Can federal crop insurance be leveraged to encourage farmer adoption of pesticide resistance management practices?

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Abstract: Uncertainty imposed by pesticide resistance is a critical aspect of farm decision making for agricultural production. There are two options available for farmers to balance pest control cost and pesticide resistance risk: purchase crop insurance or adopt resistance management (RM) practices. Even though the federal crop insurance program (FCIP) serves as the cornerstone agricultural policy in the United States, the FCIP is seldom considered with RM efforts to ensure sustainable objectives. Using a two-period intertemporal decision model and generalized directional marginal substitution coefficients, we explore the effects of four policy levers on RM effort and insurance demand. We find that the effects of all these policy levers greatly depend on the farmers' tolerance for uncertainty and time preference.

Introduction

Risk management issues have taken a central focus in the current agricultural policy debate in conjunction with the U.S. federal crop insurance program (FCIP) (Woodard, 2013). Being the world's biggest crop insurance program, the FCIP has grown into the cornerstone of agricultural support in the United States, with around $100 billion in liabilities and $10 billion in taxpayer costs annually (Woodard, 2016). The subsidized insurance program provides a key tool for U.S. farmers to manage risk. It redistributes income and, consequently, resources, toward the less desired states, and implies a cost now and a benefit later. Therefore, if properly structured, the FCIP may enable sustainability objectives, such as pesticide resistance management.

Risk imposed by weed and insect pests is a critical aspect of farm decision making for agricultural production. These pests invade farms, grow, and reproduce aggressively. They compete for resources with or feed on crops resulting in diminished crop yields. In the U.S., farmers rely heavily on pesticides (herbicides and insecticides) to control pests. Yet the effectiveness of pesticides is declining as pests evolve resistance due to widespread and repeated pesticide exposure. The net result is a population of pests that is increasingly resistant to the pesticide, which can lead to a significant crop loss, and pest control cost increases. In surveys of crop production practices, farmers reported declines in the effectiveness of the most widely used herbicide in the U.S., glyphosate, on about 40% of soybean acres in 2012, with the majority of those acres in the Corn Belt and Northern Plains (Livingston et al. 2015). Being a complex biological process, pesticide resistance evolution makes it very difficult for farmers to either predict when and how fast resistance will emerge, or determine optimal ways to devote resources to reducing this uncertainty.

The option available for farmers to balance pest control cost and pesticide resistance risk is to adopt resistance management (RM) practices. The goal of RM practices is to reduce the probability of pesticide resistance by encouraging farmers to use a more diverse set of management practices that prevent or slow the evolution of resistance and ensure high crop yields (Norsworthy et al., 2012). Like the purchase of the FCIP, the RM adoption decisions shift money from good to bad states, and imply an immediate cost, while yielding a future benefit.

Though RM practices are effective at protecting agricultural production and a more sustainable agricultural environment in the long term, adoption of RM practices by farmers has been low. The interplay between present bias, risk aversion, and technological optimism provide an explanation for low RM adoption by farmers when making intertemporal decisions with immediate and certain costs, and delayed and uncertain benefits. For example, farmers may suffer from self-control problems that they prefer to consume more of their income now instead of devoting it to implementing RM efforts to secure greater profitability in the future. Farmers may also be reluctant to choose diverse management practices and incur additional costs to reduce the risk of pesticide resistance if they optimistically believe a new pesticide will soon become available to solve their current pesticide resistance problem (Norsworthy et al., 2012). These are all possible cases that keep farmers from adopting RM practices that have substantial social value. Given its scale and scope, the FCIP has the potential to encourage RM effort investment if designed and priced properly.

This study aims to examine the possible relationship between the FCIP and the adoption of RM practices. Current interest in the broad area of the FCIP and RM practices reflects several risk influences on crop insurance demand and pesticide input use. Some efforts in this area embed the microeconomic model of crop insurance demand using Expected Utility Theory

(Miranda 1991; Carter et al. 2007; Clarke 2011; Mobarak and Rosenzweig 2012; Dercon et al. 2014; Boucher and Delpierre 2013) or Cumulative Prospect Theory (Quiggin 1991, 1993; Barseghyan et al. 2013; Petraud et al. 2015). Another recent body of research focuses explicitly on how crop insurance affects pesticide use presuming that the pesticide is a risk-reducing or risk-increasing input in production (Horowitz and Lichtenberg 1994). According to the moral hazard argument, greater coverage encourages riskier production choices, causing farmers to use more risk-increasing inputs and fewer risk-decreasing inputs (Pope and Kramer 1979; Leathers and Quiggin 1991; Horowitz and Lichtenberg 1993; Babcock and Hennessy 1996). Other related literature either examines the crop insurance demand and pesticide use with risks empirically using different data sets, or considers improving the design of the FCIP to increase the insurance demand.

These discussions have provoked the interest in the role of uncertainty in the adoption of the FCIP and pesticide use. Unfortunately, they fail to address the pesticide resistance issue raised by the overuse of pesticide, the effect of pesticide resistance risk on the FCIP demand, and further, the RM effort to control the development of resistance.

