Received: 18 November 2020 | Accepted: 3 September 2021

DOI: 10.1111/ajae.12266

ARTICLE

Trading risk for ambiguity: Production versus health under pesticide application

Daniel C. Voica[1] | **Troy G. Schmitz**[2]

[1]School of Economics and Finance, Massey University, Palmerston North, New Zealand

[2]W.P. Carey Morrison School of Agribusiness, Arizona State University, Phoenix, Arizona, USA

Correspondence
Daniel C. Voica, School of Economics and Finance, Massey University, Palmerston North, New Zealand.
Email: d.voica@massey.ac.nz

Abstract

Pesticide use reduces the variation in crop yields at the expense of potentially negative consequences to farmers and their family members. This article examines the trade-off between decreasing production risk and increasing health ambiguity because of pesticide use. We find that under ambiguity, pesticide application decreases the variation in health outcomes, whereas under risk, it decreases the expected value of health outcomes. Health insurance protects health from the pesticide damage but not from the ambiguity effect of pesticide application, and the optimal choice of pesticide application does not depend on the farmer's health preferences over risk or ambiguity. However, in the absence of health insurance, ambiguity can increase or decrease the optimal choice of pesticide compared to the risk case. This suggests that public policies around pesticide usage should be designed to reflect and account for the multitude of behavioral responses in the presence of ambiguity and risk.

KEYWORDS

ambiguity, chlorpyrifos, glyphosate, health, pesticide, producers, roundup, uncertainty

JEL CLASSIFICATION

D21, I12, Q12, Q18

1 | INTRODUCTION

In general, risk averse agents prefer to reduce risk at the expense of lower expected returns. However, examples abound where, rather than trading risk for expected returns, agents make decisions based on trade-offs between returns and health outcomes. A prevalent example from agriculture is pesticide use. The use of pesticide reduces the variation in crop yields at the expense of potentially negative health effects due to higher concentration of chemicals.

Although there is an extensive literature on the specification of technologies containing damage-control inputs and the role of risk involving pesticides (Carrasco-Tauber & Moffit, 1992; Chambers et al., 2010; Chambers & Lichtenberg, 1994; Fox & Weersink, 1995; Lansink & Carpentier, 2008; Lansink & Silva, 2004; Lichtenberg & Zilberman, 1986; Norwood & Marra, 2003; Saha et al., 1997; Wechsler & Smith, 2018), there is a lack of consensus regarding the size and direction of health effects associated with pesticide use.

The epidemiological literature has found evidence that exposure to pesticides is correlated with a variety of health issues including, but not limited to, depression (Beseler et al., 2008), increased risk of cancer (Alavanja et al., 2004; Engel et al., 2005; Fleming et al., 2003; Flower et al., 2004), chronic bronchitis (Hoppin et al., 2007; Ye et al., 2013), adverse birth outcomes (Larsen et al., 2017; Shirangi et al., 2011), and increased risk of neurologic dysfunction (Alavanja et al., 2004; Li et al., 2014) among farmers and their family members (Kamel et al., 2000; Kirrane et al., 2005). However, inadequate assessment of pesticide exposure due to methodological and ethical constraints is a major limitation of pesticide epidemiology and a source of scientific ambiguity regarding the health effects of pesticide (Alavanja et al., 2004; Larsen et al., 2017; Shirangi et al., 2011).[1] Moreover, the opposing stances taken by the World Health Organization and the Environmental Protection Agency regarding the risk of cancer associated with glyphosates have brought the issue of pesticide use back into the limelight and amplified the ambiguity surrounding their health effects (Environmental Protection Agency [EPA], 2019; WHO, 2015). The lack of an official consensus regarding the implications of pesticide use for human health suggests these effects may be perceived by farmers as ambiguous in the sense of Gilboa and Schmeidler (1989).

This article explores the trade-off between production risk and health ambiguity in the case of pesticide use. Pesticide use can be viewed as a form of crop insurance because farmers benefit from pesticide protection only if one of the "pest" infestation states is selected by nature. However, independent of the pest infestation, once pesticides are applied, the farmer also "buys" into a health lottery, where in some states of nature, health outcomes decrease. Hence, there is a trade-off between decreasing production risk and increasing health ambiguity.

Our analysis of farmers' optimal choice of pesticide application and its subsequent health effects in the presence of ambiguity is motivated by two considerations. First, the need to understand the role played by ambiguity in farmers' decisions is recognized as one of the challenges of current research in agricultural economics (Chavas et al., 2010). However, as far as we are aware, to date, only a few studies have dealt with ambiguity in agricultural economics, and they are largely confined to applications outside pesticide usage. Among these, ambiguity has been analyzed in the context of agricultural technology adoption (Barham et al., 2014; Warnick et al., 2011), environment externalities and climate change (Alpizar et al., 2011; Chambers & Melkonyan, 2017; Cheve & Congar, 2000), food safety (Chambers & Melkonyan, 2007, 2013; Melkonyan & Schubert, 2009), and structural estimation of farmers' ambiguity preferences (Bougherara et al., 2017). Two notable exceptions are Hou et al. (2020) and Couture et al. (2018). Using experimental data, Hou et al. (2020) find that ambiguity measures are more appropriate than risk measures in describing farmer's behavior because the probability distribution over the consequences of pesticide use are unknown to farmers. Couture et al. (2018) investigate the impact of information in reducing the ambiguity of pesticide use.

Second, we contribute to the pesticide literature by providing a conceptualized model of farmers' production and health behavior in the presence of risk and ambiguity. In doing so, we connect the epidemiological literature concerning the pesticide effects with the pesticide production literature. It

---

[1] For example, reviews of the epidemiological literature found evidence supporting an association between pesticide exposure and human cancer but failed to identify a causal relation between the two (Alavanja et al., 2004). Some of the reasons are the lack of high-quality evidence from epidemiologic studies (e.g., sample size, confounding effects due to application of multiple chemicals by farmers, lack of randomize control trials) and ambiguity regarding extrapolating animal bioassay data to humans or validity of biologic markers of exposure (Alavanja et al., 2004; Larsen et al., 2017).

has been recognized that farmers face a trade-off between health during pesticide application and the pressure to produce. For example, Perry and Bloom (1998), following a qualitative investigation of pesticide usage by farmers in Wisconsin, conclude that "it is the immediacy of farm sustainability that impacts directly on health attitudes and perceptions, as though health is another farm commodity, and therefore is potentially expendable." Hence, casting the choice of pesticide application as a trade-off between production gains and health losses under risk and ambiguity, respectively, may help inform and design the public policy. We show that farmers' choices under risk differ from those under ambiguity, hence sound public policy designed to alleviate the negative health effects of pesticides must be informed and account for the difference in farmer's beliefs. This may help explain why, although farmers are aware of the hazard impose by pesticides, their perceptions of relative hazard differ from those of WHO even after controlling for age, education, and farm size (Devi, 2009; Pingali & Roger, 1995).

Analyzing farmer's optimal pesticide choices in the presence of production risk and health ambiguity provides insights that may help guide and inform policy in the area of pesticide externalities. This is further supported by the fact that most U.S. farms are family run (ERS, 2006), and most pesticide users are farmers (Wilson & Tisdell, 2001). Hence, although the health externality associated with pesticide use is important (Harper & Zilberman, 1989; Paul et al., 2002; Perry & Moschini, 2020; Pimentel et al., 1992; Pimentel & Burges, 2014; Tilman et al., 2002; Wilson & Tisdell, 2001), this article investigates the private, rather than the social, optimal choice of pesticide among farmers.

We propose a two-period state contingent model where a rational farmer maximizes expected utility over consumption and maxmin expected utility over health. We find that under ambiguity, pesticide application decreases the absolute health risk (i.e., the gap between health outcomes), whereas under risk, it decreases the expected value of health outcomes. Health insurance insulates health outcomes from the pesticide damage but not from the ambiguity effect of pesticide application. Under risk, health insurance uptake increases, whereas under ambiguity the uptake can increase or decrease compared to the insurance uptake under risk. In the presence of health insurance, the optimal choice of pesticide application does not depend on the farmer's health preferences over risk or ambiguity. However, in the absence of health insurance, ambiguity can increase or decrease the optimal choice of pesticide compared to the risk case. Expected consumption increases under pesticide application, but the effect on the absolute consumption risk (the gap between state contingent consumptions) is undetermined.

