The Economics of Biotechnology under Ecosystem Disruption

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Abstract

Economic analysis of chemical pesticide use has shown that the interactions between plants, pests, damage control technology and state of the ecosystem are important variables to be considered. Hence, a bio-economic model was developed for the assessment of Bt variety and pesticide-based control strategies of the cotton bollworm in China. The model simulates plant growth, the dynamics of pest populations and of natural enemies. The model predictions are used as major inputs for a stochastic partial budgeting procedure of alternative control strategies.

Results show that: (1) productivity effects of Bt varieties and pesticide use depend on the action of natural control agents, and (2) the profitability of damage control measures increases with the severity of ecosystem disturbance. The findings highlight the importance of the choice of a counterfactual scenario in the assessment of the impact of agricultural biotechnology. Also, some doubts are raised whether the high benefits of Bt cotton varieties based on cross section comparisons are realistic.

Introduction

Some fifty years ago, scientists were enthusiastic about the introduction of synthetic pesticides in agriculture to solve the world's food problem. Scientists and policy makers are currently voicing optimism about the prospects of biotechnology. While many negative effects of pesticide use have become known, intriguingly some see biotechnology in crop protection now as a solution to the very problems that pesticide use created (e.g. Naranjo, 2005). Experience gained with economic analysis of pesticides can provide a useful guide for issues that need to be addressed when assessing the impact of biotechnology in crop protection (Zadoks and Waibel, 2000).

There are at least three concerns that have emerged from the use of pesticides: (1) pesticides not only kill pests but they also disturb the ecological balance by diminishing the populations of

beneficial organisms (predators and parasites) that provide control of pests; (2) intensive regulation is required to reduce potentially negative effects on environment and human health and to guarantee quality standards under which effectiveness is assured. This is extremely important in developing countries where the implementation of effective regulatory frameworks is extremely difficult and often has not prevented, for example, adulteration of pesticide products. Finally, (3) promotion of pesticides as easy and single solutions to pest problems has led farmers into path dependency (Regev, 1984) and has raised the hurdles of adopting integrated pest management technologies (Cowan and Gunby, 1996).

Applying the "lessons" from the economic analysis of pesticides to the case of insect resistant Bt crops[1] reveals insights for the assessment of costs and benefits of this technology. Numerous economic studies conducted in recent years concluded high benefits and good prospects for the Bt technology (mainly in cotton and maize) in the USA (Carpenter and Gianessi, 2001), Australia (Fitt, 2000), Argentina (Qaim and Traxler, 2005), China (Huang et al., 2002), South Africa (Thirtle et al., 2003) and other parts of Africa and Asia (Qaim and Zilberman, 2003; de Groote, 2005). In many of these studies, econometric methods were applied to cross sectional data from farm surveys or experimental data. While production economic methods can provide a good assessment of the static productivity of pest control agents (and other inputs), they are less suitable for capturing the interaction between control decisions and dynamic ecosystem reactions. Furthermore, such methods are limited in reflecting the influence of institutional settings that need to be in place if biotechnology solutions are to live up to their potential. For example, in China a large number of transgenic cotton varieties have quickly entered the seed market and maintaining quality has become a problem (Pemsl et al., 2005).

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[1] Varieties that contain a gene from the soil bacterium Bacillus thuringiensis and produce an endo-toxin that is lethal for certain insect pests.

A complementary tool to the production and damage control function approach (Zilberman and Lichtenberg, 1986) is bio-economic modelling (e.g. Regev et al., 1976; Gutierrez et al., 1979). Such models allow the derivation of the production function from the biological processes that govern the agro-ecosystem (Wossink and Rossing, 1998). In this approach, the state of the ecosystem as well as different institutional conditions, are taken into account using scenario analysis. Thus, the relative advantage of new pest control technologies such as Bt varieties is assessed in a dynamic perspective.