The objective of this research is to evaluate how the FCIP affects farmers' RM efforts and what changes, if any, to the FCIP can be made to strengthen farmers' RM efforts, given the role uncertainty plays in discouraging RM. This objective is accomplished using a stylized two-period mathematical model of a farmer's RM decision, in which farmer behavior is modeled with hyperbolic discounting and state contingent uncertainty. The contributions of the research include (1) the introduction of the demand for the FCIP and RM efforts into the framework of quasi-hyperbolic discounting and uncertainty, (2) the decomposition of price effects on insurance demand and RM efforts with uncertainty and impatience, using Slutsky substitution effects and generalized Arrow-Pratt characterizations of uncertainty aversion (UA) and patience aversion (PA). The results of this analysis can provide policy makers with important information on the prospects of using the FCIP to promote more sustainable pest management.

This stylized model allows us to explore how four policy levers (crop insurance price, incentives to reduce present bias, community education to rebuild farmers' subjective resistance risk assessment, and RM cost-sharing subsidy) can be used by policy makers to encourage more sustainable pest management based on the farmer's tolerance for uncertainty and preference for patience. A comparative static analysis explores the effect of alternative policy levers on RM effort and crop insurance demand by decomposing it into direct substitution and indirect income effects analogous to Agnar Sandmo's seminal 1971 *American Economic Review* analysis of price uncertainty. The state-contingent analogue to the Arrow-Pratt measures of UA and PA are used to facilitate the development of sufficient conditions for alternative policy levers to unambiguously increase a farmer's RM effort.

1. δ-MS coefficient

To facilitate the development of sufficiency conditions, we now define the directional marginal substitution coefficient developed in Hurley (2016), which is a state-contingent analogue to the Arrow-Pratt measure of risk aversion.

We assume for simplicity that a farmer is faced with one known current state of the world and S future states. $\boldsymbol{\pi}$ represents a $1 * (S + 1)$ vector of known current and future state-contingent uncertain profit and $W(\boldsymbol{\pi})$ is the utility of profit. $W(\boldsymbol{\pi})$ is assumed to be increasing in π_s, continuous, and twice differentiable. The directional marginal substitution (δ-MS) coefficient is

$$\rho^s(\boldsymbol{\pi}, \boldsymbol{\delta}) = -\frac{\sum_{r=0}^{S} \delta_r \frac{\partial^2 W(\boldsymbol{\pi})}{\partial \pi_s \partial \pi_r}}{\frac{\partial W(\boldsymbol{\pi})}{\partial \pi_s}}, \text{ for } r = 0, \dots, S, \tag{1}$$

where a gradient $\boldsymbol{\delta}$ captures the direction in which to measure substitution, such as $\frac{\partial \boldsymbol{\pi}}{\partial \alpha}$, where α can be a policy lever parameter. $\rho^s\left(\boldsymbol{\pi}, \frac{\mathbf{1}}{\mathbf{2}} * \mathbf{1}^{\boldsymbol{S+1}}\right)$ and $\rho^s(\boldsymbol{\pi}, \boldsymbol{\pi})$ equal the absolute and relative Arrow-Pratt risk aversion coefficients in the state contingent model with expected utility preferences.

As shown in Figure 1 and Figure 2, there are many possible paths to trace the individual optimum with the endowment expansion after optimum E in Figure 1 and H in Figure 2. Figure 1 depicts the case where there is an additive increase in all endowments. The path EC is parallel to the 45° certainty line, while the path EA is moving away from the 45° line and path EB is moving towards the 45° line. The directions of the paths imply that the path EA is moving towards greater risks while the path EB towards greater certainty. Assume that points A, B and C are the new optimums following the paths EA, EB and EC respectively. As the path EC is parallel to the certainty line, the marginal rates of substitution (*MRS*: the negative of the slope of the indifference curve) at point C is the same as the *MRS* at E. Thus, we have constant absolute risk aversion if the optimums follow path EC when the endowments increase additively. Now suppose the optimums follow path EA when there is an additive increase in the endowment. Then the MRS at E is the same as *MRS* at A, which are greater than the *MRS* at C. In other words, the Arrow-Pratt absolute risk aversion of RM effort in state i is smaller than that in state j, and the path EA implies a decreasing absolute risk aversion (DARA) preferences. Similarly, we have increasing absolute risk aversion (IARA) along path EB.

Figure 2 depicts the case of a proportional increase in all endowments (Ehrlich and Becker, 1972). In Figure 2, if the *MRS* is constant along a given ray from the origin, this indicates constant relative risk aversion (CRRA) and all optimums will lie on the ray, such as H and G. However, if the optimum is F after H when the endowment is increased, indicating that *MRS* is decreasing along the given ray from the origin, we have decreasing relative risk aversion (DRRA). Similarly, the path HK represents increasing relative risk aversion (IRRA).