The article is structured as follows. The model is introduced in the first section. The second and third sections present the production and health effects of pesticide usage. A comparison of ambiguity and risk effects on health outcomes is performed in the fourth section. A fifth section concludes the article.

2 | THE MODEL

In this setup, a competitive farmer facing a stochastic technology and health insurance optimizes her consumption, health, and production choices over two periods. The first period, 0, is certain, whereas the second period, 1, is uncertain. Uncertainty over the second period is represented by a finite set of states $\Omega \equiv \Lambda \times \Theta$, where Λ is the set of consumption states, and Θ is the set of health states. In the terminology of decision theory, states represent complete and mutually exclusive descriptions of the world. Table 1 illustrates the set Ω, where for simplicity $\Lambda = \{1,2,\dots,S\}$ and $\Theta = \{1,2,\dots,T\}$, and the numbers can be thought of as indexing mutually exclusive descriptions of consumption and health, respectively. For example, an intuitive interpretation of the states in Ω, for illustrative purposes say states (1,1) and (2,1), can be ("bad weather conditions for agriculture," "particles bearing strong winds") and ("slightly better weather conditions for agriculture," "particles bearing strong winds"), respectively. Uncertainty is resolved by an unbiased entity, nature, choosing

TABLE 1 Description of the states set Ω

$\Lambda \backslash \Theta$	**1**	**2**	…	**T**
1	(1,1)	(1,2)	…	(1,T)
2	(2,1)	(2,2)	…	(2,T)
⋮	⋮	⋮	…	⋮
S	(S,1)	(S,2)	…	(S,T)

from Ω. The state choice is revealed after the farmer makes all the relevant consumption, health, and production decisions, hence the uncertainty.

In the first period consumption is denoted by $q_0 \in \mathbb{R}_{++}$, whereas the second period consumption–health bundle is denoted by (q,h), where $q \in \mathbb{R}_{++}^{\Lambda}$ represents consumption resulting from productive activities (i.e., agricultural production), and $h \in \mathbb{R}_{++}^{\Theta}$ represents stochastic health outcomes. To keep the analysis simple, we assume that q and h are two dimensional vectors (that is, $|\Lambda| = 2$ and $|\Theta| = 2$, hence $|\Omega| = 4$).

The farmer is competitive and takes the input prices, $w \in \mathbb{R}_{++}^{N}$, and output price, $p = (p_1, p_2) \in \mathbb{R}_{++}^{\Lambda}$, as given.[2] To preserve simplicity, we assume $p_1 = p_2$ and normalized the remaining prices by the output price.[3] In the first period, the farmer starts with initial wealth endowments $\omega_0 > 0$ and chooses the optimal levels of stochastic period 1 output $z = (z_1, z_2) \in \mathbb{R}_{+}^{\Lambda}$, pesticide $\delta \in \mathbb{R}_{+}$, and the first and second period consumption and health, q_0, $q = (q_1, q_2)$ and $h = (h_1, h_2)$, by making the appropriate agricultural and health production decisions.

Production is characterized by a stochastic technology. More formally, technology is represented by an input correspondence $X : \mathbb{R}_{+}^{\Omega} \rightarrow R_{+}^{N}$ which maps state-contingent outputs and health outcomes into inputs sets capable of producing them. Specifically, the technology is defined as $X(z,h) = \{x \in R_{+}^{N} | x \text{ can produce } (z,h) \in \mathbb{R}_{+}^{\Omega}\}$ where $x \in R_{+}^{N}$ are inputs. The period 0 cost function associated with this technology is $c(w, z_1, z_2, h_1, h_2) = \min_x \{wx : x \in X(z,h)\}$. This cost function is an extension of Chambers and Quiggin's (2000, 2001) cost function and is assumed convex in both z and h.[4]

With probability π_q, nature selects the consumption state where the pest affects the agricultural yields. *Ex-ante* the farmer can choose to apply pesticide $\delta \in \mathbb{R}_{+}$ in order to protect against the yield loss. Applying pesticide has two effects. First, δ increases the yield in the "pest" consumption state by $f(\delta)$ for a state contingent output equal to $z_1 f(\delta)$, where z_1 is the state contingent agricultural output when $\delta = 0$, and $f(\delta)$ is a smooth and concave production function of δ with $f(\delta) > 1$ for a positive δ. The pesticide application has no effect on the output in the "no pest" consumption state.

Second, the pesticide δ reduces the health output from h_1 to $h_1 g(\delta)$, where h_1 is the health outcome corresponding to the "pesticide damage" health state when $\delta = 0$, and $g(\delta)$ is a convex damage function of δ with $g(\delta) < 1$ for a positive δ. In the absence of pesticide application, $\delta = 0$, nature chooses the health state corresponding to h_1 with probability π_h and h_2 with probability $1 - \pi_h$, reflecting the risk embedded in health outcomes. Once the pesticide is applied, $\delta > 0$, the farmer's perception of nature's choice becomes ambiguous. That is, the farmer's beliefs about the first health state in Θ are characterized by a closed probability interval $[\pi_l, \pi_u] \subseteq [0,1]$ rather than just π_h as before. Instead of a single probability measure, the farmer associates multiple probability measures with the set of health states Θ.

---

[2] Vectors are written in column format. For example, $p = (p_1, p_2)$ is a column vector, whereas $p^T = (p_1, p_2)^T$ is a row vector.

[3] We are grateful to an anonymous reviewer for suggesting this simplification.

[4] Our approach to modeling health decisions follows the same rationale as the "pool player" analogy that is part of Milton Friedman's rationale for modeling the behavior of economic agents (consumers, producers, etc.) as the optimization of some objective function. As in the case of the pool player in Milton Friedman's analogy, we do not believe that farmers act in the selection of their health outcomes the same way they do in the selection of, say, their stochastic agricultural outcome, but as long as our assumptions help explain and predict their health behavior, these assumptions are useful.

Finally, the farmer can purchase health insurance coverage $\gamma \in \mathbb{R}_{+}$ for the period 0 price $v_h \in \mathbb{R}_{++}$, where the insurance is represented by the functional

$$I = \left(I_1 1_{h_1 g(\delta) \leq h}, I_2 1_{h_2 \leq h}\right)) \tag{1}$$

$1_{h_1 \leq h_2}$ is an indicator function, which equals 1 if $h_1 g(\delta) \leq h$ and 0 otherwise, $1_{h_2 \leq h}$ equals 1 if $h_2 \leq h$ and 0 otherwise, and h is a health threshold.[5]

Farmer's preferences over consumption have the expected utility form and her preferences over health have Gilboa and Schmeidler (1989) maxmin expected utility (MEU) form.[6] Preferences over consumption and health are represented by the functional

$$W\left(q_0, q, \widetilde{h}\right) = \max_{q_0, q, \widetilde{h}} \left\{ q_0 + \beta_q E_{\pi_q}[u(q)] + \beta_h \min_{\pi \in [\pi_l, \pi_u]} \left\{ E_\pi \left[v\left(\widetilde{h}\right)\right]\right\}\right\} \tag{2}$$

where $u(\cdot)$ and $v(\cdot)$ are smooth, strictly increasing and strictly concave functions, β_r and β_h are discount factors, and $\widetilde{h} = (\widetilde{h}_1, \widetilde{h}_2)$. A MEU farmer reacts to ambiguity by evaluating every stochastic health outcome using the probability distribution that yields the lowest expected utility among all probability distributions from the probability interval $[\pi_l, \pi_u]$. Thus, a MEU farmer exhibits complete pessimism over each stochastic health outcome (i.e., she believes the worse health outcome has the highest likelihood to occur). In addition, to simplifying comparisons with previous work (Chambers, 2007; Chambers & Melkonyan, 2013), the MEU was chosen because it is a *subjectively rational* framework (Gilboa et al., 2010). Subjectively rational implies that a farmer cannot be convinced by others that her decisions are wrong. The practical consequence is that under MEU, decision makers are more progressive in adopting damage mitigating policies compared to other type of ambiguity alternatives such as incomplete expected utility (Chambers & Melkonyan, 2017). As such, MEU provides a lower bound in terms of health damages and a baseline for other type of ambiguity investigations.