In this paper, we introduce a bio-economic model that combines cotton bollworm dynamics (Gutierrez et al., 2006) with stochastic budgeting of bollworm control strategies reflecting the agro-ecosystem conditions in a major cotton growing area, in Shandong province, Northern China (see below). The model aims to reflect the situation of cotton planting several years after the introduction of Bt cotton varieties in China. It captures a situation of multiple damaging agents and accounts for the prevailing natural resource conditions as reflected by the presence of beneficial organisms. A cotton growth experiment was used to calibrate the biological model. Farm surveys conducted by the authors (Pemsl et al., 2005) and other researchers (Pray et al., 2002; Yang et al., 2005) revealed high levels of insecticide applications by (Bt) cotton farmers in China, indicating probable ecosystem disturbances, which may influence the effectiveness of pest control measures. A specific problem with the use of Bt varieties in developing countries is the quality control of seed and hence its efficacy. Evidence of this problem has been documented in India (Morse et al., 2005) and China (Pemsl et al., 2005), countries where regulation of input markets is low and enforcement of intellectual property rights is difficult. Data from 150 Bt cotton fields was collected in Shandong Province during 2002 to assess the concentration of Bt toxin. The data revealed that most farmers were using low

price Bt cotton seeds expressing low concentrations of Bt toxin[2] (Pemsl et al., 2005). The economic component of the bio-economic model reflects these technology features as found under farm conditions and includes the product and factor prices prevailing in Shandong in 2002.

Theoretical background

Damage control agents such as chemical pesticides, beneficial organisms and resistant varieties depend on the stock of natural resources that govern the productivity of an open[3] agro-ecosystem. Pest control agents' may impact on two natural resources, namely: (1) the beneficial organisms that provide natural control of pests, and (2) the susceptibility of pests to the control agent, defined as the absence of resistance at the time of technology introduction. Optimal use of pest control agents thus corresponds with the economic problem of managing exhaustible resources, i.e. how to allocate resource stocks over time (Regev et al. 1976, 1983; Dasgupta and Heal, 1979). Extracting a unit of the resource today implies that there is less of it in the future; hence, user costs exist in addition to the direct costs[4] of the control agent. Furthermore, for common property resources producers do not perceive their actions to influence the stock of these resources and as a result operate in a myopic optimisation framework (Regev et al., 1976). This can lead to an overuse of natural resources that is reflected in a rapidly rising net price of the resources (Hotelling, 1931), so that the price of an alternative technology (choke price) is reached faster. In the case of pesticides, the net price of the natural resources is reflected in a rising marginal product (Lichtenberg and Zilberman, 1986). Therefore, current levels of pesticide use can pre-determine higher use levels in the future (Fleischer, 2000). For example, the high use of pesticides in some cropping systems such as cotton in Chile and California (*sic* worldwide),

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[2] Tests were conducted by Prof. Dr. Wu Kongming, Chinese Academy of Agricultural Sciences, Beijing.

[3] This is in constrast to protected production (e.g. in glasshouses) where the environment is totally controllable.

[4] The extraction costs are the decreasing value of the resource, while user costs are inter-temporal opportunity costs or the option value of the control method available in the future.

and in tropical vegetable production (with diamond back moths as major pest), are typically triggered by prior misguided pest control interventions. Thus leading to what is called the pesticide treadmill (van den Bosch, 1978). Degradation of natural resources in pest control may also "stimulate" the introduction of new pest management technologies such as transgenic varieties. For example, Bt cotton was introduced in China at the height of an outbreak of the cotton bollworm (Wu and Guo, 2005), which may partly explain its rapid diffusion.

Thus, taking account of natural resource processes has consequences for the productivity and benefits assessment of new pest control technologies. The impact of a new damage control agent is influenced by the ecosystem state in which it is introduced. If the technology is introduced in a highly disrupted ecosystem with a reduced capacity of beneficial organism to control pests (Gutierrez and Ponsard, 2006), short-term benefits may be high but the "life span" of the technology and thus total benefits may be low. This is typically the case when the institutional settings that led to the disruption of the ecosystem in the first place are still the same, and hence the technology itself can do nothing to improve these conditions. Thus, a major question is whether Bt crops can really lead the way out of the (pesticide) treadmill in developing countries or rather steer into yet another (genetic/pesticide) treadmill (Gutierrez et al., 2006)?

