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When Do Resistance Management Practices Pay for the Farmer and Society? The Case of Western Corn Rootworm

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The Bt trait to control Western Corn Rootworm (WCR) in transgenic corn was first introduced in 2003. By 2014, about 80% of corn planted contained a Bt trait, significantly reducing corn insecticide use. This rapid and widespread adoption has led to resistance development in some Bt alleles. The near-term solutions to resistance development include voluntary adoption of resistance management practices (RMPs) including crop rotations, chemical controls, and development of new Bt alleles and other control technologies. Our results indicate that if the farmer goal is to maximize net returns or longer-term net present value per acre, crop rotations always dominate continuous corn. We also consider possible spillovers of resistance on neighboring farmers from mobile WCR. Generally, we conclude that this should not be a serious issue, especially if neighbors use RMPs.

Key words: common pool resource, game theory, pest-control efficacy, resistance management practices, Western corn rootworm.

Introduction

Genetically modified (GM) corn was first introduced in the United States in 1996 for the herbicide tolerant (HT) and insect resistance (IR) traits. The IR trait in Bt corn is engineered to express a toxin derived from a bacterium *Bacillus thuringiensis* (Bt) toxic to insects (Gassmann, Petzold-Maxwell, Keweshan, & Dunbar, 2012). The Bt trait introduced in commercial corn in 1996 was targeted to the above-ground portions of the corn plant. The trait was altered or engineered to target the below-ground root system, i.e., Western Corn Rootworm (WCR), and introduced commercially in 2003. WCR is a serious problem in corn production because the larvae feed on the corn plant roots and interfere with uptake of water and nitrogen and cause structural damage to the plant.

In 2003, the US Environmental Protection Agency (EPA) approved commercial use of Bt corn (Cry3Bb1), which is effective against WCR (Crowder & Onstad, 2005; Gassmann et al., 2014). Since then, farmers have rapidly adopted GM corn with stacked traits, including Bt and HT. By 2014, 93% of corn acres planted were GM, 76% contained both HT and Bt traits (13% having only the HT trait) and only 4% with Bt trait alone (Figure 1). As a result, corn insecticide use has decreased significantly since the release of Bt corn as indicated in Figure 2. We have gone from 14.2 million pounds of insecticides used on corn in 1996 to 1.6 million pounds of insecticide in 2010.

Prior to the introduction of Bt corn, many farmers managed corn rootworm through crop rotation since corn larvae only survive on the roots of corn and some grass species. The adult WCR are usually present in cornfields from July until frost. The adults feed on corn foliage, silks, pollen, and immature kernels. During late summer, the WCR lay eggs that remain over winter to emerge the next spring. When farmers use crop rotation, the larvae hatch on a non-host crop (such as soybeans) so the WCR larvae will not survive (Crowder et al., 2005).

When Bt corn was first registered and available for commercial use, EPA recognized a potential resistance threat and mandated planted refuges when using Bt seed. Refuges are portions of the cornfield that are not planted to Bt corn and not sprayed with insecticides to foster interbreeding between resistant and susceptible pests (Secchi & Babcock, 2003). The success of refuges depends on whether the Bt is high dose and whether the resistance gene is dominant or recessive (Gassmann et al., 2014). Therefore, when Bt crops are high dose and the resistance gene is recessive, refuges are successful in delaying resistance. However, none of the currently available Bt corn targeting WCR is high dose, and the WCR resistant Bt gene is not recessive (Gassmann, Petzold-Maxwell, Keweshan, & Dunbar, 2011).

As part of their experimental research on WCR resistance to Bt corn, Gassmann et al. (2012) collected information from farmers on use of refuges. About 25% of farmers were not in compliance with EPA refuge regulation. Gassmann et al. (2011) also found that problem fields were planted with Cry3Bb1 for at least three con-

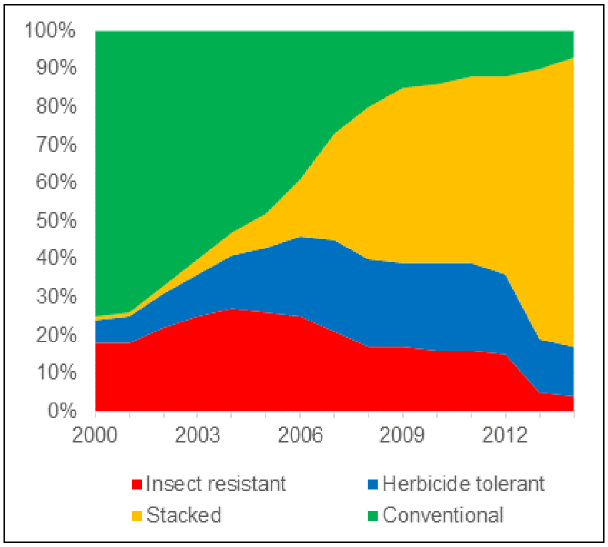

Figure 1. Percentage of type of corn seed planted in the US.