In the first period, the farmer chooses $q_0 \in \mathbb{R}_{++}$, $q = (q_1, q_2) \in \mathbb{R}^2_{++}$, $z = (z_1, z_2) \in \mathbb{R}^2_{++}$, $\widetilde{h} = (\widetilde{h}_1, \widetilde{h}_2) \in \mathbb{R}^2_{++}$, $h = (h_1, h_2) \in \mathbb{R}^2_{++}$, $\gamma \in \mathbb{R}_{+,}$ and $\delta \in \mathbb{R}_{+}$ to[7]

$$\max \left\{ q_0 + \beta_q E_{\pi_q}[u(q)] + \beta_h \min_{\pi \in [\pi_l, \pi_u]} \left\{ E_\pi \left[v\left(\widetilde{h}\right)\right]\right\} : \right. \tag{3}$$

$$q_0 \leq \omega_0 - c(w, z_1, z_2, h_1, h_2) - v_\delta \delta - v_h \gamma, \tag{4}$$

$$q_1 \leq z_1 f(\delta), \tag{5}$$

$$q_2 \leq z_2, \tag{6}$$

$$\widetilde{h}_1 \leq h_1 g(\delta) + \gamma I_1 1_{h_1 g(\delta) \leq h}, \tag{7}$$

$$\left. \widetilde{h}_2 \leq h_2 + \gamma I_2 1_{h_2 \leq h}, \right\} \tag{8}$$

---

[5] We are grateful to the editor for suggesting this representation of the health insurance.

[6] Recent studies have shown that prospect theory (PT) may be a better approximation of farmers' preferences over consumption. We decided on the expected utility framework for two reasons. First, it provides more conservative results (i.e., our results are strengthened by the PT). Second, expected utility allows for a natural comparison to the Gilboa and Schmeidler (1989) maxmin expected utility (MEU).

[7] Alternative specifications for the pesticide damage are available. For example, $r_1 + f(\delta, r_1/p_1)$ instead of $r_1 f(\delta, r_1/p_1)$, and $h_1 - g(\delta)$ instead of $h_1 g(\delta)$. However, the pesticide literature subscribes to a multiplicative function representation of the damage. For consistency with previous work, we adopted this specification.

The optimization problem has five constraints: budget constraints for the first and second periods (inequality (4) and inequalities (5) and (6), respectively), and health constraints (inequalities (7) and (8)).

The first budget constraint requires period 0 consumption, q_0, to be no larger than the difference between the initial wealth endowment, ω_0, and the combined costs of producing the output–health bundle, $c(w,z_1,z_2,h_1,h_2)$, the cost of purchasing the pesticide, $\nu_\delta \delta$, and the health insurance cost, $\nu_h \gamma$. The second period budget constraints require the available consumption in each state of nature to be bounded by the state-contingent agricultural returns, $z_1 f(\delta)$ and z_2, respectively. Similarly, health outcomes in each state of nature are bounded by the health generated via the stochastic technology, $h_1 g(\delta)$ and h_2, and health insurance, $I_1 1_{h_1 g(\delta) \leq h}$ and $I_2 1_{h_2 \leq h}$. The budget and health constraints are binding because utility is strictly increasing in consumption and health.

3 | PRODUCTION EFFECTS

In this section, we briefly analyze the production effects of pesticide application.[8] The first order conditions for determining the optimal stochastic output z_1 and z_2 in the presence of pesticide application, $\delta > 0$, are

$$\beta_q \pi_q \frac{\partial u(q_1)}{\partial q_1} f(\delta) = \frac{\partial c(w,z_1,z_2,h_1,h_2)}{\partial z_1} \tag{9}$$

and

$$\beta_q (1 - \pi_q) \frac{\partial u(q_2)}{\partial q_2} = \frac{\partial c(w,z_1,z_2,h_1,h_2)}{\partial z_2} \tag{10}$$

respectively, where $q_1 = z_1 f(\delta)$ and $q_2 = z_2$ because utility is strictly increasing in consumption. In (9) and (10), the optimal outputs z_1 and z_2 are determined by equating the marginal cost of producing z_1 and z_2, $\partial c(w,z_1,z_2,h_1,h_2)/\partial z_1$ and $\partial c(w,z_1,z_2,h_1,h_2)/\partial z_2$, respectively, with the discounted marginal utility of consumption q_1 times the pesticide effect $f(\delta)$ and the discounted marginal utility of consumption q_2, $\beta_q \pi_q (\partial u/\partial q_1) f(\delta)$ and $\beta_q (1 - \pi_q)(\partial u/\partial q_2)$, respectively.

To simplify the analysis, no complementarities (substitution) effects between health and production outcomes are assumed throughout the paper.[9] Denote by $z_1^{\star\,\delta=0}$ the optimal output z_1 in the absence of pesticide application and $z_1^{\star\,\delta>0}$ the optimal output z_1 under pesticide application. Similarly, denote $z_2^{\star\,\delta=0}$ and $z_2^{\star\,\delta>0}$. By assumption $f(\delta) > 1$, and it follows that

$$\beta_q \pi_q \frac{\partial u\left(z_1^{\star\,\delta=0}\right)}{\partial q_1} f(\delta) > \beta_q \pi_q \frac{\partial u\left(z_1^{\star\,\delta=0}\right)}{\partial q_1} = \frac{\partial c\left(w, z_1^{\star\,\delta=0}, z_2, h_1, h_2\right)}{\partial z_1} \tag{11}$$

implying $z_1^{\star\,\delta>0} f(\delta) > z_1^{\star\,\delta=0}$ (that is, the optimal consumption in the "pest" consumption state increases under pesticide application). Pesticide application has no effect on expression (10), the first order condition governing the optimal choice of output z_2, and $z_2^{\star\,\delta>0} = z_2^{\star\,\delta=0} = z_2^{\star}$. Hence, pesticide application increases the expected consumption, $E(q^{\delta>0}) > E(q^{\delta=0})$, where $q^{\delta>0} = \left(q_1^{\delta>0}, q_2^{\delta>0}\right)$ and $q^{\delta=0} = \left(q_1^{\delta=0}, q_2^{\delta=0}\right)$. The farmer's *absolute consumption risk*, the gap between q_1 and q_2

---

[8] The case where the farmer has access to financial markets in addition to the stochastic technology is available in the online Appendix S1.

[9] Formally, no complementarities (substitution) effects require $\partial^2 c/\partial h_1 \partial h_2 = 0$, $\partial^2 c/\partial z_1 \partial z_2 = 0$ and $\partial^2 c/\partial h_i \partial z_j = 0$, where $i,j = 1,2$) where c denotes the cost function $c(w,z_1,z_2,h_1,h_2)$). Allowing for complementarities (substitution) does not enrich the analysis in a meaningful way.

(Bikhchandani et al., 2013), reacts to the pesticide application. If $z_2^\star > \left[z_1^{\star\,\delta>0} f(\delta) + z_1^{\star\,\delta=0}\right]/2$, then the absolute consumption risk decreases under pesticide application compared to no pesticide application.[10] The opposite is true if $z_2^\star < \left[z_1^{\star\,\delta>0} f(\delta) + z_1^{\star\,\delta=0}\right]/2$.

Result 1. Pesticide application increases the expected consumption, $E(q^{\delta>0}) > E(q^{\delta=0})$, whereas the absolute consumption risk decreases if the output in the no-pest consumption state is strictly greater than the simple mean of the before and after pesticide application outputs in the pest consumption state, $z_2^\star > \left[z_1^{\star\,\delta>0} f(\delta) + z_1^{\star\,\delta=0}\right]/2$, and increases if the inequality is reversed.