The theory of natural resources and the conclusions that can be drawn from the economic analysis of pesticide use suggest that a bio-economic modelling approach, which takes account of the degree of ecosystem disruption and the institutional conditions governing the use of pest control inputs, can complement existing impact assessments of Bt cotton.

The Model

The bio-economic model, developed to address the issues raised above, consists of two major components: i) a biological-ecosystem model that simulates the growth of the cotton plant, as well as the dynamics of pest and the effects of the beneficial organisms and the resulting

interactions. The model allows the analysis of various pest control strategies, with the simulated output for each being, among other variable, the cotton yield for each strategy; ii) a stochastic partial budgeting model uses the yields generated by the biological model, control costs for each control strategy, and cotton prices to compute the net revenue of the different control strategies.

This section of the paper summarises the general model structure. A physiologically based, biological-ecosystem model for cotton (e.g. Gutierrez et al. 1975, 1984) was modified to simulate transgenic cotton and ten of its major pests (e.g. Gutierrez and Ponsard, 2006; Gutierrez et al., 2006). The model was calibrated to the conditions of the study location in Shandong Province, China[5]. The cotton plant model consists of several plant subunit models (i.e. leaf, stem, root, and fruit), which are linked via a metabolic pool from which photosynthate is allocated to the subunits according to biological priorities. The model simulates the mass and number dynamics of the cotton plant sub units, the time varying concentrations of toxin in the subunits, the dynamics of all insect pest populations (pests), and the evolution of resistance in response to toxin levels in each pest. The effects of natural enemies are included as feeding rates per day estimated from field studies. These rates may be reduced by the action of various control factors such as insecticides and natural enemies feeding on Bt intoxicated prey. All of the species in the model are driven by observed weather[6]. A detailed description of the model, its assumptions, and the data sets and references used to validate it are found in the above references.

For the simulations, it is assumed that all agronomic factors (such as fertilizer and irrigation) are constant and none limiting. Equation (1) shows the main structure of the cotton plant model. Cotton yield (Y_{Cot}) is a function of reproductive and vegetative growth (*GR*), loss

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[5]   To generate the data needed to parameterize the model, a cotton-growth experiment was conducted at the study site in 2002. The experiment provides information on plant growth (weekly dry-weight by subunit and yield) and pest damage as well as counts of pests and predators.

[6]   Climatic data (minimum and maximum daily temperature) for 2002 and monthly averages for the past 10 years were available from the meteorological station in Linqing County, Shandong Province.

due to pests (*L*), and other factors (*Z*) that include plant varieties, control technology and location specific characteristics.

$$Y_{Cot} = f(GR, L, Z) \tag{1}$$

The reproductive and vegetative growth (*GR*) is computed as:

$$GR(t) = (\phi*(t)(D(t)\beta - Q_{10})\lambda \tag{2}$$

with the maximum demands (*D*) scaled by the product of all supply-demands ratios of essential resources ($\phi*$) such as light, soil moisture and nitrogen, and then allocated in priority order to wastage (*1-β*), respiration (i.e. Q_{10}), and costs of conversion (*λ*) (see Gutierrez and Ponsard, 2006). Cotton and its pests are poikilotherms, i.e. body temperature and activity level depends on the surrounding temperature, and hence time and age in the model are in physiological time units (day-degrees). The plant model also captures the varying concentration of Bt toxin over time and for different plant subunits.

Yield loss from pests (*L*) is a function of plant growth (*GR*) and pest populations (P_{Pest})

$$L = f(GR, P_{Pest}) \tag{3}$$

The similarity of the resource acquisition and allocation biology across plant and animal species allows use of a generic model structure for analogous processes (Gutierrez and Baumgärtner, 1984). A time invariant model form is used for Bt immune pests (e.g. lygus, whitefly), while a time-varying distributed maturation time model is used for all noctuid species to accommodate time-varying Bt concentrations in their food that increases developmental times, and decreases fecundity and survival. Pest dynamics modules are integrated in the system in a way that there is feedback between pest attack and plant compensation. The model includes pest time-varying preferences for plant subunits. Population dynamics (P_{Pest}) are modelled for bollworm and other relevant pests. P_{Pest} depends on climatic conditions (*T*), the reproductive and

vegetative growth (*GR*) of cotton subunits (host plant), effect of beneficial organisms (*P_BO*), in- and out-migration (*M*) of insects and the use of pest control technologies (*C*) including Bt varieties and insecticides.

