Modelling of Bt corn production under choice of abatement specification

Xiangdong Shi

Department of Applied Economics

University of Minnesota at Twin Cities,

St. Paul, MN 55108

Terrence M. Hurley

Department of Applied Economics

University of Minnesota at Twin Cities,

St. Paul, MN 55108

Selected Paper prepared for presentation for the 2016 Agricultural & Applied Economics Association, Boston, MA, July 31-August 2

Modelling of Bt corn production under choice of abatement specification

Abstract

For modelling Bt corn production, we proposed a joint abatement function to capture pest life cycle. Simulation of pest adaptation to popular Bt corn varieties was developed and applied to generate random sample of abatement, where in-field parameters were adopted in favor of practical corn production. On the basis, logistic model was used to fit the sample data. The estimates were compared to those from exponential model for choice of abatement specification. At last, Cobb-Douglas production model was integrated with the pre-estimated abatement function along with farm level data and distribution of corn growers' choices, where instrument variables estimator and delta method were adopted to solve simultaneity problem induced by farm level data. The estimated marginal net return was positive, suggesting that Bt corn as pesticide is underutilized. However, the value kept decline in recent three years. We attributed the decline of marginal net return to the widespread adoption of new Bt corn varieties with blended refuge, and the insect resistance management would benefit from it.

Key words: Bt corn, production, abatement, simultaneity problem

JEL codes: Q16,C23.

Contents

I. Introduction

In the case of pest control, abatement is pest mortality caused by control agent, i.e. pesticide. In production, it is the abatement that has direct effect on crop yield. Thus, abatement rather than control agent is supposed to be a variable in production function. Abatement is not easily observed and thus usually investigated through a function of control agent level. Generally, abatement function is non-linear and may take different specifications, such as Pareto distribution, exponential distribution, logistic distribution and Weibull distribution, and can be estimated along with input demand function (Lichtenberg and Zilberman, 1986, 1989). Since Bt corn variety in practice plays the same role as pesticide, the modelling of abatement for pesticide is also appropriate for Bt corn variety (Qaim, 2009).

In empirical analysis of insecticide productivity, the choice of abatement specification is quite diversified. Some studies prefer exponential specification (Babcock, Lichtenberg and Zilberman, 1992, Norwood, 2003, Lichtenberg and Berlind, 2005); others choose logistic specification (Qaim and Zilberman, 2003, Shankar and Thirtle, 2005), depending on 'its computational tractability, ease of interpretation, and its satisfactory fit to data'. Carrasco-Tauber and Moffitt (1992) ever performed comparison of the popular abatement specifications and tended to exponential specification. But the choice needs support of evidence from biological side. On the other hand, the choice of abatement specification is purposely to substitute unobserved pest abatement for a function of control agent. An inappropriate substitute would induce measurement error (Greene, 2012). Actually, the problem addressed by Norwood (2003) also falls into this category although initial pest density probably would not play a role in the case of Bt corn under low pest pressure. In short, if we neglect the measurement error induced by choice of specification and make an inappropriate choice, the inconsistent estimation would occur.

The other problem is about estimation of abatement function. A production function incorporating abatement function can be viewed as potential yield multiplying damage abatement. In the sense, estimation of the production function is equivalent to estimation of the abatement function given the potential yield. When the estimation is performed under the assumption of normality as usual, the estimates would be inconsistent. As a matter of fact, the parameters with the abatement specification in a probability distribution can be estimated indirectly by a canonical link function and maximum likelihood approach, instead of directly by the probability function and least square, to achieve consistent estimates (Agresti, 2012). In addition, when the damage abatement is estimated through demand function and using farm level data, simultaneity problem would occur and lead to inconsistency if we fail to notice it (Hoch, 1958).

Acquiring an observable abatement function is the key of solving the problems on modelling of Bt corn production under damage control specification. Actually, as the ecologic factors impacting pest life cycle are known, simulation can be used to derive abatement function. Under the circumstance, an empirical abatement model with biological information would not only support an appropriate choice of abatement specification but also solve the problems of measurement error and inconsistent estimation. It is noted that estimation of production function with abatement function includes two components currently, pest abatement and crop loss rate. By means of biological information, the two components can be estimated separately, where the estimation of production function turn to crop loss rate, and the simultaneity problem accompanied with using farm level data is then addressed in estimation.

Preceding studies in line of biologic process concentrate on simulation of the linkage between pest suppression and Bt corn proportion or size on a field (Onstad et al, 1999, 2003, 2011, Hurley et al, 2001); abatement function is not addressed with them yet. However, investigating the function and admitting the characteristics of Bt corn is needed for modelling production of Bt corn. For the purpose, there are three issues worth considering. First of all, the control agent for Bt corn is corn seed level itself on a field instead of pesticide. Under the high dose and refuge strategy, it refers to Bt corn size or proportion. Thus, the abatement for Bt corn variety is supposed to be pest mortality induced by Bt corn variety on a whole corn field, i.e. Bt corn field along with conventional corn field as refuge.

The second issue is on type of abatement function. Generally, each of Bt corn varieties has its own abatement function, depending on characteristics of the pest(s) related to the variety of interest. Since European corn borer has two generations in one growing season, the abatement for single trait corn variety is non-linear to Bt corn size while the abatement for single trait corn regarding western corn rootworm is linear to Bt corn size due to the fact that the pest just has one generation. Stacked Bt corn variety has two traits for the borer and the rootworm respectively. Then a joint abatement is needed. In the case of pesticide, the joint abatement is product of two abatement functions under assumption of independence (Babcock, Lichtenberg and Zilberman, 1992). The joint abatement for stacked Bt corn variety is defined as a weighted average of the abatements for two single trait varieties and non-linear to Bt corn size. This type of joint abatement is equivalent to the one given exponential specification in the preceding study, but it would be different under other abatement specification, like logistic one.

Development of new Bt corn variety together with change of the strategy for IRM is the third issue worth exploring. In the end of 90s, single trait corn variety is widely adopted in production. After that, the variety is gradually replaced by stacked traits corn variety. Along with the extension of the Bt corn varieties, 20% of refuge is required for corn growers planting Bt corn to delay the development of pest resistance. However, the required refuge is costly and about 20% of non-compliance exists in practice (Jaffe, 2009, Onstad et al, 2011). Then the Bt corn varieties allowing 10% and 5% of seed mixtures started in 2010 and 2011 respectively to solve the problem. Currently, there are mainly three types of Bt corn varieties in corn seed market, i.e. stacked traits corn variety with 20% block refuge, stacked and pyramided traits variety with 10% blended refuge, and stacked and pyramided traits variety with 5% blended refuge. Simulation for acquiring observable abatement needs pay attention to each of the pests and the Bt corn varieties together.

Analogous to chemicals, Bt corn also has the problem on overused or underutilized of pesticide (Qaim and Zilberman, 2003, Shankar and Thirtle, 2005, Hutchison, et. al., 2010, Nolan and Santos, 2012, Shi, Chavas and Lauer, 2013). This paper addresses abatement function for Bt corn variety along with estimation of Bt corn productivity under choice of abatement specification. For the purpose, conceptual abatement models are proposed; ecological factors and in-field conditions are examined for modelling of pest adaptation to each of popular transgenic corn varieties, where historical data on pest density is used in simulation. From the simulation, abatement functions for each of Bt corn varieties can be derived with respect to the conceptual models. On the basis, logistic specification is adopted to fit the data generated from simulation and compared to the exponential specification for specification choice. Then an empirical production function with pre-estimated abatement is developed to capture the connection between yield and Bt corn size. The model is fitted to farm level panel data, where instrument variables estimator is adopted to solve simultaneity problem in the sense of delta method.

The paper includes six sections. The conceptual abatement functions are examined and given in section 2. Section 3 gives simulation of pest adaptation to transgenic Bt corn varieties, where abatement functions for each type of Bt corn varieties are computed and illustrated. In section 4, a random sample of abatement with regard to Bt corn size is generated; the choice of abatement specification is performed accordingly. The model of Bt corn production with pre-estimated abatement is developed in section 5, where the model is fitted to farm level panel data; estimates of the model are given with their marginal effects regarding Bt corn size. Finally, conclusion and discussion is given in section 6.

II. Abatement function

1. Production of Bt corn

On an acre of corn field, corn growers can plant single trait Bt corn or stacked trait Bt corn or both to suppress pests although single trait corn become less and less adopted in recent years. Suppose that stacked-trait corn variety has two traits, say YieldGard Plus, for preventing damage by European corn borer and corn rootworm. Then the field is divided into four blocks. The first block is for stacked-trait variety; the second and third blocks are for single trait varieties; the remaining is common refuge for planting conventional corn and complying with EPA mandatory requirement. Let the proportions of the first three blocks be $\theta_1, \theta_2, \theta_3$ respectively, the common refuge size is then $\theta_4 = 1 - \theta_1 - \theta_2 - \theta_3$ as showed in figure 1. Furthermore, suppose that the single trait variety for European corn borer is arranged on the second block and the single trait variety for corn rootworm on the third block, the refuge size regarding European corn borer is $\theta_3 + \theta_4$ or $1 - \theta_1 - \theta_2$, and the refuge size regarding corn rootworm is then $\theta_2 + \theta_4$ or $1 - \theta_1 - \theta_3$.