The pesticide effect on output choice z_1 depends on the concavity of the utility function. For example, $z_1^{\star\,\delta>0} = z_1^{\star\,\delta=0}$ if

$$\beta_q \pi_q \frac{\partial u\left(z_1^{\star\,\delta=0} f(\delta)\right)}{\partial q_1} f(\delta) = \beta_q \pi_q \frac{\partial u\left(z_1^{\star\,\delta=0}\right)}{\partial q_1} \tag{12}$$

Although the optimal choices of output z_1 and pesticide δ are simultaneously decided by the farmer, analytically the effect of pesticide on output can be thought of comprising two parts. First, the pesticide scales up the marginal utility of consumption like in (9) (the utility effect), while decreasing the marginal utility of consumption due to scaling up the consumption $q_1 = z_1 f(\delta)$ (the consumption effect). As such, the optimal choice of z_1 depends on which of the two effects dominate. For a small perturbation of pesticide δ in (12), the expression becomes

$$\frac{\partial^2 u\left(z_1^{\star\,\delta=0} f(\delta)\right)}{\partial q_1^2} z_1^{\star\,\delta=0} f(\delta) = -\frac{\partial u\left(z_1^{\star\,\delta=0} f(\delta)\right)}{\partial q_1} \tag{13}$$

which can written in the more familiar form of the Arrow-Pratt measure of relative risk aversion

$$R\left(z_1^{\star\,\delta=0} f(\delta)\right) = -z_1^{\star\,\delta=0} f(\delta) \frac{u''\left(z_1^{\star\,\delta=0} f(\delta)\right)}{u'\left(z_1^{\star\,\delta=0} f(\delta)\right)} = 1 \tag{14}$$

When $R\left(z_1^{\star\,\delta=0} f(\delta)\right) < 1$, the utility effect dominates the consumption effect and $z_1^{\star\,\delta>0} > z_1^{\star\,\delta=0}$, whereas the opposite is true when $R\left(z_1^{\star\,\delta=0} f(\delta)\right) > 1$. The advantage of casting the effect of pesticide on the output z_1 in terms of the Arrow-Pratt coefficient of relative risk aversion is that it provides an accessible testable condition for data oriented investigations.

Result 2. The optimal output in the pest consumption state, z_1, increases under pesticide application if the pesticide application scales up the marginal utility by more than the scaling up of output z_1 due to pesticide application decreases the marginal utility.

4 | HEALTH EFFECTS

In this section, we analyze the health effects of pesticide application and compare the health effects of pesticide under ambiguity to the health effects of pesticide under risk. First, we consider the case when health insurance is triggered in all states of nature, $I = (I_1, I_2)$. Second, we consider the case

---

[10] The proof of this statement is as follows. Because $z_1^{\star\,\delta>0} f(\delta) > z_1^{\star\,\delta=0}$, the absolute risk decreases only if $z_1^{\star\,\delta=0} < z_2^\star$. There are two cases. First, if $z_1^{\star\,\delta>0} f(\delta) \le z_2^\star$, then $z_1^{\star\,\delta>0} f(\delta) + z_1^{\star\,\delta=0} < 2z_2^\star$ and the result follows. Second, if $z_1^{\star\,\delta>0} f(\delta) > z_2^\star$, then the absolute risk decreases only if $z_2^\star - z_1^{\star\,\delta=0} > z_1^{\star\,\delta>0} f(\delta) - z_2^\star$ from where, by rearrangements, it follows $z_1^{\star\,\delta>0} f(\delta) + z_1^{\star\,\delta=0} < 2z_2^\star$ and the result follows.

when health insurance is not available or when the insurance is available, but it is not triggered by the farmers' health decisions (i.e., $h_1 g(\delta) > h$ and $h_2 > h$).

Under ambiguity, the farmer's beliefs about the "pesticide damage" health state are captured by the closed interval $[\pi_l, \pi_u]$ rather than the probability $\pi_r \in (\pi_l, \pi_u)$ as in the case of risk.[11] A farmer with MEU preferences solves the ambiguity by maximizing the minimum expected value of health outcomes over the probability interval $[\pi_l, \pi_u]$. If $\widetilde{h}_1 \leq \widetilde{h}_2$, then $\pi = \pi_u$ implies the lowest expected value $E_\pi[u(\widetilde{h})]$ compared to any other $\pi \in [\pi_l, \pi_u]$. Similarly, if $\widetilde{h}_1 > \widetilde{h}_2$, then π_l corresponds to a probability distribution that minimizes the expected value of health outcomes.

The first order conditions for determining the optimal health outcomes h_1 and h_2 and net health outcomes $\widetilde{h}_1$ and $\widetilde{h}_2$ in the presence of pesticide application, $\delta > 0$, and health insurance, $I = (I_1, I_2)$, are

$$P_1^h g(\delta) = \frac{\partial c(w, z_1, z_2, h_1, h_2)}{\partial h_1} \tag{15}$$

$$P_2^h = \frac{\partial c(w, z_1, z_2, h_1, h_2)}{\partial h_2} \tag{16}$$

and

$$P_1^h = \beta_h \pi \frac{\partial v\left(\widetilde{h}_1\right)}{\partial \widetilde{h}_1} \tag{17}$$

$$P_2^h = \beta_h (1 - \pi) \frac{\partial v\left(\widetilde{h}_2\right)}{\partial \widetilde{h}_2} \tag{18}$$

respectively, where $P_1^h = v_h I_1 / (I_1 + I_2)^2$ and $P_2^h = v_h I_2 / (I_1 + I_2)^2$ are state-contingent stochastic discount factors induced by the health insurance. In equations (15) and (16), the optimal health outcomes h_1 and h_2 are determined by equating the marginal effort of producing h_1 and h_2 with the stochastic discount factor P_1^h times the pesticide damage, $g(\delta)$, and stochastic discount factor, P_2^h, respectively. In equations (17) and (18), the optimal net health outcomes $\widetilde{h}_1$ and $\widetilde{h}_2$ are determined by equating the discounted marginal utility over health $\widetilde{h}_1$ and $\widetilde{h}_2$ with the stochastic discount factors.

Independent of risk or ambiguity, the pesticide application affects equally the health outcome h_1 via the direct effect $g(\delta)$ in (15). The optimal health outcome h_1 under pesticide application, $h_1^{\star\,\delta>0}$, is lower than the optimal health output h_1 in the absence of pesticide, $h_1^{\star\,\delta=0}$, because by assumption $g(\delta) < 1$. Pesticide damage $g(\delta)$ reduces the marginal value of effort that applies toward the health outcome h_1 (i.e., P_1^h is scaled down by $g(\delta)$ reducing the marginal valuation of h_1). In the absence of complementarities or substitution effects in health outcomes across states, the optimal health outcome h_2 is unaffected by pesticide application in (16).

In addition, health insurance separates the health outcome choices h_1 and h_2, equations (15) and (16), from net health outcome choices $\widetilde{h}_1$ and $\widetilde{h}_2$, equations (17) and (18). As such, the pesticide effect (i.e., the direct damage effect $g(\delta)$) does not change the optimal net health effects $\widetilde{h}_1$ and $\widetilde{h}_2$.

Result 3. Under pesticide application, $\delta > 0$, the health outcome in the pesticide damage health state, h_1, decreases independent of ambiguity and risk. Health insurance insulates the net health

---

[11] The choice may seem arbitrary considering π_h could be higher than π_u or lower than π_l. However, the choice $\pi_h \in [\pi_l, \pi_u]$ is consistent with the idea that $[\pi_l, \pi_u]$ equals $[0,1]$ as ambiguity becomes extremely severe. Hence, $\pi_h \in [\pi_l, \pi_u]$ seems the more reasonable choice of the three.

outcomes $\widetilde{h}_1$ and $\widetilde{h}_2$ from the pesticide damage $g(\delta)$ and, in the absence of complementarities or substitution effects between health outcomes across states of nature, the health outcome h_2 does not respond to pesticide damage.

Because of health insurance induced separation, the farmer reacts to the direct pesticide damage $g(\delta)$, by increasing the health insurance participation and reducing the effort put towards the affected health outcome, h_1. Specifically,

$$\gamma = \frac{P_1^h}{v_h}\left(\widetilde{h}_1 - h_1 g(\delta)\right) + \frac{P_2^h}{v_h}\left(\widetilde{h}_2 - h_2\right) \tag{19}$$

and total differentiating (19) results in

$$d\gamma = \frac{P_1^h}{v_h}\left(d\widetilde{h}_1 - g(\delta)dh_1 - h_1 g_\delta \delta\right) + \frac{P_2^h}{v_h}d\widetilde{h}_2 \tag{20}$$

where $d\delta = \delta$ because we compare the case of zero pesticide with $\delta > 0$ and $dh_2 = 0$ because independent of risk or ambiguity the pesticide has no effect on the optimal health outcome h_2 in (16).