$$P_{Pest} = f(T, GR, P_{BO}, C, M)$$

(4)

The effects of the natural enemies (i.e predators, *P_Pred*) are a function of the level of ecosystem disruption and technology factors and interact with pest populations:

$$P_{Pred} = f(T, P_{Pest}, C, M)$$

(5)

Both pesticides and Bt toxin are included in the model (as captured in *C*). Their effects on pest control are complementary as both may negatively affect pests and natural enemies.

Two different types of Bt based control strategies were included in the model, i.e. low quality (= low price) and high quality (= high price) Bt seeds. Low quality was modelled via a change in the scalar of pest susceptibility relative to high quality Bt seeds. Ecosystem disruption was incorporated in the model in three discrete steps, i.e. zero, 50 % and 75 % implying corresponding levels of beneficial organism activity reduction.

Cotton bollworm control strategies are described as combination of three different seed choices - high or low quality Bt, conventional varieties - and three intensity levels of insecticide use - no spray, moderate spray, farmers' practice (Table 1). These are compared to natural control (no pesticides and conventional seeds). For each control strategy, simulation runs of the biological model with stochastic climatic conditions were conducted for 20 consecutive years[7] providing yield distributions[8] for the various control strategies. Fitted normal distributions of

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[7] The build-up of pest resistance is not included in the model as it is suggested that the high diversity of the farming systems in the study area provides sufficient refuge for susceptible pests (Jia and Peng, 2002).

[8] The software BestFit (Palisade Corporation, integrated into the professional version of @RISK) is used to fit probability distributions to the simulated yield data.

yields provide the link with the stochastic partial budgeting model that generates the net revenues of pest control strategies.

The net revenue *(NR)* for each of *j* pest control strategies *(NR$_j$)* is the monetary value of the prevented yield loss less control costs. Thus the *NR$_j$* is a function of the change in cotton yield (ΔY_{Cot}) of the strategy as compared to the baseline natural control, the cotton price *(p$_Y$)*, the pest control strategy (C) and their unit costs *(p$_C$)*, and the interest rate *(i)* to account for the opportunity costs of capital.

$$NR_j = f(\Delta Y_{Cot}, C, i, p_y, p_c)$$

(6)

The price of cotton *(p$_Y$)* is assumed to be identical for Bt and non-Bt cotton. The costs for the control strategies comprise of costs of insecticides and associated human health costs[9], labour costs for spraying and the technology premium for Bt varieties. To account for the stochastic nature of the input variables for the partial budgeting model (yield and prices), the underlying probability distributions are used in Monte Carlo simulation (Hardaker *et al.* 1997). A cumulative distribution function (CDF) of net revenues for the pest control strategies is then generated from all NR$_j$ of each strategy. The performance of the various pest control strategies are compared by applying the criteria of first-degree stochastic dominance (Equation 7) and second-degree stochastic dominance to the resulting CDFs (Equation 8):

$$F_1(x) \le F_2(x) \le ... F_j(x)$$

(7)

$$F_1 = \int_{-\infty}^{x^*} F_1(x)dx \le F_2 = \int_{-\infty}^{x^*} F_2(x)dx \le ...... F_j = \int_{-\infty}^{x^*} F_j(x)dx$$

(8)

Based on these two criteria, the control strategies are ranked and the probabilities of negative net revenue of control are derived.

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[9] Following Rola and Pingali (1993) and Pingali et al. (1994), human health costs are assumed to equal costs of insecticides.

Results

The model shows that yields differ depending on the level of ecosystem disruption, i.e. yields are lowest in a highly disrupted ecosystem for all control strategies (see Figure 1). Yield variance among disruption levels is highest for the baseline scenario that relies entirely on natural control and generally decreases with a higher degree of control intensity, i.e. more sprays and higher quality Bt[10]. Low quality Bt combined with high levels of insecticide use performed best. Surprisingly insecticide use was more effective than high quality Bt.