The δ-MS coefficients generalize the application of Arrow-Pratt risk aversion coefficients because they allow the endowment in each state to change in all possible directions, including additively and proportionally. The undefined direction parameter $\boldsymbol{\delta}$ can be some vector that describes the marginal change in optimal choice variable with respect to the value of any policy lever. As shown in Figure 3 and 4, the change in any direction $\boldsymbol{\delta}$ can be decomposed into directions defined by Arrow-Pratt risk aversion coefficients; likewise, the Arrow-Pratt risk aversion coefficients can be decomposed into directions that have more specific economic meaning. The transformable relation embedded in the design of δ-MS coefficients is likely to make the measure of risk aversion coefficients a more realistic task. It is necessary to fill the gaps left by the Arrow-Pratt coefficients of risk aversion, since we can discern the change in economic behaviors attributable to further categorize risk and uncertainty, and adjust the policy design accordingly.

Before we start the analysis with the δ-MS coefficients, we also need a generalized notion of risk aversion including direction parameter $\boldsymbol{\delta}$.

Definition 1: Preferences exhibit increasing/constant/decreasing $\boldsymbol{\delta}$-uncertainty aversion ($\boldsymbol{\delta}$-UA) at $\boldsymbol{\pi}$ if $\rho^s(\boldsymbol{\pi}, \boldsymbol{\delta}) >/=/< \rho^t(\boldsymbol{\pi}, \boldsymbol{\delta})$ when $\pi^s > \pi^t$ for all $s, t = 1, \ldots, S$.

Definition 2: Preferences exhibit positive/neutral/negative $\boldsymbol{\delta}$-patience aversion ($\boldsymbol{\delta}$-PA) at $\boldsymbol{\pi}$ if $\rho^s(\boldsymbol{\pi}, \boldsymbol{\delta}) >/=/< \rho^0(\boldsymbol{\pi}, \boldsymbol{\delta})$ for all $s, t = 1, \dots, S$.

The $\boldsymbol{\delta}$-uncertainty aversion (as shown in Figure 3) measures how the *MRS* between uncertain profits changes along the direction of $\boldsymbol{\delta}$. It is a state-contingent analogue to relative risk aversion. The $\boldsymbol{\delta}$-patience aversion (as shown in Figure 4) measures how the *MRS* between an immediate certain profit and any uncertain profit changes in the direction of $\boldsymbol{\delta}$.

2. Model Setup

Given that crop production involves an immediate and certain cost of RM effort, and a delayed and uncertain loss caused by the pest, we delineate certain costs and uncertain losses. We assume for simplicity that a farmer is faced with S uncertain states and the known current state. The profit from the know current state, π^0, reflects the immediate costs of RM effort with certainty, $-c(e)$, which is an increasing function of RM effort e. To characterize uncertain loss from a pest, let there be S mutually exclusive states and denote π^s as the profit given pest losses associated with state s. In any state $s \in (1, \dots, S)$, the farmer's real income endowment is given with certainty by I, and the possible pest loss $L^s(e)$ with probability p^s, where $\sum_{s=1}^{S} p^s = 1, p^s \geq 0$.

RM effort has two effects on the crop production: self-insurance – a reduction in the size of a loss – and self-protection – a reduction in the probability of a loss. In other words, applying the RM practices, for example, using diverse chemical, cultural, and mechanical methods to control weeds, reduces the production and dissemination of weed seeds, which directly reduces the loss and the probability of a severe pesticide resistance situation. Therefore, both the loss and the probability in state s are functions of RM effort, and $\frac{\partial L^s}{\partial e} \leq 0$, $\frac{\partial p^s}{\partial e} \leq 0$. We define the profit function as

$$\boldsymbol{\pi} = \left(-c(e), I - L^1(e), I - L^2(e), \dots, I - L^S(e)\right). \tag{2}$$

It is assumed that the farmer chooses the optimal RM effort by maximizing his expected state contingent utility of profit prospects,

$$\max_{e\geq 0} W(\boldsymbol{\pi}) = \max_{e\geq 0} \sum_{s=1}^{S} p^s(e) U(\pi^s(e) + \pi^0(e)) \tag{3}$$

where $\boldsymbol{\pi}$ represents a vector of state-contingent profit as shown in equation (2) and $W(\boldsymbol{\pi})$ is the utility of state-contingent profit. $U(\pi^s(e) + \pi^0(e))$ is the utility of profit in state s, which is assumed to be increasing, continuous and twice differentiable.

Assuming an interior solution $(e > 0)$ the first order condition is

$$W' = \frac{\partial W}{\partial e} = \sum_{s=1}^{S} \left(\frac{\partial p^s}{\partial e} U^s\right) + \sum_{s=1}^{S} \left(p^s \frac{\partial U^s}{\partial e}\right) = 0 \tag{4}$$

where

$$\frac{\partial U^s}{\partial e} = \frac{\partial U}{\partial \pi^s} \frac{\partial \pi^s}{\partial e} = \frac{\partial U}{\partial \pi^s} \left(-\frac{\partial L^s}{\partial e} - \frac{\partial c}{\partial e}\right) \tag{5}$$

and functional arguments have been suppressed to facilitate exposition. Using the first order condition we can show that at the interior solution, the marginal benefits of RM effort must equal the marginal cost

$$\sum_{s=1}^{S} \left(\frac{\partial p^s}{\partial e} U^s\right) + \sum_{s=1}^{S} \left(p^s \frac{\partial U}{\partial \pi^s} \left(-\frac{\partial L^s}{\partial e}\right)\right) = \sum_{s=1}^{S} \left(p^s \frac{\partial U}{\partial \pi^s} \frac{\partial c}{\partial e}\right). \tag{6}$$