Under risk, probability $\pi = \pi_r$ and the pesticide application does not change the optimal values of $\widetilde{h}_1$ and $\widetilde{h}_2$ because of the health insurance induced separation in (17) and (18). As such, the change in insurance under risk, $d\gamma_r$, equals

$$d\gamma_r = -\frac{P_1^h}{v_h}\left(g(\delta)dh_1 + h_1 g_\delta \delta\right) > 0. \tag{21}$$

Under ambiguity, probability $\pi \neq \pi_r$ and the pesticide application affects both $\widetilde{h}_1$ and $\widetilde{h}_2$ in (17) and (18) despite the health insurance separation. For example, if $\pi = \pi_l < \pi_r$, the case $\pi = \pi_u > \pi_r$ is treated similarly, the optimal net health outcomes $\widetilde{h}_1$ and $\widetilde{h}_2$ under ambiguity, $\widetilde{h}_1^a$ and $\widetilde{h}_2^a$, are lower and higher, respectively, than the optimal net health outcomes $\widetilde{h}_1$ and $\widetilde{h}_2$ under risk, $\widetilde{h}_1^r$ and $\widetilde{h}_2^r$. Because $\pi_l/\pi_r < 1$, the marginal utility $\partial v(\widetilde{h}_1)/\partial \widetilde{h}_1$ must increase in (17) for the equation to hold and the optimal $\widetilde{h}_1$ decreases under ambiguity compared to risk. Similarly for $\widetilde{h}_2$. Health insurance insulates health outcomes h_1 and h_2 from the ambiguity effect (i.e., change in the probability distribution over health states). In (15) and (16), h_1 and h_2 do not respond to the ambiguity driven changes in the probability π because of the separation induced by the health insurance.

Furthermore, the absolute health risk between net health outcomes (i.e., the gap between $\widetilde{h}_1$ and $\widetilde{h}_2$) decreases under ambiguity, $\widetilde{h}_1^r > \widetilde{h}_1^a > \widetilde{h}_2^a > \widetilde{h}_2^r$, because $\widetilde{h}_1^a > \widetilde{h}_2^a$ for $\pi = \pi_l$. The change in the absolute health risk suggests farmers become more cautious with their health in the presence of ambiguity. This is due to the change in farmer's beliefs over the distribution of states of nature. Ambiguity changes the probability of the pesticide event to $\pi_l < \pi_r$, decreasing the marginal valuation of $\widetilde{h}_1$ compared to $\widetilde{h}_2$ (i.e., for $\widetilde{h}_2$ probability increases from $1 - \pi_r$ to $1 - \pi_l$). When $\pi = \pi_u > \pi_r$ the inequality is reversed $\widetilde{h}_1^r < \widetilde{h}_1^a < \widetilde{h}_2^a < \widetilde{h}_2^r$, but the absolute health risk between net health outcomes still decreases compared to risk.

Under ambiguity, the change in health insurance includes the pesticide effect (i.e., the direct effect of the damage function $g(\delta)$) but also the ambiguity effect via the change in probability π, and it equals

$$d\gamma_a = d\gamma_r + \frac{P_1^h}{v_h}d\widetilde{h}_1 + \frac{P_2^h}{v_h}d\widetilde{h}_2 = d\gamma_r + \beta_h\left(\pi_l \frac{\partial v\left(\widetilde{h}_1\right)}{\partial \widetilde{h}_1}d\widetilde{h}_1 + (1-\pi_l)\frac{\partial v\left(\widetilde{h}_2\right)}{\partial \widetilde{h}_2}d\widetilde{h}_2\right) \tag{22}$$

where the second equality follows from the first order conditions (17) and (18). Under ambiguity, insurance uptake can increase or decrease compared to the risk. For example, suppose $\pi_l \cong 0$, then

$$d\gamma_a \cong d\gamma_r + \beta_h(1-\pi_l)\frac{\partial v(\tilde{h}_2)}{\partial \tilde{h}_2} d\tilde{h}_2 > d\gamma_r \tag{23}$$

similarly, suppose $\pi_l \cong 1$ (not 1 but close to 1), then

$$d\gamma_a \cong d\gamma_r + \beta_h \pi_l \frac{\partial v(\tilde{h}_1)}{\partial \tilde{h}_1} d\tilde{h}_1 < d\gamma_r \tag{24}$$

In the presence of a health insurance, the farmer externalizes the health damage due to pesticide application. The extent to which the reliance on health insurance increases depends on whether the farmer perceives the health damage as risky or ambiguous, and on the direction of ambiguity. This suggests that public policy designed to mitigate the health effects of pesticide application must also deal with implications of farmers preferences for risk and ambiguity. In addition, identifying whether risk or ambiguity plays a role in farmer's health decisions is closely related to the farmer's willingness to subscribe to certain risk positions in their health outcomes in the presence of pesticide application.

Result 4. Under risk, pesticide application does not change the absolute health risk between net health outcomes $\tilde{h}_1$ and $\tilde{h}_2$, but increases the reliance on health insurance compared to the no pesticide case.

Result 5. Under ambiguity, pesticide application decreases the absolute health risk between net health outcomes $\tilde{h}_1$ and $\tilde{h}_2$, but the reliance on health insurance can increase or decrease compared to the risk case. Health insurance insulates the health outcomes h_1 and h_2 from the ambiguity effect (i.e., the change in the probability distribution over health states). The net health outcomes $\tilde{h}_1$ and $\tilde{h}_2$ respond to ambiguity despite the health insurance.

We briefly consider the health effects of pesticide application when health insurance is not available or when the insurance is available but it is not triggered by the farmers' health decisions (i.e., $h_1 g(\delta) > h$ and $h_2 > h$). The first order conditions for determining the optimal health outcomes h_1 and h_2 are

$$\beta_h \pi \frac{\partial v\left(\tilde{h}_1\right)}{\partial \tilde{h}_1} g(\delta) = \frac{\partial c(w, z_1, z_2, h_1, h_2)}{\partial h_1} \tag{25}$$

and

$$\beta_h(1-\pi)\frac{\partial v\left(\tilde{h}_2\right)}{\partial \tilde{h}_2} = \frac{\partial c(w, z_1, z_2, h_1, h_2)}{\partial h_2} \tag{26}$$

where the net health outcomes are $\tilde{h}_1 = h_1 g(\delta)$ and $\tilde{h}_2 = h_2$. In (25) and (26), the optimal health outcomes h_1 and h_2 are determined by equating the marginal cost of health effort with the discounted marginal utility of $\tilde{h}_1$ weighted by the pesticide damage $g(\delta)$ and discounted marginal utility of $\tilde{h}_2$, respectively.

In the absence of the separation induced by health insurance, the farmer internalizes the health damage of pesticide application. Specifically, under risk, $\pi = \pi_r$, the optimal net health outcome

$\widetilde{h}_1^{r\delta>0} = h_1^{r\delta>0} g(\delta)$ decreases, compared to the optimal net effect in the absence of pesticide application $\widetilde{h}_1^{r\delta=0}$, in response to the direct damage $g(\delta)$ in (25). As before, h_2, and by extension $\widetilde{h}_2$, do not respond to the pesticide application in the absence of complementarities or substitution effects between health outcomes across states of nature. The expected value of net health outcomes, $E\left(\widetilde{h}\right)$, decreases under pesticide application and the absolute health risk increases if the optimal net health outcome $\widetilde{h}_2 > \left(\widetilde{h}_1^{r\delta>0} + \widetilde{h}_1^{r\delta=0}\right)/2$ and decreases if $\widetilde{h}_2 < \left(\widetilde{h}_1^{r\delta>0} + \widetilde{h}_1^{r\delta=0}\right)/2$.

Under ambiguity, probability $\pi \neq \pi_r$ and the pesticide application adds an additional effect on health because of the change in probability distribution. Specifically, if $\pi = \pi_l < \pi_r$ then $\widetilde{h}_1^a > \widetilde{h}_2^a$, the optimal net health effects $\widetilde{h}_1^a < \widetilde{h}_1^{r\delta>0}$, $\widetilde{h}_2^a > \widetilde{h}_2^{r\delta>0}$, and the absolute health risk between net health outcomes under ambiguity decreases compared to the absolute health risk under risk and pesticide application. However, the expected value of the net health outcomes under ambiguity can increase or decrease compared to the risk case under pesticide application. Specifically, the difference is

$$E\left(\widetilde{h}^a\right) - E\left(\widetilde{h}^{r\delta>0}\right) = \pi_r\left[\frac{\pi_l}{\pi_r}h_1^a - h_1^{r\delta>0}\right]g(\delta) + (1-\pi_r)\left[\frac{1-\pi_l}{1-\pi_r}h_2^a - h_2^{r\delta>0}\right] \tag{27}$$

and for very small values of π_l and π_r (e.g., $\pi_l \cong 0$ and $\pi_r \cong 0$) $E\left(\widetilde{h}^a\right) - E\left(\widetilde{h}^{r\delta>0}\right) \cong h_2^a - h_2 > 0$, whereas for very large values of π_l and π_r (e.g., $\pi_l \cong 1$ and $\pi_r \cong 1$ but not 1) $E\left(\widetilde{h}^a\right) - E\left(\widetilde{h}^{r\delta>0}\right) \cong h_1^a - h_1^{r\delta>0} < 0$.

