EFFICIENT Bt REFUGE POLICIES

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Abstract

Bt cotton refuge policies are derived accounting for previously ignored aspects of production and insecticide resistance. Results indicate that producers in Louisiana may experience significant losses and use considerably more conventional insecticides under current treated-refuge policy relative efficient treated-refuge policy. Results indicate that efficient untreated-refuge policy dominates efficient treated-refuge policy with respect to long-run producer profitability, annual profit volatility, conventional insecticide use, and end-period resistance-allele frequencies, and that the current untreated-refuge policy is efficient over 20-, 30-, and 40-year planning horizons.

Introduction

Since cotton producers do not own legal rights to kill insect populations that are susceptible to insecticides, individual producers have no incentive to account for future, insecticide-resistance productivity losses arising from their pest-management decisions (Gordon, 1954; Coase, 1960; Baumol and Oates, 1988). As a result, the collective actions of producers may increase the rate of resistance development above the rate that maximizes social welfare. Concerns regarding insect-pest development of resistance to Bt cotton prompted the Environmental Protection Agency (EPA) to establish legal limits on the proportion of total acres individual producers may plant, representing the first attempt to regulate the development of insecticide resistance and the first instance of the use of refuge as a policy instrument. The current policy provides cotton producers a choice between a treated-refuge option and an untreated-refuge option: they may (1) plant Bt on 80 percent of their total acres, no Bt in any form on the remaining 20 percent, with conventional insecticides allowed throughout; or (2) plant 96 percent Bt, spray Bt acres as needed with conventional insecticides, with no insecticides allowed on the remaining four percent.

Ever since Carlson and Castle (1972) first pointed out the resource characteristics of insecticide susceptibility, pest management in the presence of increasing resistance has been viewed as an exhaustible resource allocation problem, and many studies have examined socially efficient insecticide use in this setting. Previous resistance-management studies found in the economics literature, however, have examined single-insect single-insecticide problems almost exclusively (Hueth and Regev, 1974; Regev, Shalit, and Gutierrez, 1983; Plant, Mangel, and Flynn, 1985; and Hurley, Babcock, and Hellmich, 1997). The majority of genetic and entomologic studies have followed suit, as in Georghiou and Taylor (1977a, 1977b). Since cotton producers routinely use multiple insecticides and insecticide mixtures to manage multiple insect pests, and since Georghiou (1983), Curtis (1985), Mani (1986), and Taylor (1986) suggest that toxin mixtures can reduce the rate of resistance development relative to the single-insecticide case, conventional analysis may not be well suited for the derivation of efficient refuge policies under realistic production settings.

This study derives efficient treated- and untreated-refuge policies that maximize the present value of producer profits over various planning horizons, assuming producers plant Bt and non-Bt cotton and use pyrethroids, and other conventional insecticides, to manage yield damages associated with the bollworm-budworm complex. The analysis accounts for the presence of damaging bollworm and budworm populations and the use of Bt cotton, pyrethroids, and other conventional insecticides; a relationship between insecticide resistance and producer profit; and the development of resistance in bollworms and budworms to Bt and pyrethroids that results from the profit-maximizing Bt-planting decisions of producers. Since the biological relationships employed in the analysis are estimated using Louisiana field data, refuge policy implications apply strictly to this region.

Model

The main features of the economic model are discussed in this section. See Livingston (1999) for a complete presentation. Briefly, there are two types of cotton, Bt and non-Bt. The collective actions of all Louisiana producers are characterized by a representative producer who chooses the proportion of Bt cotton to plant in Louisiana at the beginning of each growing season to maximize average profit per acre. The model of production is similar to those employed by Lichtenberg and Zilberman (1986), Harper and Zilberman (1989), and Hurley, Babcock, and Hellmich (1997). Average profit per acre is profit per Bt acre, multiplied by the proportion of Bt acres planted, plus profit per non-Bt acre, multiplied by the proportion of non-Bt acres planted. Profit per Bt acre depends on a constant pest-free yield, proportionate yield damage, and Bt and conventional insecticide treatment costs per Bt acre. Likewise, profit per non-Bt acre depends on a constant pest-free yield, proportionate yield damage, and non-Bt and conventional insecticide treatment costs per non-Bt acre.