Bt corn growers mainly concern two types of pests, European corn borer and corn rootworm. European corn borer generally has two generations over a year while corn rootworm just has one generation. Since pest density of a generation on a block depends almost completely on a grower's last choice of the block proportion, yield loss caused by European corn borer is given by $y^0 A^E (1+s) m^E$, where y^0 is pest-free yield or potential yield; m^i is marginal loss for pest i with $i = E, R$; A^i is larvae density for pest i; s is growth rate for the second generation with $s > 0$ or $s < 0$. Similarly, yield loss caused by western corn rootworm is $y^0 A^R m^R$. The pest density for the first generation of European corn borer is the average of those on transgenic corn blocks and refuge blocks and given by

$$A^E = (1-\theta_1-\theta_2)A_n^E + (\theta_1+\theta_2)A_b^E \qquad (1)$$

where A_n^E and A_b^E are pest density for first generation of European corn borer on refuge and block for Bt corn respectively. Similarly, the pest density for corn rootworm is the average of those on transgenic corn blocks and refuge blocks and is given by

$$A^R = (1-\theta_1-\theta_3)A_n^R + (\theta_1+\theta_3)A_b^R \qquad (2)$$

where A_n^R and A_b^R is pest density for corn rootworm on refuge and block for Bt corn respectively. The growth rate for the second generation of European corn borer s is the average of those on transgenic corn blocks and refuge blocks and given by

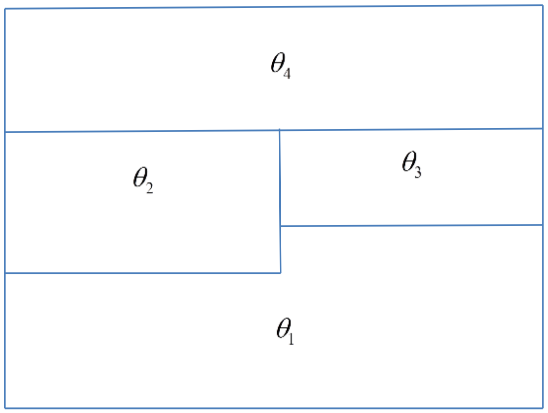


Figure 1 Proportions of blocks for corn planting

$$s = (1-\theta_1-\theta_2)s_n + (\theta_1+\theta_2)s_b \quad (3)$$

where s_n, s_b is growth rate on refuge and blocks for Bt corn respectively. Then the pest density for the second generation is given by $A^E s$. It is noted that the growth rates s_n, s_b are function of the pest density A^E and the resistance frequency of the second generation p . Thus, the growth rates actually depend on block proportions chosen by growers at the start of growing season. The rate is differs over time and must be examined year by year.

For stacked-trait corn with blended refuge, although conventional corn plants as refuge are dotted and distributed on whole field instead of a block, the computing of the pest density for European corn borer and corn rootworm keeps the same. It is still the average of those densities for Bt corn and conventional corn. Actually, the growth rate for the second generation of European corn borer s is also the average of those densities for Bt corn and conventional corn although the pest densities s_n, s_b would be different from their counterparts under block refuge. In addition, the trait(s) for stacked Bt corn is either single trait or pyramided traits. The Bt corn variety with pyramided traits can enhance pest control and delay development of pest resistance; the pyramided traits corn has nothing to do with the refuge strategy.

2. Abatement for single or pyramided trait(s) corn variety

Abatement in the case of Bt corn is defined as pest mortality induced by Bt corn on a unit field under refuge requirement. For European corn borer, abatement function AF^E is given by

$$AF^E = \frac{A_n^E(1+s_n^0) - A^E(1+s)}{A_n^E(1+s_n^0)} \quad (4)$$

where A^E is density for first generation pest, s is growth rate for second generation pest, and A^E, s is given by expression (1) and (3) respectively; A_n^E is density for first generation pest on refuge while s_n^0 is growth rate for second generation pest on conventional corn field. Due to the difference in density-dependent survival, the growth rate on conventional corn field s_n^0 may be equal to the rate on refuge s_n or maybe not, depending on their densities for first generation pest. In the case of Bt corn, as pest resistance frequency becomes low, it has $A_b^E = 0, s_b = 0$. Let Bt corn size be θ, the abatement function can be simplified into

$$AF^E = \frac{s_n^0 - s_n}{1+s_n^0} + \frac{1}{1+s_n^0}\theta + \frac{s_n}{1+s_n^0}(2\theta - \theta^2)$$

Furthermore, as pest density is sufficiently low, it has $s_n^0 = s_n$. Then we have

$$AF^E = \frac{1}{1+s_n}\theta + \frac{s_n}{1+s_n}(2\theta - \theta^2)$$

As a matter of fact, θ is abatement at first generation while $2\theta - \theta^2$ is abatement at second generation. Abatement function for European corn borer is weighted average of the abatements at these two generations.

On the other hand, western corn rootworm just has one generation during growing season. Thus, its abatement has nothing to do with the growth rate on refuge and conventional corn field as benchmark. Let AF^R be abatement function for western corn rootworm, it has

$$AF^R = \frac{A_n^R - A^R}{A_n^R} \quad (5)$$

where A^R is larvae density and given by expression (2); A_n^R is larvae density on refuge. Since pest density is sufficiently low on Bt corn plants, i.e. $A_b^R = 0$, the abatement function is simplified into $AF^R = \theta$, where θ denotes Bt corn size.

3. Abatement for stacked-trait corn variety

Stacked-trait corn variety deals with two pests, European corn borer and western corn rootworm. Then a joint abatement function mentioned by Babcock, Lichtenberg and Zilberman (1992) is applied to capture pest mortality induced by Bt corn. Let the joint abatement function be AF^{ER}, following the definition of abatement, it has

$$AF^{ER} = \frac{A_n^E(1+s_n^0) + A_n^R - A^E(1+s) - A^R}{A_n^E(1+s_n^0) + A_n^R} \quad (6)$$

By transformation, the function can be written as

$$AF^{ER} = AF^E(1-\alpha) + AF^R\alpha \qquad (7)$$

where α is weight and $\alpha = \frac{A_n^R}{A_n^E + A_n^E s_n^0 + A_n^R}$; AF^E, AF^R are abatements for two pests given by expression (4) and (5) respectively. Under low pest density, the weight is simplified as $a = \frac{1}{2 + s_n^E}$, implying that the joint abatement function for Bt corn is independent from pest density although it may be not true to the case of pesticide. Furthermore, high pest density would change the growth rate on conventional corn field, leading to fluctuation in abatement. Let error term be ε_i , the random abatement is then given by

$$AF_i^{ER} = AF_i^E(1-a) + AF_i^R a + \varepsilon_i \qquad (8)$$

where weight α, abatement AF_i^E for European corn borer and AF_i^R for western corn rootworm are closely related to larvae densities.

4. Mixed abatement function

In recent years, single trait corn variety and stacked Bt corn variety are supplied together in market although the former almost exits the market by now. Thus, a mixed abatement function is needed to capture the fact that several Bt corn varieties are planted simultaneously on corn field. Actually, single trait corn varieties just hold small portion of corn acreages in recent years. For simplicity, suppose that the acreage of single trait varieties is 50% for ECB and 50% for western corn rootworm in practice. Then acreage of stacked Bt corn plus 50% of acreage of single trait varieties is equivalent to the same size of stacked Bt corn. For example, the corn acreage is 40% of stacked Bt corn and 19% of single trait varieties. The equivalent stacked Bt corn is 40% plus half of 19%, i.e. 49.5%.

let the Bt corn size be r^E for single trait corn regarding ECB, r^R for single trait corn regarding WCR, and r^{ER} for stacked-trait corn. Their average abatement is given by

$$r^E AF^E(1-\alpha) + r^R AF^R \alpha + r^{ER} AF^{ER}$$

where $AF^E(1-\alpha)$ is the average of abatements for two pests on the field planting single trait corn for ECB while $AF^R\alpha$ is average of abatements for two pests on the field planting single trait corn for WCR. As the Bt corn size for single trait corn is sufficiently small, let $r^E = r^R = r$, the average abatement can be written as $r[AF^E(1-\alpha) + AF^R\alpha] + r^{ER} AF^{ER}$, which follows

$(r + r^{ER})AF^{ER}$, implying that we just need to apply joint abatement for stacked Bt corn in practice.

Generally speaking, a corn grower has a fix Bt corn size as the choice of Bt corn variety is made under refuge strategy. For example, as the grower chooses stacked-trait corn variety with block refuge, the Bt corn size is 80% given 20% of refuge requirement. But this is not true to a group of growers. In the group, some growers choose stacked-trait corn variety while others prefer stacked and pyramided traits variety with blended refuge. The growers planting stacked-trait corn variety may follow the 20% refuge requirement or be in non-compliance. Actually, the growers in non-compliance are either in significant deviation or not according to Jaffe (2009). Meanwhile, the growers planting Bt corn variety with blended refuge can still choose between 5% or 10% refuge. Thus, for the growers' group, as the distribution of growers' choices is given, an average of abatements can be derived.

III. Simulation on abatement

1. Pest adaptation to Bt corn

The preceding simulation of Bt corn focuses on pest adaptation to Bt corn. Early studies are on single trait corn variety with block refuge (Onstad and Gould, 1998, Onstad et al 2003, Crowder et al, 2005). Recent work turns to pyramided traits corn variety with blended refuge in favor of technique development (Davis and Onstad, 2000, Onstad, 2006, Onstad and Meinke, 2010, Onstad et al 2011, Pan, et al, 2011, Kang, et al, 2012). For pyramided traits corn variety, recessive inheritance of resistance and egg density under pyramided traits corn are addressed in literature (Crower, et al, 2005, Onstad and Meinke, 2010). Under seed mixture or blended refuge, two issues are considered. The first is larval movement between Bt corn plants and conventional corn plants (Onstad, 2006, Onstad and Meinke, 2010, Pan, et al, 2011, Kang, et al, 2012). The other is cross-pollination and low toxin expression in kernels for European corn borer (Kang, et al, 2012). These two issues can significantly promote the development of pest resistance as comparison with block refuge. On the other hand, planting Bt corn with blended refuge benefits from reducing adult dispersal and non-random mating addressed by preceding studies of Bt corn with block refuge (Crowder et al, 2005, Onstad and Meinke, 2010, Hunt, et al, 2001).

Furthermore, Bt corn is characteristic of low pest density. Thus, density-independent survival would play an important role in production (Onstad et al 2001, Crowder et al, 2005, Hibbard et al, 2010). Then modelling of abatement is needed to capture the density-independent survival instead of just concentrating on density-dependent survival. It is noted that as the pest density survey data is not that detailed and just cover the whole larvae survival from young to adult, the survival would follow binomial distribution rather than lognormal distribution or something else. Then linear probability model and non-linear logit model would be appropriate for fitting the data. Under the circumstance, maximum likelihood approach for binary response, rather than least square, is supposed to be adopted for estimation because the pest survival as binary response is 'very far from normally distributed' and 'the binomial ML estimator is more efficient than least squares' (Agresti, 2012).