The case when probability $\pi = \pi_u > \pi_r$ is treated similarly, but one scenario stands out. As before, in (25) the pesticide damage $g(\delta)$ reduces the marginal value of effort that applies towards the health outcome h_1. However, in the absence of health insurance induced separation, the ambiguity effect, $\pi_u > \pi_r$, pushes against the pesticide damage $g(\delta)$. In particular, if the ambiguity effect outweighs the damage effect, $g(\delta)\pi_u > \pi_r$, the marginal value of h_1 increases under ambiguity compared to risk. However, in general, the effect of pesticide damage may be expected to outweigh the ambiguity effect, $g(\delta)\pi_u < \pi_r$, or pushes in the same direction, $g(\delta)\pi_l < \pi_r$, reducing the marginal valuation of h_1 compared to risk.

In the absence of health insurance, the farmer internalizes the health damage due to pesticide application. Public policies designed to reduce the health damage must consider whether the farmer perceives health outcomes as risky or ambiguous in the presence of pesticide application because, under risk, the expected value of health outcomes decreases, whereas, under ambiguity, the absolute health risk decreases. Thus, the success of said public policies in mitigating the health damage will rely on selecting tools designed to incorporate the farmer's choices dependence on her health preferences.

Result 6. Under risk and in the absence of health insurance, pesticide application decreases the expected value of the net health outcomes, but the absolute health risk increases if the optimal net health outcome in the no-pesticide damage health state is strictly greater than the simple mean of the before and after pesticide application health outcomes in the pesticide damage health state, $\widetilde{h}_2 > \left(\widetilde{h}_1^{r\delta>0} + \widetilde{h}_1^{r\delta=0}\right)/2$. The absolute health risk decreases if the inequality is reversed.

Result 7. Under ambiguity and in the absence of health insurance, pesticide application decreases the absolute health risk compared to the risk case, but the expected value of the net health outcomes under ambiguity can increase or decrease compared to the risk case under pesticide application.

5 | OPTIMAL PESTICIDE CHOICE

In this section, we analyze the optimal choice of pesticide δ considering the trade-off between production and health outcomes. We consider both the case when the farmer has access to health insurance and the case when the farmer does not have health insurance or the health insurance payments are not triggered by farmer's health choices.

The first order condition for determining the optimal pesticide usage δ in the presence of health insurance is

$$\beta_q \pi_q \frac{\partial u(q_1)}{\partial q_1} z_1 f_\delta(\delta) + P_1^h h_1 g_\delta(\delta) = v_\delta \tag{28}$$

In (28), the period 0 discounted return from pesticide application, $\beta_q \pi_q \left(\partial u(q_1)/\partial q_1\right) z_1 f_\delta(\delta)$, must cover the period 0 discounted health damage, $P_1^h h_1 g_\delta(\delta)$, in addition to the price of purchasing the pesticide in period 0, v_δ. The optimal amount of pesticide δ depends on farmer's preferences over consumption, $\beta_q \pi_q \partial u(q_1)/\partial q_1$, but it is independent of her preferences over health, $\beta_h \pi \partial v(\widetilde{h}_1)/\partial \widetilde{h}_1$, because of the health insurance induced separation, P_1^h. Thus, farmers with different preferences over consumption outcomes q_1 may disagree on the marginal productivity of pesticide δ because of their subjective beliefs over the pesticide's benefits, but they will not disagree due to differences in their health beliefs.

Due to the presence of health insurance, the preferences over risk (i.e., $\pi = \pi_r$) and ambiguity (i.e., $\pi \in [\pi_l, \pi_u]$) play no role in the choice of optimal pesticide application δ. From the health perspective, a risk averse farmer and an ambiguity averse farmer will make the same pesticide choice. Their choice will account for the marginal pesticide damage, $g_\delta(\delta)$, but it will not respond to their risk or ambiguity preferences due to the health insurance induced separation. This suggests that public policies designed to reduced the ambiguity surrounding pesticide use (e.g., information dissemination campaigns) will not influence the optimal choice of pesticide application in the presence of health insurance.

Result 8. In the presence of health insurance, the optimal choice of pesticide application does not depend on the farmer's health preferences over risk or ambiguity.

In the absence of health insurance or when the health insurance's payoffs are not triggered, the first order condition for determining the optimal pesticide usage δ is

$$\beta_q \pi_q \frac{\partial u(q_1)}{\partial q_1} z_1 f_\delta(\delta) + \beta_h \pi \frac{\partial v\left(\widetilde{h}_1\right)}{\partial \widetilde{h}_1} h_1 g_\delta(\delta) = v_\delta \tag{29}$$

The interpretation of (29) is similar to that of expression (28) with the exception that, in the absence of health insurance, farmers with different preferences over health outcomes h_1 disagree on the marginal productivity of pesticides δ because of their subjective beliefs over the pesticide damage in addition to the difference in their beliefs over the pesticide's benefits.

In this case, preferences over risk and ambiguity play a role in determining the optimal choice of pesticide application δ. Specifically, the probability π can be interpreted as a weight measuring the importance of pesticide damage in the farmer's decision to apply pesticide. Under risk, $\pi = \pi_r$ whereas, under ambiguity, $\pi \in [\pi_l, \pi_u]$. If $\pi = \pi_l < \pi_r$ corresponds to the probability distribution that solves the farmer's ambiguity, then ceteris paribus ambiguity decreases the cost of pesticide compared to the risk scenario by reducing the importance of health damage in the farmer's decision to apply pesticide. Thus, in this case ambiguity increases the pesticide usage by farmers. Intuitively, for small values of π_l (that is, $\pi_l \cong 0$) the share of health damage in farmer's decision to apply pesticides is significantly reduced. On the contrary, if $\pi = \pi_u > \pi_r$, then ceteris paribus ambiguity increases the cost of pesticides compared to risk, playing a role in reducing the amount of pesticides used by the farmer. From a public policy perspective, this suggests that ambiguity reducing policies (such as information and educational campaigns) are likely to influence the optimal choice of pesticide. However, the design and efficiency of such public policies will depend on the direction of ambiguity effect on pesticide usage.

Result 9. In the absence of health insurance, ambiguity can increase or decrease the optimal choice of pesticide compared to the risk case.

6 | CONCLUSION

Although the epidemiological literature has identified an association between pesticide exposure and various illnesses, methodological limitations in the assessment of pesticide exposure have made questionable the identification of a causal relationship. This scientific ambiguity and recent disagreements between WHO and EPA regarding the health effects of active ingredients in pesticides have brought the negative implications of pesticide use for human health to the forefront of the debate involving the lingering effects of chemical use in regions with large-scale agriculture. The debate is exemplified by two examples.

First, Monsanto's parent company, Bayer, announced on July 29, 2021 that it will remove glyphosate from store shelves beginning in 2023 to avoid future lawsuits related to its potential to cause cancer, but "this move is being made exclusively to manage litigation risk and not because of any safety concern" (Bayer, 2021). Roundup is the most widely used weed killer in the United States, containing glyphosate as its main ingredient (Renda, 2021). Furthermore, although glyphosate will be replaced in Roundup, it will continue to be made available to professionals and agricultural markets Bayer (2021). Studies have found glyphosate to be a possible carcinogen. In 2019, a California man was initially awarded $75 million in punitive damages and $5 million in compensatory damages in a court case ruling that years of Roundup application likely caused non-Hodgkin lymphoma. The total damages were eventually reduced to $20 million, which was upheld by the U.S. Ninth Circuit Court (Renda, 2021). Monsanto has now set aside $4.5 billion for future Roundup-related lawsuits (Bayer, 2021). Meanwhile, global regulatory agencies, including EPA, conclude that there is no scientific evidence that glyphosate causes cancer (EPA, 2019, 2020).