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Constant pest-free yield is assumed the same on Bt and non-Bt acres. Yield damages and insecticide treatment costs, however, are increasing functions of bollworm and budworm, Bt and pyrethroid resistance levels. The link between resistance and producer profit is established by estimating relationships between: (1) average, annual larval survival rates and average, annual larval infestation levels; (2) infestation levels and average, annual pyrethroid treatments; and (3) survival rates, infestation levels, and pyrethroid treatments and average, annual proportionate yield damages. See Livingston (1999, p.64-86) for a thorough presentation of the technical details, including data sources and estimation procedures. It is assumed that the producer does not internalize future resistance costs associated with annual Bt-planting decisions, solving the same profit-maximization problem at the beginning of each growing season subject to the refuge policy, bollworm and budworm resistance levels, and the damage and cost functions.

Given the producer's constrained profit-maximization problem, constant, treated- and untreated-refuge policies that maximize the present value of producer profits over various planning horizons subject to genetic models of resistance development are derived. See Livingston (1999, p.8-44) for a complete discussion of the genetic models used to track resistance development and Livingston et al. (2000) for a concise summary. Briefly, genetic models, one for each insect, are used to relate current resistance levels and the Louisiana proportion of Bt cotton planted to survival rates of larvae facing the Bt-pyrethroid mixture, pyrethroids, or no insecticides; and to future resistance levels. As a result, the analysis accounts for Bt-pyrethroid toxin-mixture effects on resistance development under treated- and untreated-refuge scenarios (Livingston et al., 2000). Genetic-model parameters associated with Bt resistance are specified exogenously using available information; however, parameters associated with pyrethroid resistance are estimated using Louisiana field data (Bagwell et al., 1999). See Livingston (1999, p.45-61) for a thorough analysis of the effects of genetic-model parameter shifts on efficient refuge policies.

Assumptions

Input and output prices are taken as given for the Louisiana production region, which is on average responsible for only seven percent of total U.S. production. Moreover, the per-acre price received by all U.S. producers is, to a significant extent, determined by supply and demand conditions in the world market and has not changed significantly over the past 10 years (United States Department of Agriculture, 1998). Only variable costs associated with the use of Bt cotton, pyrethroids, and other conventional insecticides associated with the management of bollworm and budworm infestations are included in the producer's cost functions. All other productive factors are taken as given and assumed employed in profit-maximizing proportions independent of the proportion of Bt planted in Louisiana. That is, it is assumed that insecticide-treatment costs associated with managing other pests (e.g. boll weevils and plant bugs) and all other production costs are approximately the same on Bt and non-Bt cotton.

Louisiana acre-weighted averages are used to specify per-acre unit fees. The Bt technology fee ($32.00) is set at its 1998 value. The pyrethroid-treatment fee ($7.81) is the average cost of treating one acre during the 1998 crop year (Bagwell, 1999). The acre-weighted, average pyrethroid-treatment fee includes the cost of treating by air, weighted by the proportion of acres treated by air, plus the cost of ground treatment, weighted by the proportion of acres treated using ground sprayers. The conventional-insecticide treatment fee ($15.00) is a conservative estimate of the average unit cost of other available insecticides used to control bollworm-budworm infestations. Production is weighted by the average price per 480-pound bale received by U.S. producers over the 1987 to 1997 crop years, $305.67 per bale (United States Department of Agriculture, 1998).

Observations on pounds per harvested acre, total acres harvested, and total acres planted are used to estimate the value for pest-free bales of cotton per planted acre (United States Department of Agriculture, 1998). Pounds per harvested acre are deflated by the ratio of harvested to planted acres for the years 1987 to 1998 to obtain observations on pounds per planted acre. Pounds per planted acre are inflated by five percent to adjust yields roughly for yield damages associated with bollworm-budworm infestations. Average, annual bollworm-budworm complex yield damages for the state of Louisiana over this period are 3.4 percent, with a high of 7.5 percent and a low of 1.7 percent. The five-percent weighting factor provides a conservative estimate of the maximum obtainable bollworm-budworm-free yield. The mean of this series (1.5014) is used as the estimate for pest-free bales of cotton per planted acre.

Efficient treated- and untreated-refuge policies are computed for the five-, 10-, 20-, 30-, 40-, 50-, 100-, and 200-year planning horizons using an annual, three-percent real interest rate to discount future profit flows. For simplicity, refuge policies and profit-maximizing Bt-planting proportions are constrained to the finite set {0.00, 0.01, 0.02 … 0.98, 0.99, 1.00}. It is assumed that alternative insecticides are adopted following the end of each planning horizon, and that resistance to Bt or pyrethroids does not confer resistance in cotton insects to adopted alternative insecticides. We further assume that resistance to Bt is not conferred to cotton insects that infest other transgenic Bt crops (e.g. corn, potato, tobacco) or fruit and vegetable crops dependent on foliar Bt insecticides. Under these assumptions, refuge policies that maximize the present value of producer surplus maximize the present value of social surplus and are socially efficient.