Preceding models were developed only for each of pests from the viewpoint of single trait corn varieties; stacked Bt corn is not a concern even though it almost replaces single trait corn completely in practice. Actually, stacked Bt corn variety can control more than one pest on the same field instead of separate blocks as single trait corn variety does. Modelling of stacked Bt corn needs to capture the impact of ecological factors on each of pests, implying that the parameters in simulation must be set under the same conditions, where the connection of the pests in parameters is a reasonable concern. For instance, the initial pest density for ECB is set at the start of a growing season while the density for WCR is set at the end of the last growing season. Then the parameters for both pests are correlated to some degree since they have different climatic conditions. Thus, high initial pest density for ECB does not mean high initial density for WCR, and vice versa. Under the circumstance, the assumption of independence for joint abatement would not hold anymore. On the other hand, as the parameters take average values, we do not need consider the connection anymore. Then the pests can be examined separately in simulation for stacked Bt corn.

In terms of the current standard conditions, simulation of pest adaptation to transgenic corn is encouraging. However, some evidences show that several critical initial assumptions about the pests are problematic (Tabashnik, et al, 2009, Onstad and Meinke, 2010, Gassmann, et al, 2011, Siegfried and Hellmich, 2012, Tabashnik, et al, 2013, Andow et al 2015). The problems include (1) Bt corn hybrids are less than high dose of Bt toxins for European corn borer and western corn borer, and survival of susceptible homozygote is higher than expected. (2) for Bt toxin Cry1F, Cry3Bb and Cry34/35Ab, the initial resistance frequency is higher than standard conditions. (3) Cry3Bb and Cry1Ab are high in dominance of resistance value, showing incomplete recessive resistance. (4) the reduced efficacy of Bt corn hybrids occurs in practice. Although some Bt toxins like Cry34/35Ab for rootworm and Cry1Ab for European corn borer have good performance in field, the problematic toxins in a stacked and pyramided corn hybrid may be hazardous to whole product (Siegfried and Hellmich, 2012, Tabashnik et al, 2013). Thus, the pest adaptation to Bt corn variety would be modeled under in-field simulation conditions in favor of practical production.

In short, simulation on Bt corn includes two kinds of pests, European corn borer and western corn rootworm. The simulation needs to cover the recent progresses in pyramided traits corn variety and blended refuge and address survival of each pest to capture density-independent survivals with appropriate estimator under historic survey data. Given these, the simulation on pest adaptation to Bt corn can be developed to admit ecological factors and in-field conditions for stacked Bt corn in terms of preceding studies, from which abatement function and choice of specification can then be investigated.

2. density-independent and dependent survival

For European corn borer, the modelling uses Chiang and Hodson's data on pest density in Waseca (1959, 1972). Logit model is adopted in favor of binary choice. Meanwhile, below 1000 pests per 100 plants, survival of larvae is independent of pest density while the dependence occurs as pest density is above the value in terms of Onstad et al (1988, 1998 and 1999). Given these, the model is given by

$$\ln \frac{s_i}{1-s_i} = b_0 + b_1 d_{1i} + b_2 d_{2i} + b_3 d_{3i} \ln y_i + \varepsilon_i$$

where s_i, y_i denote survival rate and density of young larvae respectively; d_{ji} is dummy variable for generation, state change over time and density-dependent respectively. Actually, European corn borer has two generations with two states of mature larvae density, where the density is in state 1 if there are more than 100 larvae per 100 plants; otherwise, state 2. By admitting the corresponding dummy variables in the model, heterogeneity in generation and states can be examined. As for the dummy for density-dependent, as density of young larvae is above 1000

Table 1 Data summary (Chiang and Hodson, 1959, 1972)

variable	number	mean	sd	min	max
young larvae	41	390.171	719.206	2.000	3266.000
mature larvae	41	38.646	74.580	0.500	434.000
survival	41	0.203	0.203	0.002	0.778
generation	41	0.463	0.505	0.000	1.000
state	41	0.244	0.435	0.000	1.000
density-dependent	41	0.122	0.331	0.000	1.000

Table 2 Estimation for models

mature larvae	logit	p-value	probit	p-value	linear	p-value	log linear	p-value
generation	-1.104	0.000	-0.565	0.000	-0.090	0.000	-1.424	0.003
state	0.706	0.074	0.366	0.070	0.034	0.019	-0.682	0.230
log young larvae × density-dependent	-0.135	0.002	-0.070	0.002	-0.008	0.018	-0.019	0.841
_cons	-1.570	0.000	-0.947	0.000	0.166	0.000	-1.424	0.000
Log likelihood		-385.461		-380.740		-385.977		
AIC		18.998		18.768		19.023		
BIC		248.754		239.311		249.784		

Table 7 Estimation of western corn rootworm survival

variable	logit (data1)	p-value	log linear (data1, OLS)	p-value	logit (data2,2005)	p-value	linear_data2 (2005 OLS)	p-value	logit (data2, 2007)	p-value	linear_data2 (2007 OLS)	p-value
density-dependent	2.203	0.000	7.572	0.563	4.168	0.000	0.166	0.488	7.088	0.000	0.152	0.304
log young larvae × density-dependent	-0.830	0.000	-0.792	0.501	-0.424	0.000	-0.018	0.396	-0.643	0.000	-0.014	0.284
_cons	-2.460	0.000	-2.299	0.000	-2.363	0.000	0.081	0.000	-3.457	0.000	0.029	0.000
Log likelihood		-3197.090				-730.329			-2214.565			
AIC		376.481				52.381			147.838			
BIC		6062.006				879.121			3828.29			

Note: data1(Onstad et al, 2001), data2(Hibbard, et al, 2010) pests of 100 plants, d_{3i} is one; otherwise, zero. A summary of the survey data in Waseca is listed in table 1.

Non-linear probit model and linear model for binary choice are also considered here for comparison. They are estimated along with the logit model and compared to log-linear model with OLS estimates. The estimates of the models are illustrated in table 2, where logit model, probit model and linear model are similarly performed in fitting the survey data according to the statistic measures AIC and BIC. It is noted that the heterogeneity in generations and density states is statistically significant; density-independent survival is significantly different from density-dependent survival.

The density-independent survival is also important for studying western corn rootworm on Bt corn field. Before the experiment of pest mortality performed by Hibbard et al (2010), simulation of Bt corn regarding western corn rootworm mainly depends on density-dependent survival. Hibbard et al's experiment indicates that density-dependent mortality begins at 800 viable eggs per 30.5 cm (50000 eggs/100 plants). In this study, a logit model analogous to the one for European corn borer is used to fit Hibbard's data and Onstad's data (2001) on survival of western corn rootworm.

The estimates are illustrated in table 3, where data 1 and data2 are from Onstad's research and Hbbard's research respectively. In the table, logit model is compared to popular log-linear model with OLS estimator. It is noted that the statistic measures regarding Onstad's data have greater values. The possible reason is that the data has heterogeneous sources. Table 3 shows that density-dependent dummy variable in logit model is statistically significant at low significant level, implying that density-independent survival exists in practice.

3. Abatement

The simulation regarding pest adaptation to Bt corn includes single trait corn for European corn borer and western corn rootworm under block refuge, single trait corn for western corn rootworm under blended refuge, pyramided traits corn for European corn borer and western corn rootworm under block refuge and blended refuge in favor of current corn production. The models admit those recent progresses about ecological factors, including recessive inheritance of resistance, egg density under pyramided traits corn, larval movement under seed mixtures, adult dispersal and non-random mating for western corn rootworm, cross-pollination and low toxin expression in kernels for European corn borer, where the estimated density-dependent and independent survivals are admitted in the models.

Just as western corn rootworm, European corn borer also has adult dispersal and non-random mating on irrigated field (Hunt et al, 2001). The behavior would promote the resistance development under block refuge although it is not the case under blended refuge. In the study, the adult dispersal and non-random mating is simulated under block refuge, which is compared to its counterpart under blended refuge. It is noted that the cross-pollination is associated with field shape and distance. Thus, the simulation for European corn borer assumes that there is no cross-pollination under block refuge. Meanwhile, the low toxin expression in kernels still occurs to Bt corn plants with block refuge; the factor is considered in the study.

The simulation is illustrated in figure 2 and figure 3 with the parameters and reference in table 4 and table 5, where the years that the resistance frequency evolves to 50% are given for ECB and WCR respectively. The figures shows that for either ECB or WCR, the lines for resistance frequency are ordered in pyramided traits corn with block refuge , pyramided traits corn with blended refuge and single trait corn with block refuge, implying that the pest adaptation to Bt corn is sensitive to larvae movement along with cross-pollination and low toxin expression in kernels.

Furthermore, these developed models mentioned above can be combined into three models, stacked-trait corn variety with 20% block refuge, stacked and pyramided traits corn variety with 10% blended refuge, and stacked and pyramided traits corn variety with 5% blended refuge, corresponding to the popular corn hybrids, like Herculex Xtra, AcreMax Xtra and AcreMax Xtreme respectively. Then the expressions (4), (5) and (7) can be applied to compute the abatements for each Bt corn variety, where initial pests' densities are in-field mean values derived from preceding studies (Hutchinson et al, 2010, Frank et al, 2015); the computed abatements are three-year average. Actually, the abatements are gradually decreased over years, depending on development of pest resistance frequency. The lower the Bt corn size is, the more slowly the abatement is decreased. The abatements for the corn varieties are illustrated in figure 4, figure 5 and figure 6, where each joint abatement is close to ECB abatement, suggesting that the weight for ECB is greater than the one for WCR under in-field conditions, leading to non-linear joint abatement.