Second, litigation related to the pesticide chlorpyrifos is on the rise. Since 1965, farmers have been spraying chlorpyrifos on crops such as corn, citrus, apples, broccoli, and strawberries. In 2009, the American Healthy Homes Survey found traces of chlorpyrifos in more than two-thirds of the homes analyzed, suggesting that certain pesticides might remain in homes in large quantities (Stout et al., 2009). Four lawsuits were filed in July 2021 in the California Superior Court in Fresno County claiming that chlorpyrifos has been linked to neurological damage in children, inducing memory loss, attention deficit disorder, and lower IQs (Frazin, 2021; Romo, 2021). On August 18, 2021, the EPA issued a final ruling that chlorpyrifos can no longer be used in food production, in order to protect both children and farmworkers (EPA, 2021).

This article examines the trade-off between decreasing production risk and increasing health ambiguity due to pesticide use. We find that under ambiguity, pesticide application decreases the variation in health outcomes, whereas under risk, it decreases the expected value of health outcomes. Health insurance protects health from the pesticide damage but not from the ambiguity effect of pesticide application. Under risk, health insurance uptake increases, whereas under ambiguity the uptake can increase or decrease compared to the insurance uptake under risk. In the presence of health insurance, the optimal choice of pesticide application does not depend on the farmer's health preferences over risk or ambiguity. However, in the absence of health insurance, ambiguity can increase or decrease the optimal choice of pesticide compared to the risk case. Expected consumption increases under pesticide application, but the effect on the absolute consumption risk is undetermined. This suggests that public policies aiming at reducing pesticide related externalities should consider the integrative decision environment faced by farmers. Potential efficiency gains in policy implementation can be obtained by capitalizing on the type of preference for health outcome (i.e., risk and ambiguity) and the insurance-induced separation faced by farmers in health outcomes.

Naturally, our results depend on the assumptions made, but this is true for any economic model. We operate in a stylized setting, and to the extent that stylized settings differ from the real world, so do our predictions. To this end, we adhere to a conservative approach in selecting our assumptions. For example, we assumed farmers' preferences over consumption can be reasonably represented within an expected utility framework to avoid strengthening the derived results.

Future research can measure empirically the results developed in this paper. For example, the separation between the farmer's preferences over risk or ambiguity and health decisions in the presence of health insurance can be carefully exploited by using the variation in health insurance coverage over regions and time, and the extent of access to glyphosate-based pesticide by farmers. Under reasonable quasi-natural experiment conditions, the pesticide health damage can be disentangled from the ambiguity effect of pesticide application to derive implications for policy design. Similarly, field or lab experiments can be employed to measure the differential effects of risk and ambiguity over health insurance demand under pesticide application or on the health decisions in the absence of health insurance. Contingent on the magnitude of the measured effects, public policy can be designed to inform specific aspects of decision making (e.g, health insurance provision versus pesticide education and information campaigns).

ACKNOWLEDGMENTS

We thank two anonymous reviewers and the editor, Terrance Hurley, for comments that greatly improved our work. We also thank Robert G. Chambers, Andrew Schmitz, Sue Cassells, Seth Wechsler, and conference and seminar participants at AAEA 2020 and Massey University for valuable feedback. Daniel C. Voica dedicates this paper to his father, Marcel Voica, who passed away during its writing due to COVID-19 related causes.

REFERENCES

Alavanja, Michael C.R., Jane A. Hoppin, and Freya Kamel. 2004. "Health Effects of Chronic Pesticide Exposure: Cancer and Neurotoxicity." *Annual Review of Public Health* 25: 155–97. https://doi.org/10.1146/annurev.publhealth.25.101802.123020

Alpizar, Francisco, Fredrik Carlsson, and Maria A. Naranjo. 2011. "The Effect of Ambiguous Risk, and Coordination on Farmers' Adaptation to Climate Change - a Frame Field Experiment." *Ecological Economics* 70(12): 2317–26. https://doi.org/10.1016/j.ecolecon.2011.07.004

Barham, Bradford L., Jean-Paul. Chavas, Dylan Fitz, Vanessa R. Salas, and Laura Schechter. 2014. "The Roles of Risk and Ambiguity in Technology Adoption." *Journal of Economic Behavior and Organization* 97: 204–18. https://doi.org/10.1016/j.jebo.2013.06.014

Bayer. 2021. "Bayer Provides Update on Path to Closure of Roundup Litigation." https://media.bayer.com/baynews/baynews.nsf/id/Bayer-Provides-Update-on-Path-to-Closure-of-Roundup-Litigation.

Beseler, Cheryl L., Lorann Stallones, Jane A. Hoppin, Michael C. Alavanja, Aaron Blair, Thomas Keefe, and Freya Kamel. 2008. "Depression and Pesticide Exposures among Private Pesticide Applicators Enrolled in the Agricultural Health Study." *Environmental Health Perspective* 116(12): 1713–9. https://doi.org/10.1289/ehp.11091

Bikhchandani, Sushil, Jack Hirshleifer, and John G. Riley. 2013. *The Analytics of Uncertainty and Information*. Cambridge: Cambridge University Press.

Bougherara, Douadia, Xavier Gassmann, Laurent Piet, and Arnaud Reynaud. 2017. "Structural Estimation of Farmers' Risk and Ambiguity Preferences: A Field Experiment." *European Review of Agricultural Economics* 44(5): 782–808. https://doi.org/10.1093/erae/jbx011

Carrasco-Tauber, Catalina, and L. Joe Moffit. 1992. "Damage Control Econometrics: Functional Specification and Pesticide Productivity." *American Journal of Agricultural Economics* 74(1): 158–62. https://doi.org/10.2307/1242999

Chambers, Robert G. 2007. "Valuing Agricultural Insurance." *American Journal of Agricultural Economics* 89(3): 596–606. https://doi.org/10.1111/j.1467-8276.2007.00987.x

Chambers, Robert G., Giannis Karagiannis, and Vangelis Tzouvelekas. 2010. "Another Look at Pesticide Productivity and Pest Damage." *American Journal of Agricultural Economics* 95(2): 1401–19. https://doi.org/10.1093/ajae/aaq066

Chambers, Robert G., and Erik Lichtenberg. 1994. "Simple Econometrics of Pesticide Productivity." *American Journal of Agricultural Economics* 76(3): 407–17. https://doi.org/10.2307/1243653

Chambers, Robert G., and Tigran A. Melkonyan. 2017. "Ambiguity, Reasoned Determination, and Climate-Change Policy." *Journal of Environmental Economics and Management* 81: 74–92. https://doi.org/10.1016/j.jeem.2016.09.007

Chambers, Robert G., and Tigran A. Melkonyan. 2013. "Food Scares in an Uncertain World." *Journal of the European Economic Association* 11(6): 1432–56. https://doi.org/10.1111/jeea.12057

Chambers, Robert G., and Tigran A. Melkonyan. 2007. "Pareto Optimal Trade in an Uncertain Word: GMOs and the Precautionary Principle." *American Journal of Agricultural Economics* 89(2): 520–32. https://doi.org/10.1111/j.1365-2966.2007.01015.x

Chambers, Robert G., and John Quiggin. 2001. "Decomposing Input Adjustments under Price and Production Uncertainty." *American Journal of Agricultural Economics* 83(1): 20–34. https://doi.org/10.1111/0002-9092.00134

Chambers, Robert G., and John Quiggin. 2000. *Uncertainty, Production, Choice, and Agency*. Cambridge: Cambridge University Press.

Chavas, Jean-Paul, Robert G. Chambers, and Rulon D. Pope. 2010. "Production Economics and Farm Management: A Century of Contributions." *American Journal of Agricultural Economics* 92(2): 356–75. https://doi.org/10.1093/ajae/aaq004

Cheve, Morgane, and Ronan Congar. 2000. "Optimal Pollution Control under Imprecise Environmental Risk and Irreversibility." *Risk Decision and Policy* 5(2): 151–64. https://doi.org/10.1017/S1357530900000120

Couture, Stéphane, Stephane Lémarie, Sabrina Teyssier, and Pascal Toquebeuf. 2018. "The Impact of Information that Reduces Ambiguity on the Use of Pesticides: A Theoretical and Experimental Approach." *Journées internationales du Risque*: 1–24. https://hal.inrae.fr/hal-02786311

Devi, P. Indira. 2009. "Health Risk Perceptions, Awareness and Handling Behaviour of Pesticides by Farm Workers." *Agricultural Economics Research Review* 22: 263–8.