Once we add the policy levers into the profit function, we are able to turn to the comparative static effects for the policy levers by taking the total derivative of W' with respect to a general policy lever α,

$$\frac{dW'}{d\alpha} = \frac{\partial W'}{\partial \alpha} + \frac{\partial W'}{\partial e}\frac{de^*}{d\alpha} = 0 \,. \tag{7}$$

Solving for $\frac{de^*}{d\alpha}$, the general comparative statistic can be written as

$$\frac{de^*}{d\alpha} = -\frac{\frac{\partial W'}{\partial \alpha}}{\frac{\partial W'}{\partial e^*}} \,. \tag{8}$$

Given $W' = \frac{\partial W}{\partial e} = \sum_{s=1}^{S}(\frac{\partial p}{\partial e}U^s) + \sum_{s=1}^{S}(p^s \ \frac{\partial U^s}{\partial e}) = 0$, we can derive

$$\frac{\partial W'}{\partial e^*} = 2 * \sum_{s=1}^{S}(\frac{\partial p^s}{\partial e}\frac{\partial U^s}{\partial e}) + \sum_{s=1}^{S}(p^s \ \frac{\partial^2 U^s}{\partial e^2}) < 0 \,. \tag{9}$$

Above inequality ($\frac{\partial W'}{\partial e^*} < 0$) is obviously satisfied if everywhere $\frac{\partial U}{\partial e} > 0$ and $\frac{\partial^2 U}{\partial e^2} < 0$, that is, if the marginal utility of RM effort is positive and decreasing. We can also expand W' into

$$W' = \frac{\partial W}{\partial e} = \sum_{s=1}^{S}\left(\frac{\partial p^s}{\partial e}U\big(I - L^s(e) - c(e)\big)\right) + \sum_{s=1}^{S}\left(p^s \ \frac{\partial U}{\partial \pi^s}\left(-\frac{\partial L^s}{\partial e} - \frac{\partial c}{\partial e}\right)\right) = 0. \tag{10}$$

Then, taking the derivative of W' with respect to the optimal level of RM effort yields

$$\frac{\partial W'}{\partial e^*} = 2\sum_{s=1}^{S}\left(\frac{\partial p^s}{\partial e}\frac{\partial U}{\partial \pi^s}\left(-\frac{\partial L^s}{\partial e} - \frac{\partial c}{\partial e}\right)\right) + \sum_{s=1}^{S}\left(p^s \ \frac{\partial^2 U}{\partial (\pi^s)^2}\left(-\frac{\partial L^s}{\partial e} - \frac{\partial c}{\partial e}\right)^2\right)$$

$$+ \sum_{s=1}^{S}(p^s \frac{\partial U}{\partial \pi^s}\left(-\frac{\partial^2 L^s}{\partial e^2} - \frac{\partial^2 c}{\partial e^2}\right) < 0 \,. \tag{11}$$

This inequality will hold everywhere if $\frac{\partial^2 L^s}{\partial e^2} \geq 0$, $\frac{\partial^2 c}{\partial e^2} \geq 0$, and $-\frac{\partial L}{\partial e} \geq \lambda \frac{\partial c}{\partial e}$, that is the marginal productivity of self-insurance is non-increasing, while the marginal cost of RM effort is nondecreasing. The marginal productivity of self-insurance should not be smaller than the marginal out-of-pocket cost, so to ensure farmer is willing to invest in RM effort.

For a unique maximum reflected by inequality in equation (9), how optimal RM effort changes depends on the sign of $\frac{\partial W'}{\partial \alpha}$. Rearranging the expression of $\frac{\partial W'}{\partial \alpha}$ by applying the $\boldsymbol{\delta}$-MS coefficients, we can decompose the change of optimal RM effort level in response to the changes in policy levers into the effects of the farmer's tolerance for uncertainty and preference for patience.

3. A Static Decision Model

In the spirit of Ehrlich and Becker (1972), we extend our model to include a yield subsidy(k), and RM effort subsidy $(1-\lambda)$, where λ is the out-of-pocket part of RM effort cost, and the demand of crop insurance (x). Importantly, since farmers are allocating scarce wealth between crop insurance and RM effort, the newly added variables allow the model to capture the direct relation between crop insurance demand and RM effort.