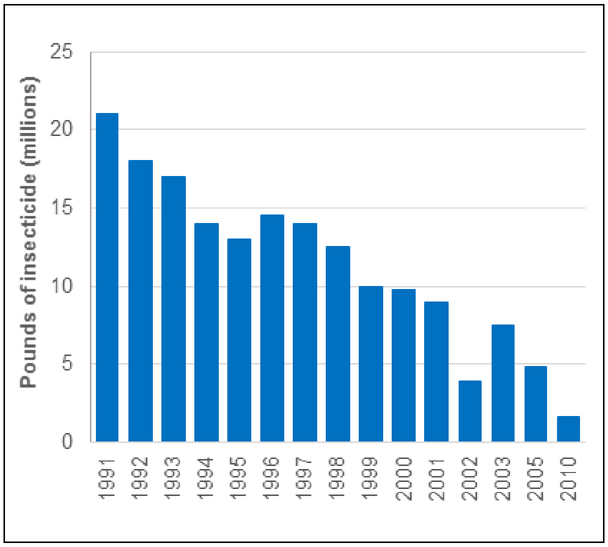

Figure 2. Pounds of insecticide used on corn planted in the United States.

secutive growing seasons. If more farmers switch to continuous corn over time, a more rapid build-up of resistance is likely. In a more recent study by Gassmann et al. (2014), the authors found that injury to Bt corn, specifically Cry3Bb1 and mCry3A, was due to resistant WCR and cross-resistance between Cry3Bb1 and mCry3A.

One of the biggest challenges of resistance management is the uncertainty surrounding resistance development. We know that resistance will develop to all modes of action based on the intensity and frequency of use, but it is uncertain how rapidly and which target pests will develop resistance. A priori, it is difficult to determine a particular RMP, or combination of RMPs, that are most efficient to implement to improve net returns in the short run and net present value (NPV) in the long run.

Another uncertainty surrounding resistance management is the potential spillovers or externalities from one's own or neighbors' failure to adopt resistance management practices. This uncertainty is tied to the mobility of the pest. If the pest is immobile, then there is no externality involved with a farmer's resistance management decision since the pest is assumed to not move beyond the farm or production unit. If a pest is mobile, the resistance management problem may be shared with neighboring farmers and becomes a common pool or externality problem. If resistance management is a common property problem, then managing resistance may call for local collective action to internalize the externality, government (EPA) intervention in the regulation and registration process, or some form of incentive or disincentive to encourage adoption of RMPs.

Given this background information and following the framework established in Miranowski and Carlson (1986), this article will address two questions. First, do farmers have an economic incentive to adopt RMPs to delay WCR resistance development by adopting RMPs in the short run and long run? If they do not adopt RMPs, what behavioral and policy factors may be creating disincentives? Second, does the mobility the WCR create externality costs that outweigh the benefits (i.e., cost savings) to individual farmer of not adopting RMPs, or are these externality costs sufficient to treat resistance management as a common property resource problem? Finally, how sensitive are the results to changing economic and production conditions in agriculture? We use a combination of biological and cultural research data, extension crop budget data, agronomic data, and informed assumptions to develop preliminary economic result of using WCR RMPs in Iowa corn production.

Biological and Cultural Data

A key input into this assessment is having research evidence based on biological and cultural data to better understand how and under which circumstances resistance would develop. We caution that only with such information (or alternatively, extensive field survey data collected over time) could we identify efficient RMPs and resistance management strategies. Entomological laboratory research at both Iowa State University (Gassmann et al., 2011, 2012, 2014) and the University of Illinois (Crowder & Onstad, 2005; Crowder et al., 2005) on WCR resistance development to different Bt alleles under different cultural and pest-control practices may provide a basis for economic evaluation. Profitability of alternative RMPs can be evaluated, resistance development forecasted, and more efficient long-run RMP strategies identified. We do need to caution that this information is necessary but not sufficient to ensure farmer adoption of RMPs. Some, and in a few cases all, RMPs may not be profitable to adopt even in the long run. Alternatively, some growers may choose to ignore the information and only make short-run decisions. Furthermore, farmer behavior may be motivated by behavioral factors other than short- and long-run profitability.

The biological information on pest mobility should also provide an economic basis for collective action or common property resource (CPR) management of WCR resistance. We use a dynamic economic model based on the resistance research under alternative cultural and pest-control practices to simulate the net returns to alternative RMPs over time. We also consider the externalities associated with a CPR and the potential payoff to collective action. The results should aid in developing optimal strategies for resistance management in WCR control.

Modeling Farmer Decisions to Adopt RMPs

Short-run Net Return Analysis

Ideally, we would like to consider WCR resistance management in the context of whole-farm operation or at least enterprise net returns or profitability. In the short run, the farmer has a fixed amount of time and cropland to allocate across the farm operation. Thus, the farmer is attempting to allocate these resources so as to maximize net returns in the short run and NPV in the long run. When maximizing farm operation net returns, it may be more profitable to allocate more attention to some production activities, e.g., specialized livestock operations, at the expense of adopting WCR RMPs. Unfortunately, we do not have appropriate data to evaluate WCR RMPs in this broader context or even at the crop enterprise level using farm-level data. So instead, we develop crop budgets for different rotations of corn and soybeans under typical Iowa production conditions to isolate net returns per acre to common cropping practices.