Table 4 Parameters and reference for simulation on ECB			
parameter	single trait corn block refuge	pyramided traits corn blended refuge	reference
initial frequency of resistance	0.001	0.001, 0.02	Siegfried et al, 2013
initial density of mature larvae (per 100 plants)	28	28	Hutchinson et al, 2010
dominance of reresistance	0.01	0.01, 0.17	Crespo et al, 2009
proportion of female	0.5	0.5	Onstad and Gould, 1998
proportion of non-random mating	0.6	0	Hunt et al, 2001
fecundity	290	290	Onstad and Gould, 1998
hutching rate (two generations)	0.67, 0.76	0.67, 0.76	Chiang and Hodson, 1959,1972
predispersal tasting survival	1	1	Kang et al, 2012
proportion of leaving Bt corn plant	0.76	0.76	Goldstein et al, 2010
proportion of leaving non-Bt corn plant	0.42	0.42	Goldstein et al, 2010
survival for larvae staying	0.8	0.8	Onstad and Guse, 1999
survival for larvae moving	0.1	0.1	Onstad and Guse, 1999
toxin survival of susceptible homozygotes	0.001	0.01, 0.01	Crespo et al, 2009
toxin survival of resistant homozygotes	1	1, 1	standard condition
pupae survival	0.89	0.89	Onstad and Gould (1998)
overwintering survival	0.18	0.18	Onstad and Gould (1998)
larvae moving to kernel			Kang et al, 2012
dominance of reresistance (Bt corn plants)	0.25	0.25, 0.25	
dominance of reresistance (non-Bt corn plants)		1, 1	
proporting of larvae moving to kernel	0.2	0.2	
proportion of cross-pollination on Bt corn plants	0	0.7	
proportion of cross-pollination on non-Bt corn plants	0	1	
toxin survival of susceptible homozygotes (Bt corn plants)	0.052	0.23, 0.23	
toxin survival of resistant homozygotes (Bt corn plants)	1	1, 1	
toxin survival of susceptible homozygotes (non-Bt corn plants)		0.77, 0.77	
toxin survival of resistant homozygotes (non-Bt corn plants)		1, 1	

Table 5 Parameters and reference for simulation on WCR				
parameter	corn block refuge	corn blended	corn blended refuge	reference
initial frequency of resistance	0.001	0.001	0.001, 0.2	Onstad and Meinke, 2010
initial density of mature larvae (per 100 plants)	61	61	61	Frank et al, 2015
dominance of reresistance	0.05	0.05	0.05, 0.3	Meihls et al, 2008
proportion of female	0.5	0.5	0.5	Crowder and Onstad, 2005
proportion of male dispersal	0.25			Onstad and Meinke, 2010
fecundity	356	356	356	Pan et al, 2011
fecundity ratio	1	1	1, 1	Onstad and Meinke, 2010
predispersal tasting survival	1	1	1	Pan et al, 2011
proportion of leaving Bt corn plant	0.5	0.5	0.5	Onstad and Meinke, 2010
proportion of leaving non-Bt corn plant	0.5	0.5	0.5	Onstad and Meinke, 2010
survival for larvae staying	1	1	1	Onstad and Meinke, 2010
survival for larvae moving	0.5	0.5	0.5	Onstad and Meinke, 2010
toxin survival of susceptible homozygotes	0.0125	0.0125	0.0125, 0.1	Pan et al, 2011, Maxwell et al, 2012
toxin survival of resistant homozygotes	1	1	1, 1	standard condition
overwintering survival	0.5	0.5	0.5	Crowder and Onstad, 2005

Figure 2 Years to 50% of ECB resistance frequency

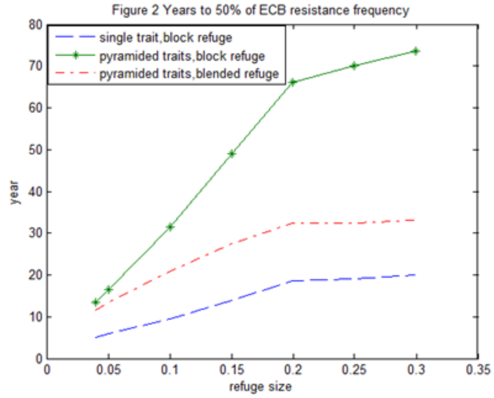


Figure 3 Years to 50% of WCR resistance frequency

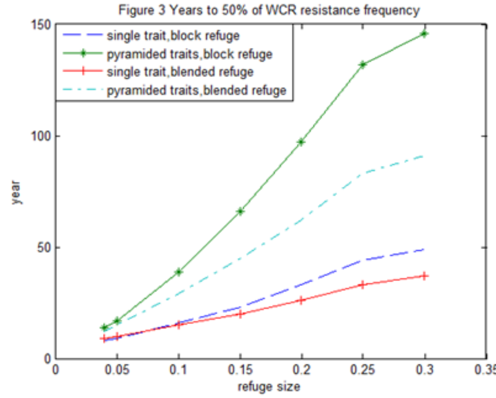


Figure 4 Abatement for stacked and pyramided traits corn variety with blended refuge(10%)

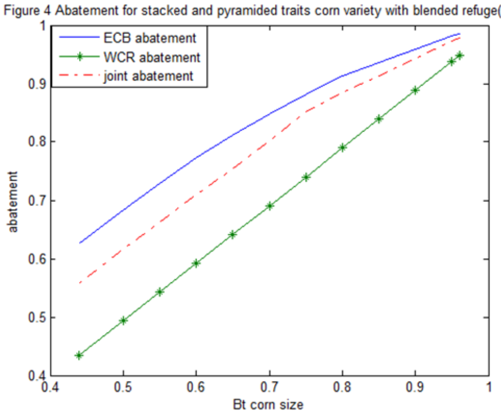


Figure 3 Abatement for stacked traits corn variety with block refuge

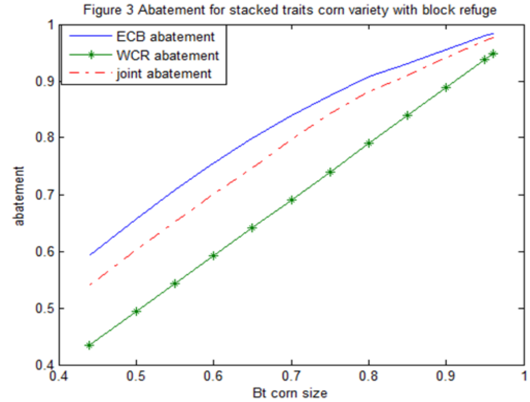
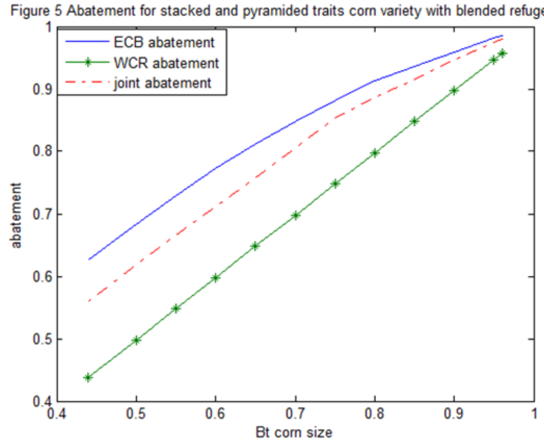


Figure 5 Abatement for stacked and pyramided traits corn variety with blended refuge(5%)



IV. Choice of abatement specification

Pest density is randomly distributed in practice. The random initial density would lead to fluctuation in pest abatement. From literature, we can find the pest density with standard deviation for ECB (Hutchinson et al, 2010) and WCR (Frank et al, 2015) respectively, where normal distribution is assumed. These in-field density values can be taken as initial pest density in simulation in favor of current production. It is noted that dependence of the values cannot be ignored, as the density values are random. In the study, 0.5 of correlation coefficient is assumed to capture analogous ecological factors on the same field but at different terms for two densities. Given the density mean vector with its variance and covariance matrix, a bivariate normal distribution is used to generate a sample of initial pest density for each pest with 500 of sample size. Then the joint abatement is simulated 500 times to generate a sample of abatement.

The algorithm is performed for each of three Bt corn varieties. The data summaries on abatement samples are illustrated in table 6, table 7 and table 8. Given these, logit model and exponential model are used to fit the data for specification choice with their OLS estimates as comparison. The estimates are given in table 9, table 10, table 11, figure 7, figure 8 and figure 9. The predicted abatements for the specifications are compared to their own sample values, where abt1, abt2 and abt3 are sample values of abatement while pabt_L and pabt_E are predicted values for logistic specification and exponential specification respectively. From the data summaries in table 6 to table 8, it can be observed that the mean abatements are ordered from traditional stacked-trait corn with 20% block refuge to new stacked-pyramided traits corn with10% of blended refuge and stacked-pyramided traits corn with 5% of blended refuge, where the Bt corn with 5% of blended refuge has the greatest value of abatement.

From table 9 to15, logistic specification has significantly lower in statistic measures AIC and BIC than exponential specification for each of Bt corn varieties, suggesting that logistic specification is appropriate for abatement function. An explanation is that the abatement would be seriously under-estimated by exponential specification at high Bt corn size, which is showed in figure 7 to 9. Meanwhile, the MLE estimates of the specifications are different from their corresponding OLS estimates. The former captures the binomial feature of abatement and thus is more appropriate than its OLS counterparts. Furthermore, likelihood ratio test is performed to test whether the three models on abatement are identical. In the test, the estimates for three Bt corn varieties are compared to the one derived from merged data, where chi2(4) = 4665.60 with Prob > chi2 = 0, suggesting that the hypothesis is rejected and the three models are significantly different.