To identify the factors that affect the productivity of control inputs, yields are regressed in a multivariate linear regression on the different control inputs. The sample is separated for the different levels of ecosystem disruption and the explanatory variables are the use of a Bt-variety and insecticides (both as dummy variable), additional dummies for the intensity of the control (high quality Bt-seed and intensive use of insecticides) and an interaction term for Bt toxin and insecticides. All parameters are highly significant ($\alpha = 0.01$) and the overall fit of the regression model was high. The intercept is the yield level that is realized without crop protection intervention under the different levels of ecosystem disruption (see baseline yields in Figure 1).

The most striking result is that the productivity of the control changes dramatically with increasing disturbance of the ecosystem. Consider first the case of zero disruption of natural enemies (coefficients displayed row one of Table 2). The use of a Bt-variety yields a meagre 146 kg of additional yield per hectare as compared to the non-Bt baseline. The disturbing impact on natural enemies is higher and hence yield increase is even less, if high quality Bt-seed is used. Similarly, the application of insecticides leads to a reduction in yield as the disturbing effect of natural control outweighs the pest control effect of the applications.

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[10] resistance to the control technologies was assumed not to exist

A high intensity of control (Bt-variety and insecticide use) compensates for part but not all of the disruption caused by the control intervention. These results confirm findings from the literature on pesticide use (e.g. Ehler et al., 1974; Eveleens et al., 1974; Falcon et al., 1968; Gutierrez et al. 1975) that demonstrated the existence of the pesticide treadmill in cotton. For the two scenarios with disrupted ecosystems, the baseline yield is lower (due to lower activity of natural enemies) and the use of external control is much more rewarding. The use of a Bt-variety adds 1.8 and 2.4 tonnes per hectare compared to the baseline for the 50 and 75% disruption, respectively. In principle the use of insecticides replaces natural control but the levels assumed for the simulation do not reach the impact provided by the Bt-variety. For these last two scenarios, a higher intensity of control increases the yield level further (positive coefficients for the Bt quality and insecticide intensity variables). A combination of insecticides and Bt-variety results in a relatively smaller return to the separate control measures (the interaction term of Bt-toxin and insecticides is negative). For high ecosystem disruption, bollworm control pays off well with net revenues from US$550 to US$ 1,150 per hectare at $F(x) = 0.5$ (Figure 2). In this case a high level of insecticide use is stochastically dominant over S6 because the negative ecosystems effect of low insecticides use exceeds its pest damage abatement effect. For a high degree of ecosystem disruption, the use of low quality Bt seed and moderate insecticides use (S 4) is the most economical cotton bollworm control strategy according to second-degree stochastic dominance.

For a medium disruption level and a risk averse decision-maker, the low quality Bt seed without insecticide use is the best option. This strategy (S3) dominates strategy 1 (high quality Bt seed without insecticides) applying the criteria of second-degree stochastic dominance. For a 0.5 ecosystem disruption, the modal values of the net revenues are lower and range from US$200 to US$750 per hectare. Finally, for an undisrupted ecosystem (Figure 3), natural control of cotton bollworm is the most economical strategy (see Falcon et al. 1968; Gutierrez et al., 1975 for

bollworm in California). Yet low-quality Bt-seed without the application of chemical insecticides for bollworm might be an attractive strategy for risk averse farmers.