First we analyze the net returns per acre of four different crop rotations: 1) corn-corn (CC) rotation without a RMP, 2) CC rotation with a RMP, 3) corn-soybean (CS) rotation, and (4) corn-corn-soybean (CCS) rotation. To find net returns we need the return (price*quantity) minus the costs of production. The specific equation used is:

$$\begin{aligned}\text{Net returns per acre} = {} & \text{price per bushel} * \text{bushel per acre} \\ & - \text{seed expense} - \text{herbicide expense} \\ & - \text{nitrogen expenses} - \text{other chemical expense} \\ & - \text{insecticide expense} - \text{machine expense} \\ & - \text{other expenses} \qquad (1)\end{aligned}$$

The price per bushel was estimated based on the historical average soybean and corn price ratio. The 20-year average corn to soybean price ratio is 2.5, so we used a price of $4.50/bu for corn and $11.25/bu for soybeans. We also used price ratios of 2.25 and 2.0 to test the sensitivity of the results. The results do not change until the soybean-corn price ratio is less than 2.0. The costs[1] per acre are based on estimates from the Estimated Cost of Crop Production in Iowa—2015 (Plastina, 2015). The seed and insecticide cost data were gathered from central Iowa seed and chemical suppliers. We assume that all farmers are using biotech seed, which includes Bt-corn and HT corn and soybeans. According to the (US Department of Agriculture (USDA), National Agricultural Statistics Service (NASS) Quick Stats data (n.d.), 93% of all corn planted was biotech, and 94% of all soybean planted was biotech.

For assumed yields, we selected the high-yield options from the Estimated Costs of Crop Production in Iowa—2015: 200 bushels per acre for corn following soybeans, 185 bushels for corn following corn, and 55 bushels for soybeans following corn (Plastina, 2015). However, Plastina (2015) does not have cost and returns for CCS rotation. For this rotation we used the CS rotation prices and yields; for the second year of corn we used yield from the continuous corn rotation since corn was planted two years in a row.

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[1] *The machine expenses consist of preharvest machinery and harvest machinery expenses. Harvest machinery expenses consists of the expenses for a combine, grain cart, haul, dry, and handle (auger). The other chemical expenses include phosphate, potash, and lime. Lastly, other costs consist of crop insurance and miscellaneous expenses. Only variable costs were used since fixed costs were assumed not to vary by crop rotation or resistance management practice. When WCR insecticide chemical was involved, application costs were included.*

The CC rotation without a RMP results in selection pressure for resistant pests to develop. When WCR becomes resistant to the below-ground Bt allele planted, WCR cause damage to the plant root system and reduce yield. Therefore, the CC yield is expected to decrease by the fourth year.[2] If the farmer ignores the resistance problem, then the yield remains at this decreased level. However, if the farmer recognizes resistance and uses an insecticide to control the WCR pest, we assume yield increases but the yield is not fully restored to the pre-resistance level.

When the farmer uses a CS rotation, the WCR does not survive on soybean plants so there is no resistance build-up from year to year. Similarly, with the CCS rotation, the resistant pest population does not increase sufficiently to damage corn before soybeans re-enter the rotation, especially if below-ground Bt corn is planted. We do assume reduced yield from second-year corn due to planting corn two years in a row.

When corn is planted in a CS or CCS rotation, the average net returns are greater than CC rotation net returns. However, during the soybean years of the CS and CCS rotations, the net returns are less than the CC rotation net returns before resistance causes yield reduction. Before resistance causes a decrease in yields with a CC rotation, average net returns are $493/acre/year. The two-year average with a CS rotation is $498.13/acre. Therefore, before resistance builds up the CS rotation is $5.13/acre more profitable than a CC rotation. When pest resistance reduces yields and a farmer uses an insecticide, the net returns per year decreases to $418/acre. With a CS rotation, resistance does not develop to Bt-corn since the pests do not survive on the soybean crops. Therefore the average net returns for a CS rotation remains remain at $498.13/acre. The CS rotation is $80.13/acre more profitable than a CC rotation (see Table 7).

Next, we determined and compared the NPV[3] for each rotation. CC rotation without resistance management practices results in the lowest NPV. When a 5% discount rate is used, the NPV is $5,258 while the NPV for a CC rotation with a RMP used is $5,548. In this scenario, using a RMP with a CC rotation is more profitable than not using a RMP. A specific type of RMP is a CS rotation or a CCS rotation. The NPV for a CS rotation is $6,642 and the NPV for a CCS rotation is $6,489. Both rotations have NPVs that are greater than the NPV for the CC rotation and more profitable over the long run (i.e., 20 years). Without considering the effects from a common pool resource problem, we would recommend farmers use a CS rotation to increase net returns and manage the WCR population.

Modeling Long-run Farmer Pest-control Decisions

Most farm input management decisions are relatively short run in nature, recurring annually. The farmer decides to produce a crop with the least cost combination of variable inputs, including pest control, to produce a given level of output. Over time, some pests may become resistant to a specific pesticide input (e.g., a single mode of action), especially with widespread use and greater frequency of application (e.g., glyphosate, Bt corn).