Table 6 data summary for stacked Bt corn variety, block refuge					
variable	number	mean	sd	min	max
abatement	500	0.54	0.30	0.05	0.97
Bt corn size	500	0.48	0.29	0.04	0.96
initial pest density (ECB)	500	34.71	13.87	6.68	61.78
initial pest density (WCR)	500	65.51	10.91	43.82	87.71
pest density on conventional corn field	500	1915.41	1189.86	335.97	4307.30
mortality on Bt corn field and refuge	500	702.27	259.16	196.13	1144.39
suvival on Bt corn field and refuge	500	1213.14	1269.40	12.47	4027.09

Table 7 data summary for stacked and pyramided Bt corn variety, blended refuge (10%)					
variable	number	mean	sd	min	max
abatement	500	0.57	0.29	0.10	0.97
Bt corn size	500	0.49	0.30	0.04	0.96
initial pest density (ECB)	500	26.02	12.52	8.51	50.41
initial pest density (WCR)	500	63.16	12.06	40.02	97.94
pest density on conventional corn field	500	1733.50	1044.82	340.59	3651.55
mortality on Bt corn field and refuge	500	691.21	210.11	331.00	1044.57
suvival on Bt corn field and refuge	500	1042.28	1066.49	9.59	3269.57

Table 8 data summary for stacked and pyramided Bt corn variety, blended refuge (5%)					
variable	number	mean	sd	min	max
abatement	500	0.58	0.29	0.10	0.98
Bt corn size	500	0.51	0.30	0.04	0.96
initial pest density (ECB)	500	27.16	8.68	10.49	50.91
initial pest density (WCR)	500	61.22	8.50	39.70	79.25
pest density on conventional corn field	500	1608.85	905.64	419.46	3341.96
mortality on Bt corn field and refuge	500	679.67	200.35	322.76	974.97
suvival on Bt corn field and refuge	500	929.18	937.75	10.86	2936.20

Table 9 Estimates of joint abatement for stacked Bt corn variety, block refuge								
variable	logistic	p-value	exponential	p-value	logistic_ OLS	p-value	exponential_OLS	p-value
Bt corn size	5.716	0.000	-1.935	0.000	5.927	0.000	-3.325	0.000
_cons	-2.453	0.000	0.038	0.000	-2.579	0.000	0.457	0.000
Log likelihood		-5551.436		-7722.865				
AIC		22.214		30.899				
BIC		667.727		5010.585				

Table 10 Estimates of joint abatement for stacked and pyramided Bt corn variety, blended refuge (10%)								
variable	logistic	p-value	exponential	p-value	logistic_ OLS	p-value	exponential_OLS	p-value
Bt corn size	5.083	0.000	-1.941	0.000	5.476	0.000	-3.332	0.000
_cons	-2.071	0.000	-0.011	0.000	-2.210	0.000	0.404	0.000
Log likelihood		-3114.773		-7380.165				
AIC		12.467		29.529				
BIC		-4129.544		4401.240				

Table 11 Estimates of joint abatement for stacked and pyramided Bt corn variety, blended refuge (5%)								
variable	logistic	p-value	exponential	p-value	logistic_ OLS	p-value	exponential_OLS	p-value
Bt corn size	5.022	0.000	-1.928	0.000	5.615	0.000	-3.498	0.000
_cons	-2.070	0.000	-0.010	0.000	-2.276	0.000	0.481	0.000
Log likelihood		-3616.842		-8496.766				
AIC		14.475		33.995				
BIC		-3048.370		6711.479				

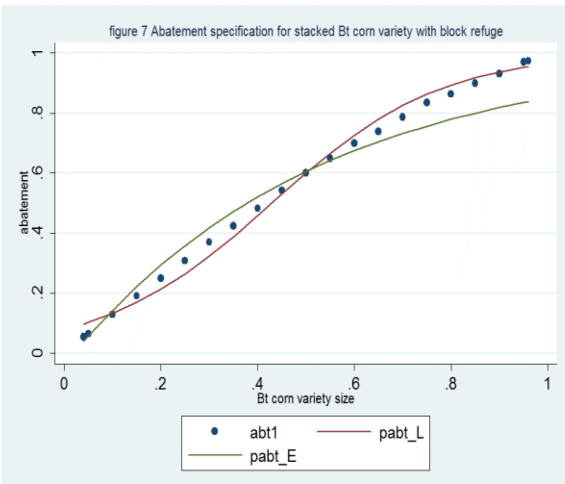


figure 7 Abatement specification for stacked Bt corn variety with block refuge
abatement
0
.2
.4
.6
.8
1
Bt corn variety size
abt1
pabt_L
pabt_E

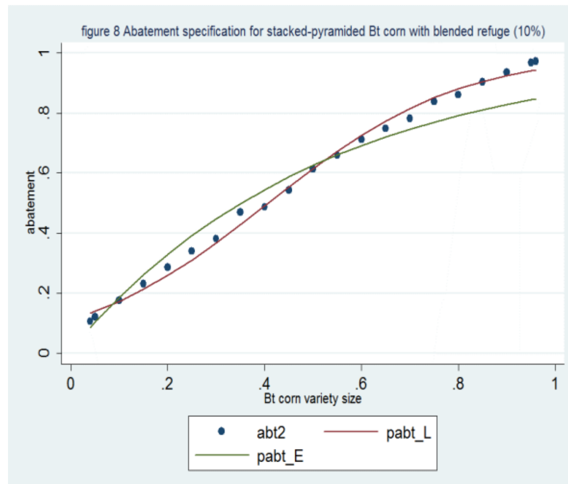


figure 8 Abatement specification for stacked-pyramided Bt corn with blended refuge (10%)
abatement
0
.2
.4
.6
.8
1
Bt corn variety size
abt2
pabt_L
pabt_E

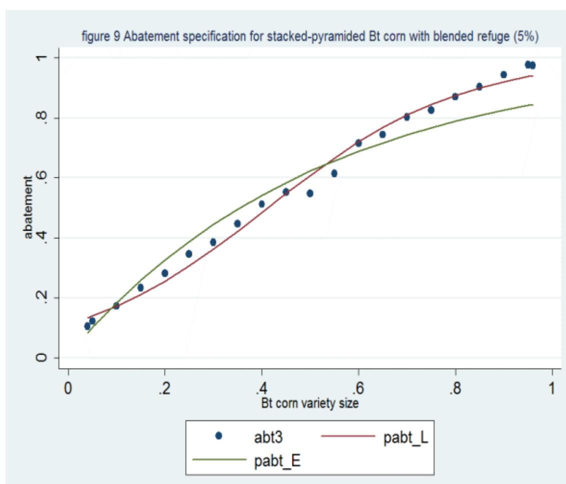


figure 9 Abatement specification for stacked-pyramided Bt corn with blended refuge (5%)
abatement
0
.2
.4
.6
.8
1
Bt corn variety size
abt3
pabt_L
pabt_E

V. Bt corn production with pre-estimated abatement

1. Model of Bt corn production

For conventional corn, the production function incorporating pesticide just considers two kinds of variables, pesticide and others (Lichtenberg and Zilberman, 1986, 1989). Unlike conventional corn, Bt corn variety is bundled with pesticide such that corn seed takes two roles, seed itself (seed quality and planting density) and pesticide. Thus, pesticide for Bt corn is a function of corn seed level while corn seed level itself also contributes to the yield as a input in production. In empirical analysis, it is needed to separate the two roles and estimate the effects for each of them. Acturally, Bt corn has its own feature on measuring dose level. Under the high dose and refuge strategy in pest management, the dose level for Bt corn is measured by Bt corn size or proportion of an acre rather than pesticide level. That is, the higher the Bt corn size is, the higher the dose level is. Then, assessment of dose level for Bt corn takes the same rule as the one for conventional corn: comparing marginal benefit to marginal cost in pesticide. If marginal productivity of Bt corn at a size is more than marginal cost, pesticide is underutilized; otherwise, it is overused.

The purpose of using abatement function lies in the measurement error on estimation of pesticide productivity under Cobb-Douglas production function. The problem can be solved through incorporating biological information in abatement function according to Lichtenberg and Zilberman (1986, 1989). Concretely, abatement function with respect to pesticide level is nonlinear just as it is for Bt corn regarding European corn borer. If Cobb-Douglas production function fails to admit the non-linearity of abatement function, the marginal effect of natural and omitted factors would be underestimated while the marginal productivity of pesticide would be overestimated. It is noted that the production function with damage control specification is also capable of separating the bundled roles of Bt corn variety since the abatement function addresses the role of Bt corn as pesticide, leaving the role of quality and planting density to corn seed level. Then let y denote yield, V_0 be seed level or planting density on a field, C be chemical level, Z be other input factors, and B be constant, the empirical model on Bt corn production can be written as

$$y = BZ^{\alpha_z} C^{\alpha_c} V_0^{\alpha_0} A^{\alpha_1}(V_1)$$

where A is abatement, a function of Bt corn size V_1. From the abatement specification choice mentioned in preceding section, the abatement takes logistic specification or exponential specification although the latter has the problem of under-estimation.

2. Simultaneity problem for using farm level data

Farm level data is usually an available data source for estimating pesticide productivity. Although experiment data is preferable for its randomness, farm level data has its own advantages and contains more information comparatively. Actually, the information on production in the data includes those about growers' preferences, agronomy, management, market and policy, etc., determining a grower's choice of production. Although this level of data is aggregated to some degree, it can be treated as information for a representative grower and analyzed to obtain some significant implication for decision maker's reference.

It is noted that farm level data has simultaneity problem, that is, the independent variables in production function are correlated with error term (Hoch, 1958). Shankar and Thirtle (2005) ever noticed the problem in their study of transgenic cotton. But the problem was not addressed. As a matter of fact, the simultaneity problem is usually solved by instrumental variable estimation (Brundy and Jorgenson, 1971, Bowden and Turkington, 1984). However, application of non-linear abatement function would lead to change in probability distribution and thus difficulty in estimation as the simultaneity problem is presented. Therefore, it is needed to examine the change through a farm's optimization problem.

Let price of corn be p, prices of the input factors be w_z, w_c, w_0, w_1 respectively, k be potential marginal herbicide level, and V_0^m be maximum planting density technically. Corn growers' optimization problem without policy constraint is given by

$$\begin{aligned} \max_{Z,C,V_0,V_1} \quad & pBZ^{\alpha_z} C^{\alpha_c} V_0^{\alpha_0} A^{\alpha_1}(V_1) - w_z Z - w_c C - w_0 V_0 - w_1 V_1 \\ st. \quad & V_1 \le V_0 \\ & C \le kV_1 \\ & V_0 \le V_0^m \\ & Z > 0, C > 0, V_0 > 0, V_1 > 0 \end{aligned}$$

Let λ_i be Lagrange multiplier with $i = 1,2,3$, Lagrange function for the problem is

$$L = pZ^{\alpha_z} C^{\alpha_c} V_0^{\alpha_0} A^{\alpha_1}(V_1) - w_z Z - w_c C - w_0 V_0 - w_1 V_1 - \lambda_1 (V_1 - V_0) - \lambda_2 (C - kV_1) - \lambda_3 (V_0 - V_0^m)$$

Then the demand functions derived from the first order condition can be written as

$$\begin{aligned} Z &= \frac{\alpha_z py}{w_z} \\ C &= \frac{\alpha_c py}{w_c + \lambda_2} \\ V_0 &= \frac{\alpha_0 py}{w_0 - \lambda_1 + \lambda_3} \\ A &= 1 - \frac{w_1 + \lambda_1 - k\lambda_2}{\alpha_1 bpy} \end{aligned}$$

$$V_1 - V_0 \leq 0,\ C_1 - kV_1 \leq 0,\ V_0 - V_0^m \leq 0$$

In practice, corn growers can gain high marginal return from planting Bt corn. Thus, the first constraint is viewed as policy constraint with $\lambda_1 > 0$ in favor of refuge requirement. Then some growers choose Bt corn with block refuge; others choose Bt corn with 10% blende refuge or 5% blended refuge. Of those growers planting block refuge, some of them are in non-compliance. Meanwhile, with high marginal return under refuge requirement, growers can benefit from raising chemical level and planting density. Under the circumstance, chemical level and seed level are not independent variables anymore; they are function of Bt corn size. These associations are important in choosing instrument variables to solve simultaneity problem.