Individual farmer utility depends on both RM effort and crop insurance purchases: $U(e,x)$. Values of e and x should be chosen simultaneously to maximize the state-contingent expected utility function

$$\max_{e\geq 0, x\geq 0} W(\boldsymbol{\pi}) = \max_{e\geq 0} \sum_{s=1}^{S} p^s U(\pi^s + \pi^0)\,, \tag{12}$$

where the adjusted profit function is

$$\boldsymbol{\pi} = \left(-\lambda c(e) - \upsilon x, (I - L^1(e))(1+k) + r\left(L^1(e)\right)x, \ldots, (I - L^S(e))(1+k) + r\left(L^S(e)\right)x\right) \tag{13}$$

where $\upsilon < 1$ is the price of insurance. The term υx measures the premium. $r\big(L^s(e)\big)$ denotes the indemnity function if pesticide resistance occurs, where $0 \leq r\big(L^s(e)\big) \leq 1$, $\frac{\partial r}{\partial L} > 0$, and the term $r\big(L^s(e)\big)x$ measures the coverage of potential loss. The crop insurance described in the profit function is able to redistribute the difference between the coverage and the premium to hedge against the risk of a contingent, uncertain loss brought by the pest problem.

The first order conditions are

$$W_e' = \frac{\partial W}{\partial e} = \sum_{s=1}^{S}\left(\frac{\partial p^s}{\partial e}U^s\right) + \sum_{s=1}^{S}\left(p^s\frac{\partial U^s}{\partial e}\right) = 0, \tag{14}$$

where, $\frac{\partial U^s}{\partial e} = \frac{\partial U}{\partial \pi^s}\frac{\partial \pi^s}{\partial e} = \frac{\partial U}{\partial \pi^s}\left(-\frac{\partial L^s}{\partial e}(1+k) + \frac{\partial r}{\partial L^s}\frac{\partial L^s}{\partial e}x - \lambda\frac{\partial c}{\partial e}\right)$, and

$$W_x' = \frac{\partial W}{\partial x} = \sum_{s=1}^{S}\left(p^s\frac{\partial U^s}{\partial x}\right) = \sum_{s=1}^{S}\left(p^s\frac{\partial U^s}{\partial \pi^s}\left(r\big(L^s(e)\big) - \upsilon\right)\right) = 0. \tag{15}$$

Using the first order condition in equation (14), the marginal benefit from RM application must equal the marginal cost for an interior solution:

$$\sum_{s=1}^{S}\left(\frac{\partial p^s}{\partial e}U^s\right) + \sum_{s=1}^{S}\left(p^s\ \frac{\partial U}{\partial \pi^s}\left(-\frac{\partial L^s}{\partial e}(1+k) + \frac{\partial r}{\partial L^s}\frac{\partial L^s}{\partial e}x\right)\right) = \lambda\frac{\partial c}{\partial e}\sum_{s=1}^{S}\left(p^s\ \frac{\partial U}{\partial \pi^s}\right).$$

While the first order condition in equation (15) implies the real price of insurance equals the ration of the weighted sum of marginal utility of profit from states with uncertainty to the marginal utility of the certain profit: $\upsilon = \frac{\sum_{s=1}^{S}\left(p^s\frac{\partial U^s}{\partial \pi^s}r\big(L^s(e)\big)\right)}{\sum_{s=1}^{S}\left(p^s * \frac{\partial U^s}{\partial \pi^s}\right)} = \frac{\sum_{s=1}^{S}\left(p^s\frac{\partial U^s}{\partial \pi^s}r\big(L^s(e)\big)\right)}{\frac{\partial U}{\partial \pi^0}}$.

To ensure the maximum solution, we also need the second-order optimality conditions

$$W_{ee}' < 0,\ W_{xx}' < 0, \text{ and } W_{ee}'W_{xx}' - (W_{ex}')^2 > 0. \tag{16}$$

Turning to the comparative static effects for crop insurance price, we need to solve for $\frac{de^*}{dv}$ and $\frac{dx^*}{dv}$. Applying the definition of the directional marginal substitution ($\boldsymbol{\delta} - MS$) coefficients and the Hessian matrix (H), we can express $\frac{de^*}{dv}$ and $\frac{dx^*}{dv}$ as

$$\frac{de^*}{dv} = \frac{1}{|H|} * \begin{vmatrix} -W'_{ev} & W'_{ex} \\ -W'_{xv} & W'_{xx} \end{vmatrix}, \text{ and } \frac{dx^*}{dv} = \frac{1}{|H|} * \begin{vmatrix} W'_{ee} & -W'_{ev} \\ W'_{xe} & -W'_{xv} \end{vmatrix},$$

and expressions of $W'_{ee}, W'_{ex}, W'_{ev}, W'_{xe}, W'_{xx}$, W'_{xv} involving six types of directional marginal substitution coefficients.

Result 1- effects of related subsidies:

For a farmer facing risk in pesticide resistance and efficacy of RM effort,

a) decreasing $\frac{\partial \boldsymbol{\pi}}{\partial k}$-UA and negative $\frac{\partial \boldsymbol{\pi}}{\partial k}$-PA imply a positive relationship between optimal RM effort and yield subsidy (k);

b) increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial \lambda}$-UA and positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial \lambda}$-PA imply a negative relation between optimal RM effort and RM out-of-pocket share (λ).