Initially, each pesticide is endowed with a stock of efficacy (i.e., killing potency or target pest-control effectiveness) that is gradually depleted with the level and frequency of use (Miranowski & Carlson, 1986). In the longer run, the farmer may face increasing pest-control costs as efficacy is depleted and she has to shift to crop rotations, supplemental tillage, different or more chemical modes of action or residual pesticides, and related practices. If RMPs are adopted early in the process, the long-run profitability of pest-control modes of action may be greater than if more extreme pest control adjustments are needed as efficacy is depleted over time. Unfortunately, the rate of resistance development is highly uncertain, especially with rapid and varied adoption of new biotech plant-incorporated protectant (PIP) traits or technologies over space and time (Livingston et al., 2015). Prior to the introduction of HT and IR biotech traits, pesticide patents played a role in managing resistance to insects and weeds for the life of the patent. Following the Bayh-Dole Act[4] and intellectual property protection, the licensing of biotech traits has completely restructured the industry and no longer pro-

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[2] *Assumptions on resistance development and management were based on Gassmann et al. (2011, 2012, 2014), Wechsler (2015), and private communication with commercial seed and agronomic representatives.*

[3] *The NPVs presented here are with a 5% discount rate. The NPVs with no discount rate and 3% discount rate can be seen in the Appendix.*

[4] *The Government Patent Policy Act of 1980 (Bayh-Dole Act) granted certainty of title to all institutions for inventions made with federal funding, thus shifting ownership from the government to the inventor. This Act played an important role in facilitating biotechnology transfer to the private sector and, ultimately, in agricultural seed and chemical industry structure.*

vides for a more efficient allocation of pest-control efficacy over the life of the patent (Lacy & Miranowski, 2015).

Not all pest-control and resistance-management costs are easily monetized, especially when it comes to simplicity, convenience, and flexibility in larger-scale farming operations. For example, a pest-control option that offers greater flexibility in timing application diminishes the risk that adverse weather could delay application. That flexibility may be worth more than the actual cost of the control option to the farmer. As with most natural resource allocation problems, RMP costs are more up front and benefits are typically more distant and uncertain. The long-run distribution of costs and benefits from RMPs and the uncertainty surrounding resistance development may discourage adoption.

If the pest is immobile, then the farmer can manage pest resistance most efficiently. If the pest is mobile (e.g., WCR beetles) and can travel between farms by flight, wind, water, wildlife, and transport on farm equipment, then one farmer's pest may become a problem for neighboring farmers. According to Gassmann et al. (2012), an adult WCR typically moves roughly 40m per day. The mobility of the pest becomes problematic when the pest from an unmanaged field or a field without a RMP moves to a managed field or a field with a RMP. Now the farmer who is using a RMP may suffer crop damage from resistant pests that migrated from a neighboring unmanaged farm. In this sense, pesticide efficacy (effectiveness of the pesticide being used to kill target pests) is a common pool resource (CPR) or common property resource (Lacy & Miranowski, 2015). This is the dilemma that farmers face with insect resistance to Bt PIPs. Without an option to manage common-property pest-control efficacy, free-riders will eventually deplete efficacy for everyone.

The CPR (in this case, pesticide efficacy) is a stock variable, meaning that there is a flow of resource units over time that can be extracted and are depletable. For example, when Bt corn is used, the efficacy of that strain of Bt is being extracted. With each use of Bt corn without RMPs, the trait becomes less effective at killing WCR. When Bt corn is first planted, about 2% of the pest population survives; these pests are considered resistant to the Bt trait (Gassmann et al., 2014). These pests mate and increase the population of the resistant pests. Then Bt corn is planted a second year and 2% of the non-resistant pests survive and are added to the resistant pest population.

If pest-control efficacy is a depletable CPR, it implies that the more Person A uses the resource, the less there will be for Person B to use. For example, say we have two neighboring farmers, Farmer 1 and Farmer 2. If Farmer 1 plants Bt corn then at least 0.01% of his pests are resistant and this decreases the effectiveness of Bt corn on his farm. But these pests are mobile and can move to Farmer 2's farm. Now, when Farmer 2 plants Bt corn, the effectiveness of the trait will be lower and not at full strength due to the migration of resistant pests from Farm 1 to Farm 2. Therefore, the decision of one farmer affects the pest population on neighboring farms. We will evaluate this further in a CPR game theory context.

Common Pool Resource Game Framework

We analyze pesticide efficacy and RMPs in a game theory framework. Assume we have two farmers with identical farms (Farmer 1 farms on Farm 1 and Farmer 2 farms on Farm 2). Specifically, the farmers face the same costs, WCR density, and the same yield before resistance occurs. Both farmers use an insecticide (this can be chemical and/or plant with Bt gene) and have the option of using RMPs (such as using insecticides with different modes of action or planting refugees). The RMPs are costly to the farmer but have future benefits of less resistance buildup on their farm. Using a single insecticide or Bt crop has immediate benefits but higher future costs associated with faster resistance buildup.

Both farmers can choose to use RMPs or not while applying insecticides or planting Bt crops. If a farmer uses RMPs, they face costs (c) but also have future, discounted benefits (δb). The resistance management strategies are costly for a farmer to implement. For example, if a farmer decides to use an insecticide with a different mode of action or a combination of insecticides, she may incur greater chemical and management costs than the costs associated with the insecticide originally used. But using RMPs slows down the resistance build-up on the farm. Therefore, farmers experience future benefits from using RMPs. The benefits are discounted so they can be compared in present values.

If a farmer does not use RMPs, they do not face current costs but do face future costs (δn), which represent the decrease in insecticide efficacy or Bt efficacy on their farm. For example, a farmer may decide to use the same mode of action every season to reduce immediate costs. This encourages more selection pressure for resistance development and causes resistance to develop at a faster rate on the farm. As a result, the farmer faces higher future costs since overuse will render this mode of action ineffective in the future.