Results

For each planning horizon below, the analysis begins in 1999 using predicted initial bollworm Bt (0.0139), budworm Bt (0.0015), bollworm pyrethroid (0.6501), and budworm pyrethroid (0.9461) resistance levels (Livingston et al., 2000). Note the high, initial bollworm and budworm pyrethroid-resistance levels. According to the genetic models used to track resistance development in the current analysis, budworm and bollworm susceptibility to pyrethroids may be completely exhausted in the very near future.

Table 1 presents efficient refuge policies and measures of policy effectiveness when refuge acres are treated with conventional insecticides. Refuge policies are defined as the minimum proportions of total Louisiana acres that must be planted with non-Bt cotton. Measures of policy effectiveness are the annualized present value (APV) of per-acre producer profits attainable over the planning horizon, the average annual number of conventional insecticide treatments, the standard deviation of annual profits, and end-period Bt-resistance levels. APV entries denote the profit levels that, if received each year over the horizon, result in the obtained present values. APV measures of profitability are used because they allow comparisons across planning horizons of different durations. Since all factors of production are not accounted for in the analysis, APV levels do not characterize realistic profitability figures. However, they are useful for purposes of comparison across efficient and current refuge policies, or across treated- and untreated-refuge policies.

As demonstrated by Livingston et al. (2000), Bt susceptibility is a resource that is mined more rapidly when higher proportions of Bt are planted in Louisiana. As is the case with any resource, the efficient rate of exploitation decreases with the length of the planning horizon. Accordingly, efficient refuge requirements increase with the horizon. Because of the high initial levels of pyrethroid resistance, average profit per acre increases with the proportion of Bt planted. Because of this and the slow rate of Bt-resistance development, the efficient refuge policy is no refuge policy for the five- and 10-year horizons. Because Bt susceptibility must be maintained for successively longer periods of time, the efficient refuge increases with the horizon but converges to an infinite-time-horizon maximum of only 21 percent, slightly higher than the current, 20-percent treated-refuge policy.

Table 2 presents measures of policy effectiveness for the current treated-refuge policy. As expected, per-acre annualized present values are higher and conventional insecticide treatments are lower for efficient policies relative to the current policy, especially for the five- through 50-year planning horizons. The intransigent onset of Bt resistance in the bollworm, and later in the budworm, coupled with increasing refuge policies reduce the profit advantage enjoyed by the efficient policy over longer planning horizons. Annual profit volatilities are generally comparable between the efficient and current policies, as are end-period Bt resistance levels.

Table 3 presents efficient refuge policies and measures of policy effectiveness when refuge acres are not treated with conventional insecticides. As was the case for efficient treated-refuge policies, efficient untreated-refuge policies do not restrict the producer for the five- and 10-year horizons. The current untreated-refuge policy is efficient for the 20-, 30-, and 40-year horizons, but not for the 50-, 100-, and 200-year horizons, where efficient policies increase slightly above the current, four-percent untreated refuge.

More importantly, a comparison of tables 1 and 3 demonstrates that untreated-refuge policies significantly dominate treated-refuge policies with respect to every measure of policy effectiveness. As suggested by the end-period pyrethroid-resistance levels reported in table 4, this is because pyrethroid susceptibility in both insects is regenerated to usable levels under untreated refuge, whereas pyrethroid susceptibility is completely exhausted under treated refuge. This is remarkable given the high, initial pyrethroid-resistance levels and suggests that susceptibility to pyrethroids is a renewable resource under untreated refuge. As a result, the use of untreated refuge leads to a toxin-mixture effect that significantly reduces the rate of Bt-resistance relative to the treated-refuge case (Livingston, 1999; Livingston et al., 2000).

Summary

In a companion dynamic-programming analysis of the term structure of efficient refuge policies, Livingston (1999) demonstrates that the length of the planning horizon and the availability and adoption of alternative technologies are significant determinants of refuge policy. Likewise, the current analysis demonstrates that levels of efficient treated- and untreated-refuge policies depend on the length of the planning horizon, or the number of years in which Bt must be maintained as a profitable technology. Information regarding the availability or the arrival of replacement technologies is therefore shown to be a crucial determinant of efficient resistance-management policy.