Result 2- effects of crop insurance price:

a) a higher crop insurance price (v) will increase the optimal level of RM effort (e), when the preferences exhibit constant $\frac{\partial \boldsymbol{\pi}}{\partial x}$-UA, constant $\frac{\partial \boldsymbol{\pi}}{\partial e}$-UA and constant $\frac{\partial \boldsymbol{\pi}}{\partial v}$-UA; and positive $\frac{\partial \boldsymbol{\pi}}{\partial x}$-PA, positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial e}$-UA, and neutral/negative $\frac{\partial \boldsymbol{\pi}}{\partial v}$-PA;

b) a higher crop insurance price (υ) will reduce the optimal crop insurance demand (x), when the preferences exhibit constant $\frac{\partial \boldsymbol{\pi}}{\partial x}$-UA, constant $\frac{\partial \boldsymbol{\pi}}{\partial e}$-UA and constant $\frac{\partial \boldsymbol{\pi}}{\partial \upsilon}$-UA; and positive $\frac{\partial \boldsymbol{\pi}}{\partial x}$-PA, positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial e}$-UA, and neutral $\frac{\partial \boldsymbol{\pi}}{\partial \upsilon}$-PA.

The results illustrate sufficiency conditions if we are expecting a positive relation between insurance price and optimal RM effort level, and a negative relation between insurance price and optimal amount of insurance purchased. For example, with preference exhibiting constant risk aversion in the directions of $\frac{\partial \boldsymbol{\pi}}{\partial x}, \frac{\partial \boldsymbol{\pi}}{\partial e}, \frac{\partial \boldsymbol{\pi}}{\partial \upsilon}$, as well as positive patience aversion with respect to $\frac{\partial \boldsymbol{\pi}}{\partial x}$, positive/neutral patience aversion with respect to $\frac{\partial \pi}{\partial e}$, and neutral/negative patience aversion with respect to $\frac{\partial \boldsymbol{\pi}}{\partial \upsilon}$, farmers will increase their optimal RM effort in response to an increase in the insurance price.

4. Two-period Intertemporal Decision Model

Since both insurance decisions and RM effort decisions imply a cost now and a delayed benefit, we develop intuition from the intertemporal nature of the decisions by collapsing the structure to a two-period model of crop production, where a farmer's utility is based on immediate, certain cost in insurance purchasing and RM effort in the first period, and the benefits in the second period brought by these two risk control methods.

In each period, the farmer derives utility $U(\pi)$ from the net profit $(U'(\pi) > 0, U''(\pi) < 0)$. Following Laibson (1997), we assume quasi-hyperbolic discounting (QHD) agents with (β, μ)-preferences. The traditional discount factor is $\mu \in (0,1]$ whereas $\beta \in (0,1]$ denote the present-bias factor. The profit function in period 1 is $\pi^0 = -c(e)$. In period 2, there are two mutually exclusive states: the state in which pesticide resistance occurs with probability p^1, $\left(p^1 = p(e), \frac{\partial p}{\partial e} \leq 0\right)$, and the profit is $\pi^1 = I - L(e)$; and the state in which pesticide resistance does not occur with probability $1 - p^1$, and the profit is $\pi^2 = I$.

The goal for this section is to explore how four policy levers (crop insurance price, incentives to reduce present bias, community education to rebuild farmers' subjective resistance risk assessment, and RM cost-sharing subsidy) can be used by policy makers to encourage more sustainable pest management.

Individual farmers live for two periods, $t = 1, 2$. In the first period, a farmer chooses how much effort (e) to devote to RM and how much crop insurance (x) to purchase, with subjective beliefs (γ) about the prospect of resistance in the future period. RM effort reduces the probability (p^1) that pesticide resistance occurs, while crop insurance reimburses a farmer for crop losses when pesticide resistance occurs. The costs of RM efforts ($c(e)$) and crop insurance (υx) are certain and incurred in the first period. In the second period, nature determines whether or not pesticide resistance occurs. In the case where pesticide resistance occurs, the farmer's loss (L) can be reduced by either RM efforts or crop insurance purchased in the first period, or both. If the farmer takes RM effort in period one and pesticide resistance occurs in period two, his RM efforts proportionally subsidized at a given rate(σ). Thus, a QHD farmer maximizes

$$\max_{e \geq 0, x \geq 0} W = U(\pi^0) + \beta\mu\left(\gamma U(\pi^N) + (1-\gamma)\sum_{s=1}^{2} p^s U(\pi^s)\right)$$

s.t. $\quad \pi^0 = -c(e) - \upsilon x$

$$\pi^1 = I - L(e) + r\big(L(e)\big)x + \sigma c(e)$$

$\pi^2 = \pi^N = I$

$p^1 = p(e)$

$p^2 = 1 - p(e)$

$\gamma =$ subjective belief of no resistance for sure. (17)

Values of e and x should be chosen simultaneously to maximize the above state-contingent expected utility function.