Since WCR is mobile, a farmer's payoff depends on the other farmer's WCR management decision as well. Specifically, if Farmer 1 uses RMPs, this farmer faces the cost of RMPs plus future benefits. If Farmer 2 is not implementing RMPs, then the resistance pests from Farm 2 may move onto Farm 1. As a result, Farmer 1's RMP will not be as effective at delaying resistance development and now Farmer 1 only receives a fraction of the future benefits. Mathematically, we represent this as $(-c + \delta (b/k))$. At the same time, the non-resistant pests from Farm 1 may travel to Farm 2. Therefore, the resistance build-up on Farm 2 may be slower due to the spillover benefits from RMPs used by Farmer 1. Farmer 2 will only face a fraction of the future costs due to less-resistant pests in the future. Mathematically, we represent this as $(-\delta (n/r))$. On the other hand, if Farmer 2 uses RMPs while Farmer 1 also uses RMPs, then both farmers receive the full future benefit of the RMP $(-c + \delta b)$. Similarly, if both farmers do not use RMPs, they both face the full future cost of their decisions $(-\delta n)$.

The matrix for a two-player game is displayed in Table 1. The top left payoffs are for Player 2 and the bottom right payoffs are for Player 1 in each cell. All the costs and benefits are measured in per-acre costs to the farmer. Using a RMP is costly to the farmer, such that $c > 1$. The future costs and benefits to the farmer are both non-negative $(n, b > 0)$. The discount factor and fractions are all positive but less than 1 $(0 < \delta, \frac{1}{r}, \frac{1}{k}, < 1)$.

Suppose Farmer 1 decides to use a RMP, then Farmer 2 can choose between using a RMP and not using a RMP. If Farmer 2 implements a RMP, both farmers face the cost of the RMP and gains the future benefit of the RMP and receive $(-c + \delta b)$. This can be seen in the top left payoff cell of Table 1. However, if Farmer 2 chooses to not use a RMP, then Farmer 2 does not face the current cost of the RMP and future cost is less due to the benefit of Farmer 1 using a RMP. Now, Farmer 1's payoff is $(-c + \delta (b/k))$ and Farmer 2's payoff is $(-\delta (n/r))$, which can be seen in the top right payoff cell of Table 1. In this case, Farmer 2 is free riding off Farmer 1's use of a RMP. Holding Farmer 1's decision fixed at using a RMP, Farmer 2 will choose to use a RMP only if $n > r ((c/\delta) - b)$. Since the game is symmetrical, the same solution will occur when Farmer 1 chooses whether to use a RMP if Farmer 2 is using a RMP.

Next, suppose Farmer 1 decides not to use a RMP and Farmer 2 can choose between using a RMP and not using a RMP. If Farmer 2 uses a RMP and faces the cost of the RMP but only gains a fraction of the future benefit. Farmer 1 benefits from Farmer 2's RMP and has a lower future cost. The payoff for Farmer 1 is $(-\delta (n/r))$ and the payoff for Farmer 2 is $(-c + \delta (b/k))$, which can be seen in the bottom left payoff cell in Table 1. If Farmer 2 does not use a RMP, then both farmers only face the future cost of their decisions to not use RMPs. Both farmers' payoffs are $(-\delta n)$, which is represented in the bottom right payoff cell in Table 1. Farmer 2 will only choose to use a RMP when Farmer 1 is not using a RMP if $n > (c/\delta) - (b/k)$. Again, since the game is symmetrical, the same solution will occur when Farmer 1 chooses whether to use a RMP if Farmer 2 is not using a RMP.

Table 1. Net return matrix for CPR game framework.

		Player 2			
		RMP		**No RMP**	
Player 1	**RMP**	$-c + \delta b$	$-c + \delta b$	$-c + \delta b \frac{b}{k}$	$-\delta \frac{n}{r}$
	No RMP	$-\delta \frac{n}{r}$	$-c + \delta b \frac{b}{k}$	$-\delta n$	$-\delta n$

Common Pool Resource Game Solution

We will assume both farmers are using a CC rotation and have the option of using a RMP or not. The payoffs in the game are NPV over 20 periods. Each scenario has long-term implications so the future effects of a current decision must be taken into account. If a farmer chooses to not use a RMP today, this will increase the resistant pest population in the following period; this may decrease the returns for this and future periods. The discount rate used is 5%. We considered lower discount rates and found the results not to be sensitive.

We evaluated the effects of different RMPs. Specifically, we consider the implications of different yield penalties related to the other farmer's RMP decisions. If Farmer 1 is using a RMP while Farmer 2 is not, then Farmer 1 will suffer a slight yield loss due to the damage from migrating resistant pests from Farm 2. Farmer 2's yield will be slightly higher than what it would be without a RMP since his resistant pest population is lower due to the non-resistant pests from Farm 1. Using our simulation results, we find that a yield penalty (from a neighbor's actions) above 9 bushels/acre will decrease a farmer's yield such that using a RMP is not as profitable as not using a RMP. In this case, when a farmer uses a RMP, she has to bear the costs of the RMP while her neighbor does not use a RMP and free rides (she

Table 2. Net return matrix for CPR game with 10bu/acre penalty.

