dynamics refuge / conventional pesticide
  - Simulations on one particular pest/crop model
  - Optimal decisions of a monopolist selling *Bt* seeds *versus* social optimum
  - Technical: If finite time horizon, introduce bequest function.