Turning to the comparative static effects, we need to solve for $\frac{de^*}{d\beta}, \frac{de^*}{d\gamma}, \frac{de^*}{d\upsilon}, \frac{de^*}{d\sigma}$ and $\frac{dx^*}{d\beta}, \frac{dx^*}{d\gamma}, \frac{dx^*}{d\upsilon}, \frac{dx^*}{d\sigma}$. Applying the definition of the directional marginal substitution coefficients and the Hessian matrix(H), we can arrange the terms in a way that enables us to explore the effect of uncertainty tolerance and patience preference on the optimal RM effort choice and insurance demand.

Result 2 – effects of crop insurance price:

For a farmer facing uncertainty in pesticide resistance and efficacy of RM effort,

a) a higher crop insurance price (υ) will lead to a higher level of optimal RM effort (e) in period 1, when the preferences exhibit increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial x}$-UA and positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial x}$-PA;

b) a higher crop insurance price (υ) will reduce the optimal level of insurance purchased (x) in period 1, when the preferences exhibit increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial e}$-UA and positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial e}$-PA.

Result 3 – effects of present bias:

For a farmer facing uncertainty in pesticide resistance and efficacy of RM effort,

a) a higher present bias (a lower β) will increase the level of optimal RM effort (e) in period 1, when the preferences exhibit increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial x}$-UA and positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial x}$-PA;

b) a higher present bias (a lower β) will reduce the optimal level of insurance purchased (x) in period 1, when the preferences exhibit increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial e}$-UA and positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial e}$-PA.

Result 4 – effects of farmers' subjective resistance risk assessment:

For a farmer facing uncertainty in pesticide resistance and efficacy of RM effort,

a) the preferences exhibiting increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial x}$-UA will reinforce a positive relation between the optimistic belief of pesticide resistance (γ) and the level of optimal RM effort (e); the preferences exhibiting positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial x}$-PA will reinforce a negative relation;

b) the preferences exhibiting increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial e}$-UA will reinforce a negative relation between the optimistic belief of pesticide resistance (γ) and the level of optimal insurance demand (x); while the preferences exhibiting positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial e}$-PA will reinforce a positive relation.

Result 5 – effects of RM cost-sharing subsidy:

For a farmer facing uncertainty in pesticide resistance and efficacy of RM effort,

a) the preferences exhibiting increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial x}$-UA will reinforce a positive relation between the RM effort cost-sharing subsidy (σ) and the level of optimal RM effort (e); the preferences exhibiting positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial x}$-PA will reinforce a negative relation;

b) the preferences exhibiting increasing/constant $\frac{\partial \boldsymbol{\pi}}{\partial e}$-UA will reinforce a negative relation between the RM effort cost-sharing subsidy (σ) and the level of optimal insurance demand (x); while the preferences exhibiting positive/neutral $\frac{\partial \boldsymbol{\pi}}{\partial e}$-PA will reinforce a positive relation.

5. Discussion and Conclusion

Uncertainty tolerances are not time preferences, but uncertainty and time are intertwined. Similarly, farmers' preferences for certainty and patience may vary drastically when provided with different policy levers. Attributing the effects on RM effort and crop insurance demand to Arrow-Pratt coefficients of risk aversion is too simplistic and tells us little about where the risk comes from (uncertainty or impatience), whether such risk should be tamed, and if so, how it should be done. We argue that the marginal rate of substitution holds more information than what Arrow-Pratt's absolute and relative risk aversion can convey.

We characterized the comparative static effects of four policy levers (crop insurance price, related subsidies, incentives to reduce present bias, and community education to rebuild farmers' subjective resistance risk assessment) for increasing RM effort and crop insurance demand by decomposing the effects into directional substitution effects using a state-contingent approach. This motivates us to distinguish between two different types of aversion: tolerance for uncertainty and preference for patience, and compare their contributions to relations between optimums (optimal RM effort and crop insurance demand) and policy levers before any policy changes are made.

Every coin has two sides, and every policy lever may have two effects. A farmer with a higher yield subsidy may invest more in RM efforts, so to ensure himself a long-run, sustainable gain from controlled resistance problem; alternatively, he may also decide to use more pesticide and enjoy the convenience and flexibility it may bring. Presuming that the yield subsidy encourages RM effort will result in faulty analysis, since the effect is heavily relied on the farmer's risk attitude. The same law shall apply to all the other policy levers.

Compared with the difficult determination of a farmer's general risk preference, experiments targeted at certain policy levers are easier to conduct and allow us to make predictions based on the farmer's risk preference. Conjunction with our results, (for example, a preference exhibits decreasing $\frac{\partial \boldsymbol{\pi}}{\partial k}$-UA and negative $\frac{\partial \boldsymbol{\pi}}{\partial k}$-PA manages to reinforce a positive relation between optimal RM effort and yield subsidy), the government agency can modify their method used in insurance design to reflect more information regarding the marginal rate of substitution, and promote the adoption of RM practices in the end.

With an increased emphasis in the U.S. of supporting agriculture through the FCIP, there is increasing interest in using these programs to also promote more sustainable farming practices. Therefore, policy makers who wish to support RM effort must understand the implications of their policies in an uncertain world. Then, policy levers to reduce uncertainty in crop production can be clearly stated and necessary to encourage adoption of RM effort and crop insurance demand.