		Farmer 2			
		RMP		No RMP	
Farmer 1	RMP	5,548	5,548	5,200	5,607
	No RMP	5,607	5,200	5,258	5,258

Table 3. Net return matrix for CPR game, analyzing per period net return with 10bu/acre penalty.

		Farmer 2			
		RMP		No RMP	
Farmer 1	RMP	418	418	373	425.5
	No RMP	425.5	373	380.5	380.5

receives the benefit of using a RMP without bearing the cost). As a result, both farmers would realize the benefit of free riding and choose to not use a RMP. However, in our model, farmers will choose to use a RMP and not free-ride until the yield penalty from neighboring farmers' decisions is at least 9 bushels/acre.

As can be seen in Table 2, with the 10 bushel/acre penalty, if Farmer 1 chooses to use a RMP, then Farmer 2 can choose to use a RMP and receive $5,548 or not use a RMP and receive $5,607. Farmer 2 will choose to not use a RMP when Farmer 1 is using a RMP. If Farmer 1 chooses to not use a RMP,[5] then Farmer 2 can choose to use a RMP and receive $5,200 or not use a RMP and receive $5,258. Farmer 2 will choose to not use a RMP. Since Farmer 2 will choose to not use a RMP regardless of what Farmer 1 has chosen, we consider Farmer 2 to have a dominant strategy not to use a RMP. Since the game is symmetrical, Farmer 1 also has a dominant strategy not to use a RMP.

However, if it is socially optimal to use RMPs to reduce resistance development to a Bt-allele, some type of intervention would be needed to incentivize farmers to use RMPs. One type of intervention could be regulatory, such as mandating farmers to use a particular RMP, e.g., requiring farmers to plant a refuge. However, this would require some form of enforcement to ensure the mandated RMP is being planted. An alternative option would be a voluntary community-based program that provides farmers with a subsidy to use a RMP. For example, if the RMP is to use an insecticide with a different mode of action, then a coupon could be provided to subsidize the cost of an alternative insecticide when purchasing seed corn.[6]

The subsidy must increase net returns and NPV such that the net return with a RMP is greater than the net return without a RMP. Net return per acre for each period after the 6th period is displayed in the Table 3. If Farmer 1 chooses to use a RMP, then Farmer 2 can choose to use a RMP and receive $418/acre for that period or not use a RMP and receive $425.50/acre for that period. Farmer 2 will choose to not use a RMP and receive $425.50/acre since this option provides the greatest net return. To incentivize Farmer 2 to use a RMP the net return must be greater than $425.50/acre. Therefore, a subsidy[7] greater than $7.50/acre should be sufficient to incentivize Farmer 2 to use a RMP.

If Farmer 1 chooses to not use a RMP then Farmer 2 can choose to use a RMP and receive $373/acre for that period or not use a RMP and receive $380.50/acre period. Again, in order to incentivize Farmer 2 to use a RMP the net returns must be greater than $380.50/acre for that period. Therefore, the subsidy must be greater than $7.50/acre to incentivize the farmer to use a RMP. With a subsidy greater than $7.50/acre, Farmer 2 will choose to use a RMP regardless of what Farmer 1 chooses. She has a dominant strategy to use a RMP. Since the game is symmetric, Farmer 1 also has a dominant strategy to use a RMP with a subsidy greater than $7.50/acre.

We also considered a yield penalty of 5 bushels/acre (Table 4) instead of 10 bushels/acre. Assume Farmer 1 chooses to use a RMP and Farmer 2 can choose to use a RMP and receive $5,548 or not use a RMP and receive $5,432. Farmer 2 will choose to use a RMP since the payoff from using a RMP is greater than the payoff from not using a RMP. Now assume Farmer 1 chooses to not use a RMP and Farmer 2 can choose to use a RMP and

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[5] *If Farmer 1 is not using a RMP and Farmer 2 is using a RMP, we assumed Farmer 1's yields increased by 10 bushels/acre for the 7th period and all remaining periods. We also assumed Farmer 2's yields decreased by 10 bushels/acre for the 7th period and all remaining periods.*

[6] *For example, Monsanto offers Roundup rewards programs to users of Roundup Ready corn, soybean, and cotton seed to cost-share the purchase of specific residual herbicides for control of resistant weeds.*

[7] *The subsidy must cover the decreased net return from using a RMP. The net return from using a RMP is $418/acre while the net return from not using a RMP is $425.50/acre. Therefore the subsidy is equal to $425.50−$418 = $7.50.*

Table 4. Net return matrix for CPR game with 5bu/acre penalty.

		Farmer 2			
		RMP		**No RMP**	
Farmer 1	**RMP**	5,548		5,374	
			5,548		5,432
	No RMP	5,432		5,258	
			5,374		5,258

receive $5,374 or not use a RMP and receive $5,258. Again, Farmer 2 will choose to use a RMP. Farmer 2 chooses to use a RMP no matter what Farmer 1 decides, i.e., dominant strategy. Since the game is symmetrical, the same holds for Farmer 1, and free-riding does not pay for either farmer and no intervention will improve social welfare.