Another issue is on input demand functions under non-linear abatement. Lichtenberg and Zilberman ever gave a demand function for control agent under each assumed distribution of abatement (1986). The problem is how to connect distribution of the control agent to non-linear abatement function and then estimate the production function. Actually, demand for abatement rather than control agent can be directly derived from the primal optimization problem given logistic abatement function. Since abatement is a function of control agent, i.e. Bt corn size, distribution of abatement is also associated with distribution of Bt corn size. As for the latter, although refuge requirement regulates Bt corn seed level and affects its distribution, release of new Bt corn varieties and diversified combinations of the varieties give growers more and more flexibility in choice. Given this and considering the characteristic of aggregation for farm level data, it is reasonable to assume that logarithmic Bt corn seed level is normally distributed in the sense of the central limit theorem, which follows that logarithmic abatement is approximately normally distributed with some specific expectation and variance by delta method (DeGroot and

Schervish, 2002). Then the instrumental variable estimation can be applied to solve the simultaneity problem for production function.

3. Farm level data

The farm level data used in the study is sourced from farm financial database, FINBIN, contributed by farm management associations, where actual farm inputs and output for corn production along with prices and annual Bt corn size from National Agricultural Statistics Service are adopted to fit the production model. The data include 56 farms each year in Waseca County, MN. Eight years from 2008 to 2015 are chosen to avoid selectivity problem addressed by preceding studies (Shankar and Thirtle, 2005, Shi, Chavas and Lauer, 2013). The farms in the data are different in tenure and corn planting size. Tenure has two types, owned land or cash rent. A farm is defined as big farm if its corn planting size is more than 250 acres; otherwise, it is treated as a small farm. Then the farms of interest are divided into four groups with respect to their tenure and planting scale, big farm with owned land, small farm with owned land, big farm with cash rent and small farm with cash rent. Concretely, each group has 8, 17, 15 and 16 farms respectively. The grouping generates a panel data with 8 years and 4 groups and makes it possible to model corn production for heterogeneous farms.

The annual Bt corn size or proportion in the data covers single trait corn and stacked-trait corn. They are merged in the mixed way as mentioned in the preceding section. On the other hand, the Bt corn size value involves all types of Bt corn varieties, with block refuge or blended refuge, in recent years. 2012 Corn and Soybeans Classics meetings gives a distribution of corn growers' choices (Mahanna and Thomas, 2014). The distribution of choices for 608 corn growers in Illinois is 10% of conventional corn variety, 53% of Bt corn variety with structural refuge, 37%

of Bt corn variety with integrated refuge. Of the growers choosing integrated refuge, 40% is Bt corn variety with 10% blended refuge and 60% is Bt corn variety with 5% blended refuge. We attribute the rapid increase of Bt corn size in 2013 to the widespread adoption of the new varieties. Then Bt corn size for each Bt corn variety can be computed, from which abatement is derived.

The percentage of corn grower's choice and average of joint abatement are summarized in table 12, where the impact of non-compliance is taken into account. Along with the computed abatements, inputs and output per acre are illustrated in table 13. Table 14 gives prices received or paid together with expenses, where expense for block refuge is derived from preceding study (Hyde et al, 2000). Meanwhile, corn seed price is weighted average of Bt corn seed price and non-Bt corn seed price regarding their shares in Minnesota. In addition, chemicals price index and fertilizer price index are also adjusted regarding their shares in Minnesota.

4. Estimation

The empirical panel data model is given by

$$\log yield_{it} = a + u_i + \gamma_f \log fertilizer_{it} + \gamma_l \log labor_{it} + \gamma_a \log abatement_{it} + \gamma_{ac} \log acre_{it} + \varepsilon_{it}$$

where the variable acre is not determined in corn grower's optimization problem for choice of Bt corn size and thus is exogenous while the variables fertilizer, labor and abatement are endogenous. To solve the simultaneity problem, instrument variables are used in estimation. A suggestion is that the inputs and output prices are taken as instrument variables (Moss, 2005). In the study, the instrument variables for these endogenous variables are corn price, Bt corn seed

Table 12 Percentage of corn grower's choice and average of joint abatement

year	bt corn size(%)	coventional corn(%)	100% bt corn, block refuge(%)	90% bt corn, block refuge(%)	80% bt corn, block refuge(%)	90% bt corn, blended refuge(%)	95% bt corn, blended refuge(%)	abatement (logistic)	abatement (exponentia)
2015	79	12.6	6.55	3.53	40.32	14.8	22.2	0.807	0.716
2014	82	8.98	7.02	3.78	43.22	14.8	22.2	0.840	0.745
2013	79.5	11.98	6.63	3.57	40.82	14.8	22.2	0.812	0.721
2012	56.5	32.17	8.82	4.75	54.26	0	0	0.619	0.544
2011	56	33.33	8.74	4.71	53.78	0	0	0.613	0.539
2010	55	34.52	8.58	4.62	52.82	0	0	0.602	0.529
2009	52.5	37.5	8.19	4.41	50.42	0	0	0.575	0.505
2008	49.5	41.07	7.73	4.13	47.22	0	0	0.539	0.474

Note: (1) percentage of grower's choice in 2013-2015 is sourced from survey in 2012 Corn and Soybean Classics (Mahanna and Thomas, 2014)
(2) percentage of non-compliance is 20% (Jaffe,2009), where 65% of non-compliance is in significant deviation

Table 13 Inputs and output per acre

variable	number	mean	sd	min	max
yield (bu)	32	182.51	16.81	143.12	214.71
acres	32	305.44	204.82	105.38	790.24
labor (hrs)	32	2.97	0.77	1.79	4.57
fertilizer	32	48.54	10.55	23.86	68.31
chemicals	32	24.72	3.95	18.38	35.53
seed (80kk)	32	0.47	0.02	0.43	0.55
Bt corn size (%)	32	63.75	13.11	49.50	82.00
abatement (logistic)	32	0.67	0.12	0.53	0.83
abatement (exponential)	32	0.59	0.10	0.47	0.74
indemnity payment ($)	32	45.87	77.08	0.00	248.01
mid-term precepitation (in)	32	7.17	2.61	3.49	12.56

Table14 Prices received or paid and expenses

variable	number	mean	sd	min	max
corn price ($/bu)	32	4.62	1.04	3.52	6.65
land rent/expense ($/ac)	32	152.90	49.24	74.59	249.41
labor price ($/hr)	32	25.99	12.69	6.48	54.39
fertilizer price index	32	330.89	47.70	267.46	424.73
chemicals price index	32	137.27	5.14	130.35	143.58
dry expense ($/bu)	32	10.20	7.58	1.34	22.76
seed price ($/80kk)	32	230.56	40.11	155.71	276.68
Bt seed price ($/80kk)	32	256.75	34.96	184.00	293.00
non-Bt seed price ($/80kk)	32	167.75	29.29	115.00	197.00
expense for block refuge($/ac)	32	4.85	1.04	3.68	6.95
direct production cost($/ac)	32	3.04	0.81	1.76	5.09

price, non-Bt corn seed price, fertilizer price index, labor price. Since Bt corn size is closely related to chemical (herbicide) level, planting density, effort for block refuge and production management, the dummy variables of chemicals, seed level, expense for block refuge and direct production cost are also chosen as instrument variables. These dummy variables together with others are listed in table 15, where dry expense, indemnity payment and mid-term precipitation are exogenous variables. On the basis, two-stage least squares fixed effects estimator for panel data is adopted to fit the data. The estimates under logistic abatement are listed in table 16 with those regarding exponential abatement as comparison. Hausman specification test is performed, where chi2(7) is equal to 76.67 with p-value=0. Thus, the null hypothesis of difference in coefficients not systematic is rejected. The test for the model under exponential abatement has the similar result with chi2(7) =69.09 and p-value=0.

5. Marginal effects

Table 16 gives output elasticities of abatement in the second and sixth columns, where the elasticity of abatement under logistic abatement is higher than the one under exponential abatement although the difference is not significant. From the estimates, marginal effects for Bt corn is computed and listed in table 17, where the output elasticity in Bt corn size under logistic abatement is less than one and significantly greater than the one under exponential abatement, showing the difference in choice of specification and the decrease of return.

Under logistic abatement, marginal product in Bt corn size is 1.46 bushel in 1% of Bt corn size increase, leading to $5.78 of marginal net return in $1.13 of input cost. The high marginal net return as such would put strong pressure on the compliance with refuge requirement. Actually, the higher the marginal net return is, the more the pressure is. Consequently, great social cost is required for restricting corn growers' choice. It is noted that the high marginal net return occurred from 2008 to 2012, where the marginal net return is $8.17 in $1.02 of input cost. During 2013-2015, the marginal net return is lowered to $1.79 in $1.31 of input cost. The decline of marginal net return is accompanied with the rise of Bt corn size to 80% in the three years, showing the effect of new Bt corn varieties extension. The widespread adoption of Bt corn with blended refuge would reduce non-compliance and finally save social cost for insect resistance management.