Under the current treated-refuge policy, producers in Louisiana may experience significant and unnecessary profit losses, while using considerably more conventional insecticides relative to efficient treated-refuge policies. More importantly, efficient untreated-refuge policies are shown to dominate efficient treated-refuge policies with respect to long-run profitability, conventional insecticide use, annual profit volatility, and end-period resistance levels. Remarkably, pyrethroid susceptibility is regenerated using relatively small-untreated refuges, leading to a toxin-mixture effect that reduces the rate of Bt-resistance development.

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Table 1. Efficient treated-refuge policies and measures of effectiveness.

Horizon[a]	Policy[b]	APV[c]	Foliar[d]	Volatility[e]	Resistance[f]
5	0.00	397.59	1.94	4.27	0.0166, 0.0023
10	0.00	395.82	2.04	3.44	0.0218, 0.0058
20	0.03	388.12	2.38	3.18	0.0460, 0.0348
30	0.07	378.46	2.79	3.42	0.2062, 0.0376
40	0.10	364.18	3.55	32.12	0.9996, 0.2645
50	0.14	351.22	4.21	36.18	1.0000, 0.0462
100	0.21	321.24	6.86	74.88	1.0000, 0.9264
200	0.21	313.09	9.29	79.21	1.0000, 0.9264

a. Length of planning horizons in years.

b. Minimum treated-refuge proportion of total Louisiana cotton acres.

c. Annualized present value in dollars.

d. Average, annual number of foliar insecticide treatments.

e. Standard deviation of annual profits over the planning horizon.

f. Bollworm and budworm Bt resistance levels, respectively.

Table 2. Current treated-refuge policies and measures of effectiveness.

Horizon[a]	Policy[b]	APV[c]	Foliar[d]	Volatility[e]	Resistance[f]
5	0.20	356.62	3.77	10.97	0.0155, 0.0016
10	0.20	352.02	3.91	8.88	0.0180, 0.0017
20	0.20	349.63	3.98	6.64	0.0264, 0.0021
30	0.20	348.82	4.01	5.52	0.0484, 0.0026
40	0.20	348.36	4.03	4.88	0.1970, 0.0034
50	0.20	343.21	4.41	25.68	0.9998, 0.0050
100	0.20	321.16	7.00	78.69	1.0000, 0.9264
200	0.20	313.02	9.36	79.81	1.0000, 0.9264

a. Length of planning horizons in years.

b. Minimum treated-refuge proportion of total Louisiana cotton acres.

c. Annualized present value in dollars.

d. Average, annual number of foliar insecticide treatments.

e. Standard deviation of annual profits over the planning horizon.

f. Bollworm and budworm Bt resistance levels, respectively.

Table 3. Efficient untreated-refuge policies and measures of effectiveness.

Horizon[a]	Policy[b]	APV[c]	Foliar[d]	Volatility[e]	Resistance[f]
5	0.00	397.59	1.94	4.27	0.0166, 0.0023
10	0.00	395.82	2.04	3.44	0.0218, 0.0058
20	0.04	395.53	0.93	1.92	0.0291, 0.0024
30	0.04	395.89	0.90	1.66	0.0612, 0.0034
40	0.04	395.85	0.91	1.91	0.5410, 0.0053
50	0.05	394.22	0.70	1.81	0.5526, 0.0051
100	0.07	387.16	0.82	12.82	1.0000, 0.0237
200	0.08	381.62	3.13	56.87	1.0000, 1.0000

a. Length of planning horizons in years.

b. Minimum untreated-refuge proportion of total Louisiana cotton acres.

c. Annualized present value in dollars.

d. Average, annual number of foliar insecticide treatments.

e. Standard deviation of annual profits over the planning horizon.

f. Bollworm and budworm Bt resistance levels, respectively.

Table 4. Treated and untreated refuge end-period pyrethroid resistance.

Horizon	Untreated Refuge Resistance[a]	Treated Refuge Resistance[a]
5	0.9946, 0.9728	0.9946, 0.9728
10	1.0000, 0.9876	1.0000, 0.9876
20	0.4521, 0.1767	1.0000, 0.9972
30	0.4524, 0.1764	1.0000, 0.9993
40	0.4958, 0.1764	1.0000, 0.9998
50	0.4001, 0.1442	1.0000, 1.0000
100	0.6416, 0.1050	1.0000, 1.0000
200	0.5468, 0.6930	1.0000, 1.0000

a. Bollworm and budworm pyrethroid resistance levels, respectively.