Another example of when the CPR problem does not require intervention is when farmers adopt resistance management practices—CS or CCS rotations—on neighboring fields. Not only are these rotations more profitable, but spillover WCR from neighboring fields are destroyed during the soybean year. Therefore, there is not enough time for the resistant pests to multiply and damage the crops. Although these pests are mobile, they do not move at a fast rate. So if the neighboring farmer is using a CC rotation without a RMP, there will not be sufficient time for WCR to travel far into the corn field and seriously damage the crop. Any resistant pests that remain on the field during the corn year will not survive the soybean year.

Although it may be a commonly held belief that Iowa and Midwest farmers have been shifting away from CS and CCS to CC rotations over time, longer-run crop rotation trends do not support this belief. Hendricks, Smith, and Sumner (2014), using field-level data for Illinois, Iowa, and Indiana, 2000-2010, study the response of corn and soybean acreage to price shocks and find that aggregate acreage responds more to price shocks in the short run than in the long run. They conclude that farmers who change rotations due to price shocks have an incentive to change back to their rotations to capture the benefits of crop rotation. Although not a specific measure of the use of crop rotations, we have compared the share of corn acres in aggregate corn and soybean for the same three states, 2000-2015 (USDA, n.d.). With the exception of 2007, the share of corn acres in aggregate acres has been between 50-60%. Given that multi-year planting of soybeans are uncommon in these three states, these data would suggest that CS and CCS rotation dominate in the longer run consistent with the rotation profitability we report.

Table 5. Summary of WCR resistance management payoffs and sensitivity to discount rates and CPR problems.

	NPV		
	0%	**3%**	**5%**
Both farmers using RMP	8,980	6,637	5,548
Both farmers not using RMP	8,418	6,263	5,258
Other farmer not using RMP while I use RMP (yield loss)			
2 bu loss	8,846	6,548	5,479
5 bu loss	8,643	6,413	5,374
10 bu loss	8,306	6,188	5,200
Other farmer using RMP while I do not (yield gain)			
2 bu gain	8,553	6,353	5,328
5 bu gain	8,756	6,488	5,432
10 bu gain	9,093	6,713	5,607

Summary, Policy Implications, and Conclusions

What are the direct costs and benefits of adopting RMPs in corn and soybean production? Using laboratory data and partial crop budgets, we develop some preliminary insights. Not only do RMP costs, benefits, and pest mobility vary widely by crop, pest, and location, but behavioral factors may also limit adoption of RMPs even if RMPs are more profitable in the long run.

Our results indicate that CS and CCS rotations (or RMPs) dominate other WCR pest-control options. Based on summaries in Tables 5 and 6 we can take away some useful WCR policy implications. The standard practice of relying on a single mode of pest control may be simple, flexible, and convenient, but it is less profitable both in the short run and especially the long run. Even if the farmer substitutes chemical controls in the CC rotation after resistance to a particular Bt allele is recognized, this strategy remains less profitable than CS and CCS rotations.

Using a CS or CCS rotation greatly reduces the CPR aspect of the resistance problem since corn larvae only survive on roots of corn and some grass species. The adult WCR are usually present in cornfields from July until frost and lay eggs during late summer. The WCR larvae emerge the following spring. When farmers use crop rotation, the larvae hatch on a non-host crop (such as soybean) so the WCR larvae do not survive (Crowder et al., 2005). Since the CS or CCS rotations are a form of RMP and provide farmers with higher long-run net returns, we would expect most farmers to adopt a rota-

Table 6. Impact of using different price ratios for Corn-Soy and Corn-Corn-Soy rotations.

	NPV		
	0%	3%	5%
Corn-corn no RMP	8,418	6,263	5,258
Corn-corn RMP	8,981	6,638	5,548
Corn-soy	10,544	7,742	6,442
Corn-corn-soy	10,572	7,785	6,489
Different price ratios			
2.5 corn to soybean ($4.50 corn and $11.25 soybean)			
CS	10,544	7,742	6,442
CCS	10,572	7,785	6,489
2.25 corn to soybean ($4.50 corn and $10.125 soybean)			
CS	9,925	7,288	6,066
CCS	10,139	7,477	6,237
2.0 corn to soybean ($4.50 corn and $9.00 soybean)			
CS	9,307	6,835	5,690
CCS	9,706	7,168	5,986

tion. Yet, it is widely held that a significant portion of US corn acres are planted to continuous corn and that the CC portion is increasing over time. However, according to US Department of Agriculture data, in 2010, 71% of planted corn acres were rotated during the previous 3 years, and in 2014, 84% of planted corn acres were rotated during the previous 3 years (USDA, n.d.). Hendricks et al. (2014) used field-level data to estimate the short-run response to price shocks. Although not a direct measure of crop rotation, an alternative measure is to compare the percent corn acres in total corn and soybean acres in the three leading corn-producing states, 2000-2015. Although there are a few exceptional years, Iowa has maintained roughly 23 million corn and soybean acres and has gone from 53% to 57% corn acres, Illinois slightly under 22 million acres and from 52% to 54% corn acres, and Nebraska from 13 to over 14 million acres and has maintained 64% corn acres over the 2000-2015 period. Although this does not constitute a measure of crop rotation, corn and soybean are the two principal crops and soybean is seldom planted two years in a row, leading us to conclude that crop rotation has been a relatively stable practice over the long run in spite of changes in pest-control technology.