Conclusions

The bio-economic simulation model explains the observed decision-making behaviour of farmers in the study area. Overwhelmingly, they opt for the cheaper and lower quality Bt seeds and continue to spray insecticide against the cotton bollworm. Model results also show the importance of the interaction between ecosystem disruption and pest control strategies. If farmers in China operate in agro-ecosystems that have been disturbed by prior pest control interventions, it is not surprising that the Bt technology shows good yield effects as measured against natural control (see also Gutierrez, 2005). On the other hand, since both, insecticide applications and Bt cotton varieties can reduce the population of beneficial organisms[11], cross section comparisons between farmers using Bt with those who do not are flawed. That indiscriminate insecticide use has a stronger side effect on beneficial insects does not validate conclusions drawn from such comparisons. Whether Bt varieties will actually reduce excessive levels of pesticides, diminish the level of ecosystem disturbance and hence cause additional environmental and health benefits requires the interaction between the state of the ecosystem and human interferences to be taken into account. Furthermore, static with and without comparisons ignore the possibility of emergence of secondary pests under Bt regimes resulting in additional pesticide use (Gutierrez et al., 2006). Hence, the choice of the counterfactual (that is the alternative to which the situation resulting from the use of the new technology is compared) in impact assessment of agricultural biotechnology can pre-determine the results of such comparisons. To measure impact of Bt under on-farm conditions requires the availability of

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[11] Naranjo (2005) compared natural enemy abundance in long run studies of Bt and conventional cotton. The trends in the data show 6% lower natural enemy populations that coupled with effects of feeding on Bt intoxicated prey.

baseline data that allow the use of "difference in difference" models. Such models consider both, "before and after" and "with and without" comparisons. Yang et al. (2005) were able to show that in Bt cotton production, pesticide reduction is related to farmers' understanding of the technology rather than the technology itself.

In the search for sustainable solutions, it is therefore worthwhile considering a situation without ecosystem disruption as baseline. Through such a comparison, a clearer indication of the benefits of biotechnology technology and those of improving the institutional conditions that govern their use in farmers' field in developed as well as developing countries will be obtained. Reform of the prevailing crop protection policy and investments to improve farmer understanding of the ecosystem in the context of integrated pest management are thus required in order to realize the full benefits of pest control technologies. Thus, what is most needed to push the pest control and hence the yield frontier is a policy environment that allows implementation of sustainable integrated pest management systems.

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**Table 1:**   Overview of potential CBW control strategies

Insecticide treatment	Seed choice		
	Bt high quality	Bt low quality	Non Bt
No spray	Strategy 1	Strategy 3	*Baseline*
Moderate spray (3 sprays)	Strategy 2	Strategy 4	Strategy 6
Farmers' practice (6 sprays)	–	Strategy 5	Strategy 7

Table 2:   Linear regression results for different levels of ecosystem disruption

	Ecosystem disruption		
	0	0.5	0.75
Intercept	4,324.72	2,308.72	1,193.47
Bt toxin [dummy]	145.96	1,757.36	2,392.67
Bt quality [dummy]	-33.06	179.40	300.63
Insecticide [dummy]	-274.18	996.67	1,782.63
Insecticide intensity [dummy]	-37.09	369.44	553.03
Insecticide * Bt toxin	216.92	-923.65	-1,384.10
Adj. R^2	0.869	0.974	0.981

Note: Dependent variable: yield in kg per hectare

Source: Estimated from the results of the biological model
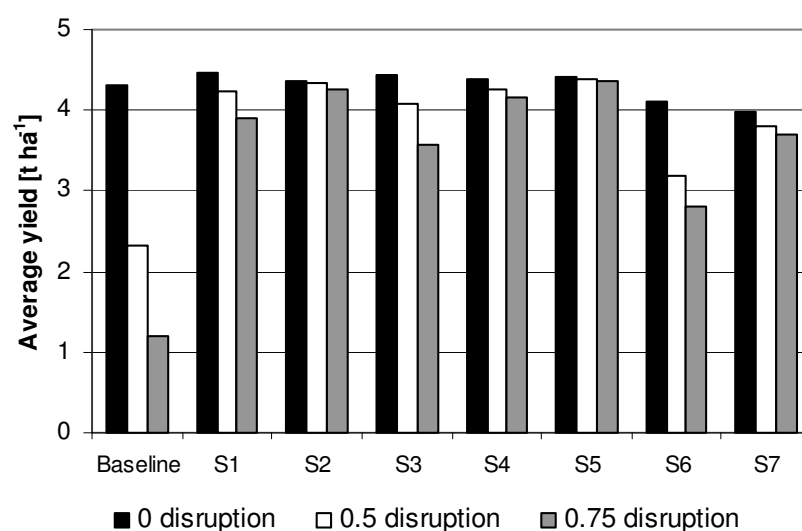
Figure 1:   Seed cotton yield [t ha^{-1}] for the control strategies (Baseline, S1 – S7) by degree of ecosystem disruption