Table 15 Dummy variables

variable	number	mean	sd	min	max
seed	32	0.50	0.51	0	1
chemcals_high level	32	0.06	0.25	0	1
chemcals_low level	32	0.53	0.51	0	1
expense for block refuge	32	0.41	0.50	0	1
indemnity payment	32	0.25	0.44	0	1
dry expense	32	0.50	0.51	0	1
mid-term precipitation	32	0.63	0.49	0	1
direct production cost_high level	32	0.84	0.37	0	1
direct production cost_low level	32	0.34	0.48	0	1

Table 16 Estimates of models for panel data

	logistic abatement		exponential abatement	
variable	Coef.	p_value	Coef.	p_value
log abatement	0.427	0.045	0.416	0.043
log labor	0.166	0.052	0.167	0.050
log fertilizer	0.227	0.002	0.226	0.002
log land	0.268	0.004	0.267	0.004
indemnity payment	-0.398	0.000	-0.397	0.000
dry expense	0.120	0.000	0.119	0.000
midterm precipitation	0.078	0.006	0.077	0.007
constant	2.854	0.000	2.912	0.000
R-square		0.835		0.835
Wald test	Prob > chi2 =	0.000	Prob > chi2 =	0.000

Table 17 Marginal effects (1 % of acre)

	logistic abatement				exponential abatement			
year	output elasticity in Bt corn size	marginal product in Bt corn size	marginal return	marginal net return	output elasticity in Bt corn size	marginal product in Bt corn size	marginal return	marginal net return
2008-2015	0.469	1.461	6.906	5.779	0.353	1.106	5.206	4.079
2008-2012	0.543	1.875	9.193	8.173	0.414	1.431	6.973	5.953
2013-2015	0.344	0.773	3.095	1.790	0.252	0.564	2.262	0.956

VI. Conclusion and suggestion

Abatement is usually unobservable because it is hard to perform field survey. As the ecologic factors that impact pest life cycle are known, simulation can be used for deriving abatement function, where density-independent survival usually plays a key role on Bt corn field. As abatement is non-linear with respect to Bt corn size, measurement error would occur if Bt corn size replaces abatement as variable in popular Cobb-Douglas production function. This is true to the abatement function for European corn borer but not to the one for western corn rootworm. Since stacked Bt corn variety involves European corn borer, non-linearity also occurs to this type of corn variety. The simulation shows that growth rate of the second generation cannot be ignored and thus gives evidence to support the theoretical implication.

As for choice of abatement specifications, logistic specification outperforms exponential specification in the case of Bt corn, and thus is preferred. The choice is made not only because the specification has significant statistic measures AIC and BIC, but also because the specification can capture the practical abatement at high Bt corn size. Comparatively, the exponential specification is not appropriate for the curve that features convex at low level but concave at high level. Thus, it is expected that exponential specification perform better if the modelling just concentrates on the abatement at high Bt corn size. In short, the pre-estimated abatement function can be used in modelling of production function with damage control specification in the case of Bt corn. The application not only makes the abatement observable but also assists us to solve the problem occurred in estimation.

The farm level data together with Bt corn size are summarized from producer. Then average of abatements is computed in favor of the summarized data. The estimated productivity of Bt corn size embodies nothing but the contribution of Bt corn as pesticide in whole of corn production. In estimation, instrument variables estimator is aimed at the simultaneity problem under farm level data while delta method concerns the linearity of pre-estimated abatement to instrument variables along with OLS estimator. The estimation is performed with respect to these approaches, where the estimates with logistic abatement are considered more practical than the one with exponential abatement in terms of the choice of abatement specification.

The productivity of Bt corn as pesticide is computed from the estimates, where the marginal net return regarding Bt corn size is positive, implying that the pesticide in Bt corn variety is underutilized. In recent three years after rapid extension of new varieties with blended refuge, the value is lowered with the rise of Bt corn size. It is noted that the assessment is performed under the situation that more than 50% of growers are planting Bt corn variety with structural refuge. It is expected that more growers would turn to the Bt corn varieties with integrated refuge while the marginal net return would be further lowered.

Whether will Bt corn with block refuge gradually be replaced by Bt corn with blended refuge? This is still an open problem. The assessment performed in this study is in short-term. It is still not clear whether corn growers can benefit from planting Bt corn with blended refuge in the long run. There are some worries from entomologists. The first is that some in-field conditions violate the initial assumptions for IRM. The second is that the reduced efficacy of Bt corn hybrids occurred in practice. The third is that the problematic toxins in a stacked and pyramided corn hybrid may be hazardous to the whole product. Actually, the third problem has been observed in our simulation. Thus, a long-term assessment of corn grows' welfare is needed, where a corn grower's aggregate welfare for choosing block refuge can be compared to the one for blended refuge.

Reference

Agresti, Alan, Categorical Data Analysis, Wiley-Interscience, 2012

Andow, David A., Steven G. Pueppke, Arthur W. Schaafsma, Aaron J. Gassmann, Thomas W. Sappington, Early Detection and Mitigation of Resistance to Bt Maize by Western Corn Rootworm (Coleoptera: Chrysomelidae), Journal of Economic Entomology, 1–14, 2015

Chiang, H. C., A. C. Hodson, 1958, "Population Fluctuations of the European Corn Borer, Pyraustanubilalis, at Waseca, Minnesota, 1948 to 1957", Annals of the Entomological Society of America, Vol. 52, pp.710-724

Chiang H.C. and A.C. Hodson, Population Fluctuations of the European Corn Borer, Ostrinia nltbilalis at Waseca, Minnesota, 1948.702, Environmental Entomology, Vol. 1, no. 7-16, 1972

Buttel, Frederick, Jeanne Merrill, Lucy Chen, Jessica Goldberger, Terrance Hurley, Bt Corn Farmer Compliance with Insect Resistance Management Requirements: Results from the 2002 Minnesota and Wisconsin Farm Polls, Staff Papers 13659, University of Minnesota, Department of Applied Economics, 2005

Babcock, Bruce A., Erik Lichtenberg and David Zilberman, Impact of Damage Control and Quality of Output: Estimating Pest Control Effectiveness, American Journal of Agricultural Economics, Vol. 74, No. 1, 163-172, 1992

Blackwell, Melanie and Angelos Pagoulatos, The Econometrics of Damage Control, American Journal of Agricultural Economics, Vol. 74, No. 4, 1040-1044, 1992

Carrasco-Tauber, Catalina and L. Joe Moffitt, Damage Control Econometrics: Functional Specification and Pesticide Productivity, American Journal of Agricultural Economics, Vol. 74, No. 1, 158-162, 1992

Carrière, Yves, Neil Crickmore, Bruce E Tabashnik, Optimizing pyramided transgenic Bt crops for Sustainable Pest Management, Nature Biotechnology, Vol.33, No.2, 2015

Crespo, Andr´e LB, Terence A Spencer, Analiz P. Alves, Richard L Hellmich, Erin E. Blankenship, Leonardo C. Magalh˜aes, Blair D. Siegfried, On-plant survival and inheritance of resistance to Cry1Ab toxin from Bacillus thuringiensis in a field-derived strain of European corn borer, Ostrinia nubilalis, Pest Management Science, 65:1071–1081, 2009

Davis, Paula M. and David W. Onstad, Seed Mixtures as a Resistance Management Strategy for European Corn Borers (Lepidoptera: Crambidae) Infesting Transgenic Corn Expressing Cry1Ab Protein, Journal of Economic Entomology, 93(3):937-948, 2000

DeGroot, M.H. and M. J. Schervish, Probability and Statistics, Addison Wesley, 2011

Deitloff, Jennifer, Mike W. Dunbar, David A. Ingber, Bruce E. Hibbard, Aaron J. Gassmanna, Effects of refuges on the evolution of resistance to transgenic corn by the western corn rootworm, Diabrotica virgifera virgifera LeConte, Pest Management Science, 72(1):190-8, 2016

Fox, Glenn and Alfons Weersink, Damage Control and Increasing Returns, American Journal of Agricultural Economics, Vol. 77, No. 1, 33-39, 1995

Frank, Daniel L., Ryan Kurtz, Nicholas A. Tinsley, Aaron J. Gassmann, Lance J. Meinke, Daniel Moellenbeck, Michael E. Gray, Larry W. Bledsoe, Christian H. Krupke, Ronald E. Estes, Patrick Weber, and Bruce E. Hibbard, Effect of Seed Blends and Soil-Insecticide on Western and

Northern Corn Rootworm Emergence from mCry3A + eCry3.1Ab Bt Maize, Journal of Economic Entomology, 108(3):1260-1270, 2015

Gassmann, Aaron J., Jennifer L. Petzold-Maxwell, Eric H. Clifton, Mike W. Dunbar, Amanda M. Hoffmann, David A. Ingber, and Ryan S. Keweshan, Field-evolved Resistance by Western Corn Rootworm to Multiple Bacillus Thuringiensis Toxins in Transgenic Maize, PNAS, Vol. 111, No. 14, 2014

Goldstein J. A., C. E. Mason and J. Pesek, Dispersal and Movement Behavior of Neonate European Corn Borer (Lepidoptera: Crambidae) on Non-Bt and Transgenic Bt Corn, Journal of Economic Entomology, Vol. 103, no. 2: 331-339, 2010

Greene, William H., Econometric Analysis, Prentice Hall, 2012

Griliches, Zvi, The Demand for Fertilizer: An Economic Interpretation of a Technical Change, Journal of Farm Economics, Vol. 40, No. 3, 591-606, 1958

Hennessy, David A., Damage Control and Increasing Returns: Further Results, American Journal of Agricultural Economics, Vol. 79, No. 3, 786-791, 1997

Hibbard B. E., T. T. Vaughn, I. O. Oyediran, T. L. Clark, M. R. Ellersieck, Effect of Cry3Bb1-Expressing Transgenic Corn on Plant-to-Plant Movement by Western Corn Rootworm Larvae (Coleoptera: Chrysomelidae), Journal of Economic Entomology, 98(4): 1126-1138, 2005

Hibbard Bruce E., Lisa N. Meihls, Mark R. Ellersieck, David W. Onstad, Density-Dependent and Density-Independent Mortality of the Western Corn Rootworm: Impact on Dose Calculations of Rootworm-Resistant Bt Corn, Journal of Economic Entomology, 103(1): 77-84, 2010