In addition to controlling the CPR aspect of resistance, using a CS or CCS rotation reduces the need for refuges. As previously stated, refugees are most successful when the Bt is high dose but all of the available Bt corn targeting WCR is considered low dose. Gassmann et al. (2011) found that fields with resistant WCR were planted with Cry3Bb1 for at least 3 consecutive growing seasons. Refugees were designed to slow the growth of resistant WCR by including non-Bt crops in a field so non-resistant WCR would survive, thus resulting in interbreeding between resistant and non-resistant WCR. Because WCR cannot survive on soybeans, the resistant gene dies during the soybean year in the CS and CCS rotation. Therefore, crop rotation is a more effective policy prescription than refugees.

If pests are immobile between farms, farmers independently bear costs and capture benefits of non-RMP and RMP pest-control decisions (Miranowski & Carlson, 1986). However, many weed, insect, and disease pests in corn and soybean production are mobile between farms, to varying degrees. Therefore, benefits and costs of pest management can be influenced by neighbors' behaviors. Our net present value analysis indicates that it is always more profitable for a farmer to use a crop rotation over continuous corn. Additionally, the results of our game-theoretic model indicates it is more profitable for farmers to use a RMP regardless of what neighboring farmers are doing if the externality yield loss due to increased pest mobility is low (specifically less than 9 bu/acre). However, if the externality yield loss exceeds 9 bu/acre, then neighboring farmers may choose to not use a RMP and free-ride off of neighboring farms RMPs.

There are some issues that require further investigation. First, CC rotations with and without a RMP continues to be used even when less profitable. A number of economically-motivated reasons come to mind, including preference for own feed supply and biosecurity of livestock operations, corn silage and stover harvest options, or joint profitability achieved by economies of size, which we cannot measure in our accounting model. We did not consider potential returns from corn stover or stalks, leaves, and cobs that remain in the field post-harvest. Stover may be a feed and bedding source for livestock and feedstock for biofuel and thermal energy conversion. Alternatively, Hurley and Frisvold (2014) argue that farm size trends put a premium on simplicity, convenience, flexibility, and coupling of important agronomic management traits in the seed.

Second, it is assumed that WCR move slowly between fields unless adult WCR beetles are subjected to strong winds during the feeding stage (FIFRA Scientific Advisory Panel, 2013). As climate continues to evolve, movement of adults could increase WCR spillover problems unto neighboring and more distant fields. Third, we have not attempted to address how the availability of crop insurance and increased subsidization in the 2014 Farm Bill may alter future farmer behavior and use of RMPs. Currently, there are no specific requirements for adoption of RMPs in WCR management.

What can we infer from our results for WCR resistance management policy in Iowa and other leading corn states? CS and CCS rotations will likely continue to dominate CC production systems and minimize the CPR spillover impacts. At the same time, a significant number of corn acres will continue to be planted to CC rotation, as they have been in recent history, especially in some areas of Iowa and other Midwest states. Because we live in a dynamic sector of the economy, researchers, extension, and the agricultural industry needs to continually update the agricultural community on resistance development and monitoring, resistance management practices and options, and the potential returns to adoption of RMPs.

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Appendix

Corn-Corn Rotation—No RMP

If a farmer is using continuous Bt corn, there is selection pressure for resistant pests to develop. These resistant pests can survive with Bt corn and will damage a farmer's crops. By the third year of continuous corn there will be enough resistant pests to impact the yield. The resistant pest population will continue to increase and damage crops (see Table 7).

Corn-Corn Rotation—RMP

This is the same situation as above, however, in the seventh period the farmer decides to start using insecticides to manage the resistant pests. Adding insecticides reduces the pest population and the damage caused by the pests so the yield increases but is not fully recovered. We are assuming that the farmer is using a RMP to manage his/her insecticide use. Therefore, there is not a problem with resistance to the insecticide (see Table 7).

Table 7. Net return calculations.

Year	Net return for CC without RMP	Net return for CC with RMP	Net return for CS rotation	Net return for CCS rotation
2015	493	493	581.5	581.5
2016	493	493	414.75	514
2017	493	493	581.5	414.75
2018	448	448	414.75	581.5
2019	403	403	581.5	514
2020	380.5	380.5	414.75	414.75
2021	380.5	418	581.5	581.5
2022	380.5	418	414.75	514
2023	380.5	418	581.5	414.75
2024	380.5	418	414.75	581.5
2025	380.5	418	581.5	514
2026	380.5	418	414.75	414.75
2027	380.5	418	581.5	581.5
2028	380.5	418	414.75	514
2029	380.5	418	581.5	414.75
2030	380.5	418	414.75	581.5
2031	380.5	418	581.5	514
2032	380.5	418	414.75	414.75
2033	380.5	418	581.5	581.5
2034	380.5	418	414.75	514
2035	380.5	418	581.5	414.75

Corn-Soy Rotation

When a farmer uses a corn-soybean rotation the corn rootworm cannot survive on soybean plants. Therefore, there is no selection pressure for resistant pests to develop and multiply from year to year. A corn-soybean rotation is considered a RMP (see Table 7).

Corn-Corn-Soy Rotation

A corn-corn-soybean rotation is also a RMP and does not give pests enough time to develop resistance and start to damage crops. The yield decreases during the second year of corn since the farm does not experience the added benefits from having soybeans the year before (see Table 7).

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