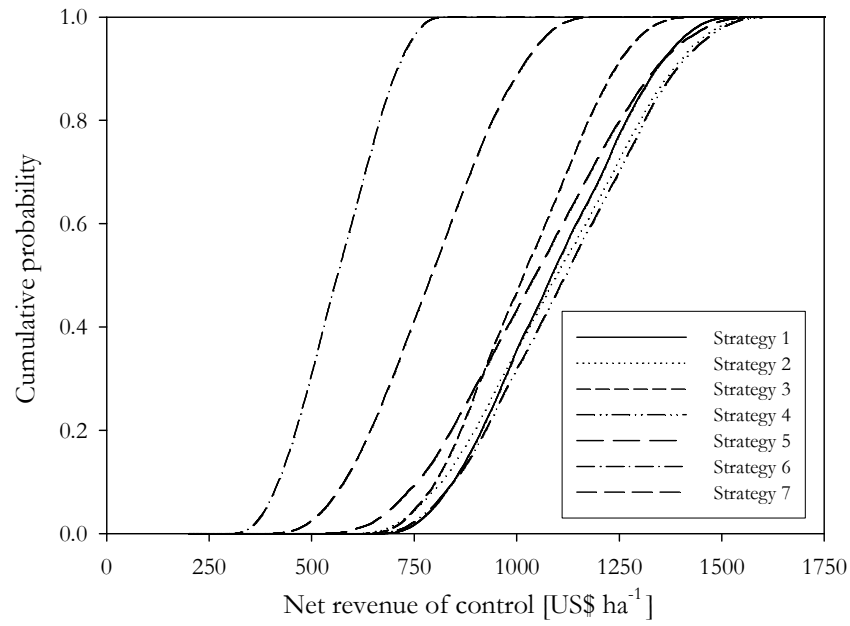Source: Results from the biological model

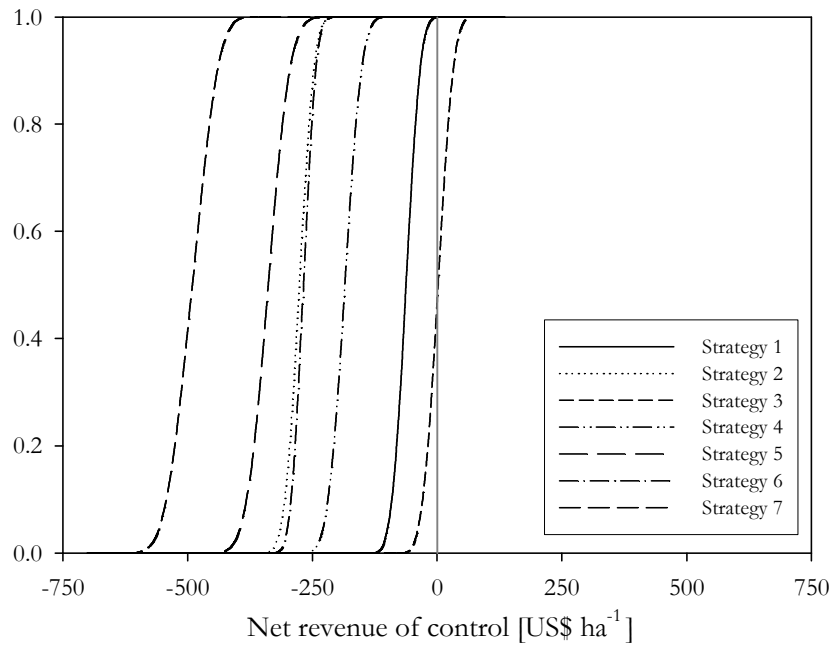**Figure 2:**   Simulation results of bio-economic model, 0.75 disruption

Figure 3:   Simulation results of bio-economic model, 0 disruption