Hunt, T. E., L.G. Higley, J. F. Witkowski, L. J. Young, R. L. Hellmich, 2001, Dispersal of adult European corn borer (Lepidoptera: Crambidae) within and proximal to irrigated and non-irrigated corn, Journal of Economic Entomology 94, 1369–1377

Hurley, Terrance M., Langrock, Ines, Ostlie Ken, Estimating the Benefits of Bt Corn and Cost of Insect Resistance Management Ex Ante, Journal of Agricultural and Resource Economics, vol. 31(02), 2006

Hurley, Terrance M., Paul D. Mitchell, Marlin E. Rice, Risk and the Value of Bt Corn," American Journal of Agricultural Economics, vol. 86(2), 345-358, 2004

Hurley, Terrance, Silvia Secchi, Bruce Babcock, Richard Hellmich, Managing the Risk of European Corn Borer Resistance to Bt Corn, Environmental & Resource Economics, vol. 22(4), 537-558, 2002

Hurley, Terrance M., Bruce A. Babcock, Richard L. Hellmich, Bt Corn And Insect Resistance: An Economic Assessment Of Refuges, Journal of Agricultural and Resource Economics, Vol. 26(01), 2001

Hutchison, W. D., E. C. Burkness, P. D. Mitchell, R. D. Moon, T. W. Leslie, S. J. Fleischer, M. Abrahamson, K. L. Hamilton, K. L. Steffey, M. E. Gray, R. L. Hellmich, L. V. Kaster, T. E. Hunt, R. J. Wright, K. Pecinovsky, T. L. Rabaey, B. R. Flood, E. S. Raun, Areawide Suppression of European Corn Borer with Bt Maize Reaps Savings to Non-Bt Maize Growers, Science, Vol 330, 222-225, 2010

Hyde, Jeffrey, Marshall A. Martin, Paul V. Preckel, Craig L. Dobbins, & C. Richard Edwards1, The Economics of Within-field Bt Corn Refuges, AgBioForum, Vol 3, No. 1, 63-68, 2000

Jaffe, Gregory, Complacency on the Farm, Center for Science in the Public Interest, 2009

Jarvis, J. L. and W. D. Guthrie, Ecological Studies of the European Corn Borer (Lepidoptera: Pyralidae) in Boone County, Iowa, Environmental Entomology, Vol. 16: 50-58, 1987

Just Richard E., Rulon D. Pope, The Agricultural Producer: Theory and Statistical Measurement, Chapter for Handbook of Agricultural Economics, Bruce L. Gardner and Gordon C. Rausser, Elsevier Science, 2001

Kang J, D. W. Onstad , R. L. Hellmich , S. E. Moser , W. D. Hutchison , and J. R. Prasifka, Modeling the Impact of Cross-Pollination and Low Toxin Expression in Corn Kernels on Adaptation of European Corn Borer (Lepidoptera: Crambidae) to Transgenic Insecticidal Corn, Environmental Entomology, 41(1):200-211, 2012

Kuosmanen, Timo, Diemuth Pemsl and Justus Wesseler, Specification and Estimation of Production Functions Involving Damage Control Inputs: A Two-Stage, Semiparametric Approach, American Journal of Agricultural Economics, Vol. 88, No. 2, 499-511, 2006

Lichtenberg, Erik and Ayesha V. Berlind, Does it matter who scouts? Journal of Agricultural and Resource Economics, 30(2):250-267, 2005

Lichtenberg, Erik, Agriculture and Enviornment, Chapter for Handbook of Agricultural Economics, Bruce L. Gardner and Gordon C. Rausser, Elsevier Science, 2001

Lichtenberg, Erik and David Zilberman, The Econometrics of Damage Control: Reply, American Journal of Agricultural Economics, Vol. 71, No. 2, 445-446, 1989

Lichtenberg, Erik and David Zilberman, The Econometrics of Damage Control: Why Specification Matters, American Journal of Agricultural Economics, Vol. 68, No. 2, 261-273, 1986

Mahanna, Bill and EV Thomas, Refuge in a Bag Protects Corn Traits, Silage Zone, DuPont Pioneer, 2014

Meihls, Lisa N., Matthew L. Higdonb, Blair D. Siegfriedc, Nicholas J. Millerd, Thomas W. Sappingtond, Mark R. Ellersiecke, Terence A. Spencerc, and Bruce E. Hibbarda, Increased Survival of Western Corn Rootworm on Transgenic Corn within Three Generations of On-plant Greenhouse Selection, PNAS, Vol.105, No.49, 19177–19182, 2008

Moss, Charles B, Production Economics: an Empirical Approach, Department of Food and Resource Economics, University of Florida, 2005

Nolan Elizabeth and Paulo Santos, Genetic Modification and Yield Risk in Corn: Parametric and Non-parametric Analysis, 17th ICABR Conference, 2013

Nolan Elizabeth and Paulo Santos, The Contribution of Genetic Modification to Changes in Corn Yield in the United States, American Journal of Agricultural Economics 94(5):1171–1188, 2012

Norwood, F. Bailey and Michele C. Marra, Pesticide Productivity: Of Bugs and Biases, Journal of Agricultural and Resource Economics, 28(3):596-610, 2003

Onstad, David W., Paul D. Mitchell, Terrance M. Hurley, Jonathan G. Lundgren, R. Patrick Porter, Christian H. Krupke, Joseph L. Spencer, Christine D. Difonzo, Tracey S. Baute, Richard L. Hellmich, Lawrent L. Buschman, William D. Hutchison, John F. Tooker, Seeds of Change: Corn Seed Mixtures for Resistance Management and Integrated Pest Management, Journal of Economic Entomology, 104(2): 343-352, 2011

Onstad David W. and J. Meinke Modeling Evolution of Diabrotica virgifera virgifera (Coleoptera: Chrysomelidae) to Transgenic Corn With Two Insecticidal Traits, Journal of Economic Entomology, 103(3): 849-860, 2010

Onstad, David, Modeling Larval Survival and Movement to Evaluate Seed Mixtures of Transgenic Corn for Control of Western Corn Rootworm (Coleoptera: Chrysomelidae), Journal of Economic Entomology, 99(4): 1407Ð1414, 2006

Onstad, David W., Charles A. Guse, Joseph L. Spencer, Eli Levine, Michael E. Gray, Modeling the Dynamics of Adaptation to Transgenic Corn by Western Corn Rootworm (Coleoptera: Chrysomelidae), Journal of Economic Entomology, 94(2): 529-540, 2001

Onstad, D.W and C.A. Guse, Economic Analysis of Transgenic Maize and Nontransgenic Refuges for Managing European Corn Borer (Lepidoptera: Pyralidae), Journal of Economic Entomology, Vol. 92, no. 6, 1256-1265, 1999

Onstad, D.W and F. Gould, Modeling the Dynamics of Adaptation to Transgenic Maize by European Corn Borer (Lepidoptera: Pyralidae), Journal of Economic Entomology, Vol. 91, no. 3, 585-593, 1998

Onstad, D.W, Simulation Model of the Population Dynamics of Ostrinia nubilalis (Lepidoptera: Pyralidae) in Maize, Environmental Entomology, 17(6): 969-976, 1988

Pan, Zaiqi, David W. Onstad, Timothy M. Nowatzki, Bruce H. Stanley, Lance J. Meinke, and J. Lindsey Flexner Western Corn Rootworm (Coleoptera: Chrysomelidae), Dispersal and Adaptation to Single-Toxin Transgenic Corn Deployed with Block or Blended Refuge, Environmental Entomology, 40(4):964-978, 2011

Pandey, Sushil, The Econometrics of Damage Control: Comment, American Journal of Agricultural Economics, Vol. 71, No. 2, 443-444, 1989

Petzold-Maxwell, Jennifer L., Ximena Cibils-Stewart, B. Wade French, Aaron J. Gassmann, Adaptation by Western Corn Rootworm (Coleoptera: Chrysomelidae) to Bt Maize: Inheritance, Fitness Costs, and Feeding Preference, Journal of Economic Entomology, 105(4):1407-1418, 2012

Qaim, Matin, The Economics of Genetically Modified Crops, Annual Review of Resource Economics, 1:665–93, 2009

Qaim, Matin and David Zilberman, Yield Effects of Genetically Modified Crops in Developing Countries, SCIENCE, Vol 299, 900-902, 2003

Secchi, Silvia, Terrance M. Hurley, Richard L. Hellmich, Managing European Corn Borer Resistance to Bt Corn with Dynamic Refuges," Staff General Research Papers 2010, Iowa State University, Department of Economics, 2001

Shankar, Bhavani and Colin Thirtle, Pesticide Productivity and Transgenic Cotton Technology: The South African Smallholder Case, Journal of Agricultural Economics, Vol. 56, No. 1, 97-116, 2005

Shi, Guanming, Jean-Paul Chavas, Joseph Lauer, Commercialized Transgenic Traits, Maize Productivity and Yield Risk, Nature Biotechnology, Vol.31, No.2, 111-114, 2013

Shi, Guanming, Jean-Paul Chavas, Joseph Lauer, Elizabeth Nolan, An Analysis of Selectivity in the Productivity Evaluation of Biotechnology: An Application to Corn, American Journal of Agriculture Economics, 95(1), 2013

Showers, W.B., R. L. Hellmich, M. E. Derrick-Robinson, W. H. Hendrix, Aggregation and dispersal behavior of marked and released European corn borer (Lepidoptera: Crambidae) adults, Environmental Entomology 30,700–71, 2001

Siegfried, Blair D. and Richard L. Hellmich, Understanding successful resistance management: The European corn borer and Bt corn in the United States, GM Crops and Food 3:3, 184-193, 2012

Tabashnik, Bruce E, Thierry Brévault, Yves Carrière, Insect resistance to Bt crops: lessons from the first billion acres, Nature Biotechnology, Vol. 31, No.6, 2013

Tabshnik, Bruce E., J.B.J. Van Rensburg, Yves Carrie R.E., Field-Evolved Insect Resistance to *Bt* Crops: Definition, Theory, and Data, Journal of Economic Entomology, 102(6): 2011-2025, 2009