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Figure 1. Absolute Arrow-Pratt Risk Aversion

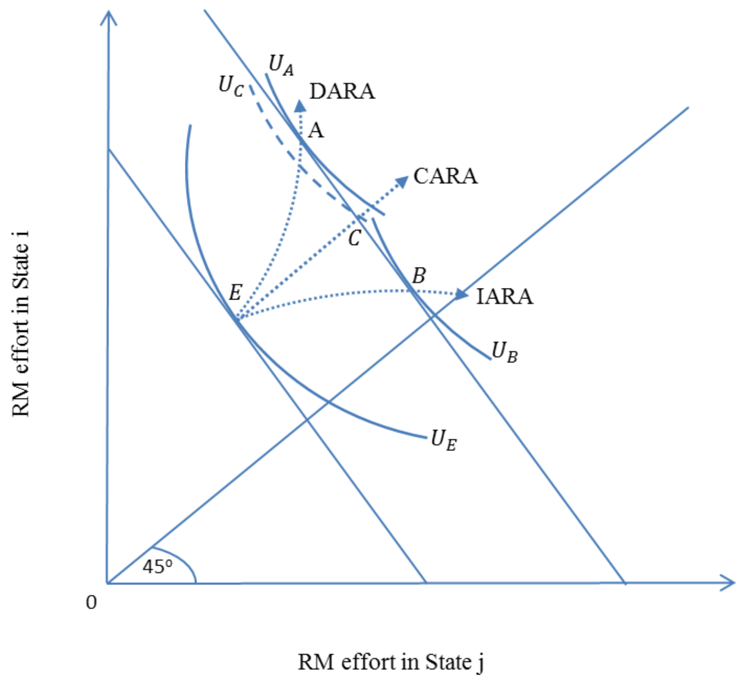

Figure 2. Relative Arrow-Pratt Risk Aversion

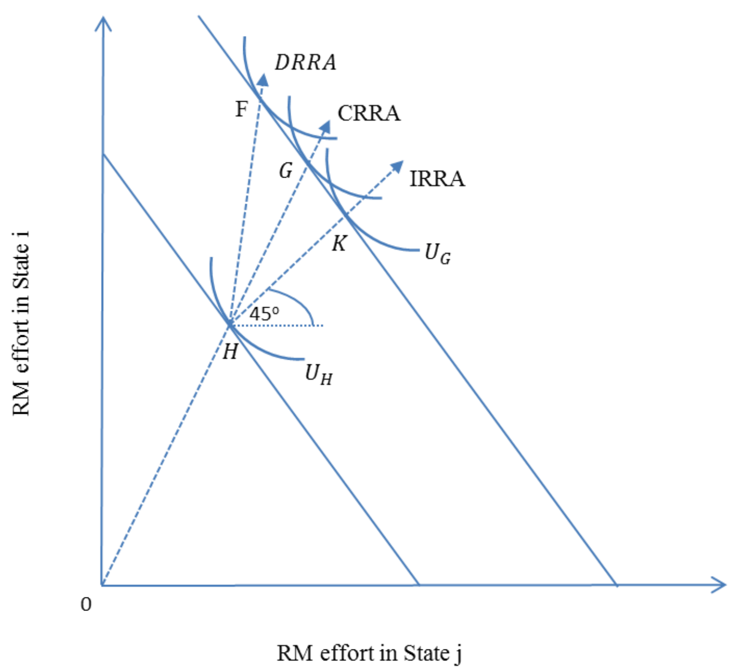

Figure 3. **δ**-uncertainty aversion

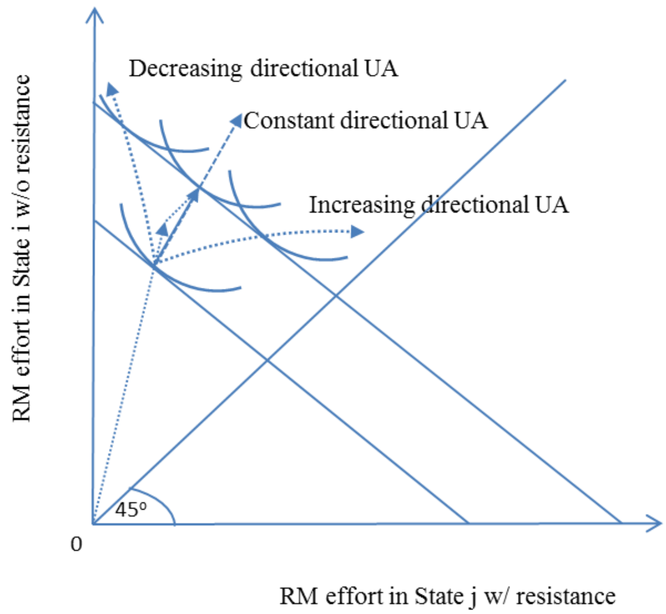

Figure 4. δ-patience aversion