Engel, Lawrence S., Deirde A. Hill, Jane A. Hoppin, Jay H. Lubin, Charles F. Lynch, Joy Pierce, Charles Samanic, Dale P. Sandler, Aaron Blair, and Michael C. Alavanja. 2005. "Pesticide Use and Breast Cancer Risk among Farmers' Wives in the Agricultural Health Study." *American Journal of Epidemiology* 161(2): 121–35. https://doi.org/10.1093/aje/kwi022

Environmental Protection Agency. 2021. "EPA Takes Action to Address Risk from Chlorpyrifos and Protect Children's Health." https://www.epa.gov/newsreleases/epa-takes-action-address-risk-chlorpyrifos-and-protect-childrens-health.

Environmental Protection Agency. 2019. "EPA Takes Next Step in Review Process for Herbicide Glyphosate, Reaffirms No Risk to Public Health." https://www.epa.gov/newsreleases/epa-takes-next-step-review-process-herbicide-glyphosate-reaffirms-no-risk-public-health.

Environmental Protection Agency. 2020. "Glyphosate." https://www.epa.gov/ingredients-used-pesticide-products/glyphosate.

Fleming, Lora E., Orlando Goméz-Marín, Diane Zheng, Fangchao Ma, and David Lee. 2003. "National Health Interview Survey Mortality among US Farmers and Pesticide Applicators." *American Journal of Industrial Medicine* 43(2): 227–33. https://doi.org/10.1002/ajim.10162

Flower, Kori B., Jane A. Hoppin, Charles F. Lynch, Aaron Blair, Charles Knott, David L. Shore, and Dale P. Shandler. 2004. "Cancer Risk and Parental Pesticide Application in Children of Agricutural Health Study Participants." *Environmental Health Perspectives* 112(5): 631–5. https://doi.org/10.1289/ehp.6586

Fox, Glenn, and Alfons Weersink. 1995. "Damage Control and Increasing Returns." *American Journal of Agricultural Economics* 77(1): 33–9. https://doi.org/10.2307/1243886

Frazin, Rachel. 2021. "Lawsuits Warn Newly Banned Pesticide Might Linger for Years in Homes." *The Hill*. https://thehill.com/policy/energy-environment/569280-lawsuits-warn-newly-banned-pesticide-might-linger-for-years-in.

Gilboa, Itzhak, Fabio Maccheroni, Massimo Marinacci, and David Schmeidler. 2010. "Objective and Subjective Rationality in a Multiple Prior Model." *Econometrica* 78(2): 755–70. https://doi.org/10.3982/ECTA8223

Gilboa, Itzhak, and David Schmeidler. 1989. "Maxmin Expected Utility with Non-Unique Prior." *Journal of Mathematical Economics* 18(2): 141–53. https://doi.org/10.1016/0304-4068(89)90018-9

Harper, Carolyn R., and David Zilberman. 1989. "Pest Externalities from Agricultural Inputs." *American Journal of Agricultural Economics* 71(3): 692–702. https://doi.org/10.2307/1242025

Hoppin, Jane A., Martin Valcin, Paul K. Henneberger, Greg J. Kullman, David M. Umbach, Stephanie J. London, Michael C. Alavanja, and Dale P. Sandler. 2007. "Pesticide Use and Chronic Bronchitis among Farmers in the Agricultural Health Study." *American Journal of Industrial Medicine* 50(12): 969–79. https://doi.org/10.1002/ajim.20523

Hou, Lingling, Pengfei Liu, Jikun Huang, and Xiangzheng Deng. 2020. "The Influence of Risk Preferences, Knowledge, Land Consolidation, and Landspace Diversification on Pesticide Use." *Agricultural Economics* 51(5): 759–76. https://doi.org/10.1111/agec.12590

Kamel, Freya, William Boyes, Beth Gladen, Andrew Rowland, Michael Alavanja, Aaron Blair, and Dale Sandler. 2000. "Retinal Degeneration in Licensed Pesticide Applicators." *American Journal of Industrial Medicine* 37(6): 618–28. https://doi.org/10.1002/(sici)1097-0274(200006)37:6618::aid-ajim63.0.co;2-e

Kirrane, Ellen F., Jane A. Hoppin, Freya Kamel, David M. Umbach, William K. Boyes, Anneclaire J. DeRoos, Michael Alavanja, and Dale P. Sandler. 2005. "Retinal Degeneration and Other Eye Disorders in Wives of Farmer Pesticide Applicators Enrolled in the Agricultural Health Study." *American Journal of Epidemiology* 161(11): 1020–9. https://doi.org/10.1093/aje/kwi140

Lansink, Alfons O., and Alain Carpentier. 2008. "Damage Control Productivity: An Input Damage Abatement Approach." *Journal of Agricultural Economics* 52(3): 11–22. https://doi.org/10.1111/j.1477-9552.2001.tb00935.x

Lansink, Alfons O., and Elvira Silva. 2004. "Non-Parametric Production Analysis of Pesticide Use in Netherlands." *Journal of Productivity Analysis* 21: 49–65. https://doi.org/10.1023/B:PROD.0000012452.97645.30

Larsen, Ashley E., Steven D. Gaines, and Olivier Deschênes. 2017. “Agricultural Pesticide Use and Adverse Birth Outcomes in the San Joaquin Valley of California.” *Nature Communications* 8: 1–9. https://doi.org/10.1038/s41467-017-00349-2

Li, Yifan, Chao Zhang, Yanhong Yin, Fang Cui, Jinyang Cai, Zhaohui Chen, Yanhing Jin, et al. 2014. “Neurological Effects of Pesticide Use among Farmers in China.” *International Journal of Environmental Research and Public Health* 11(4): 3995–4006. https://doi.org/10.3390/ijerph110403995

Lichtenberg, Erik, and David Zilberman. 1986. “The Econometrics of Damage Control: Why Specification Matters.” *American Journal of Agricultural Economics* 68(2): 261–73. https://doi.org/10.2307/1241427

Melkonyan, Tigran A., and Jens Schubert. 2009. “Food Safety Regulations under Ambiguity.” *American Journal of Agricultural Economics* 91(5): 1389–96. https://doi.org/10.1111/j.1467-8276.2009.01353.x

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

Paul, Catherina J.M., V. Eldon Ball, Ronald G. Felthoven, Arthur Grube, and Richard F. Nehring. 2002. “Effective Costs and Chemical Use in United States Agricultural Production: Using the Environment as a ‘Free’ Input.” *American Journal of Agricultural Economics* 84(4): 902–15. https://doi.org/10.1111/1467-8276.00356

Perry, Edward D., and Giancarlo Moschini. 2020. “Neonicotinoids in U.S. Maize: Insecticide Substitution Effects and Environmental Risk.” *Journal of Environmental Economics and Management* 102: 1–19. https://doi.org/10.1016/j.jeem.2020.102320

Perry, M.J., and F.R. Bloom. 1998. “Perceptions of Pesticide Associated Cancer Risks among Farmers: A Qualitative Assessment.” *Human Organization* 57(3): 342–9. https://doi.org/10.17730/humo.57.3.653wk71255172971

Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D’Amore. 1992. “Environmental and Economic Costs of Pesticide Use.” *Bioscience* 42(10): 750–60. https://doi.org/10.2307/1311994

Pimentel, D., and M. Burges. 2014. *Environmental and Economic Costs of the Application of Pesticides Primarily in the United States*. Dordrecht: Springer.

Pingali, P.L., and P.A. Roger. 1995. *Impact of Pesticide on Farmer Health and the Rice Environment*. Dordrecht: Springer.

Renda, Matthew. 2021. “Bayer to Pull Glyphosate from Stores Due to Cancer Lawsuits.” *Courthouse News*. https://www.courthousenews.com/bayer-to-pull-glyphosate-from-stores-due-to-cancer-lawsuits/.

Romo, Vanessa. 2021. “EPA Will Ban A Farming Pesticide Linked To Health Problems In Children.” *National Public Radio*. https://www.npr.org/2021/08/18/1029144997/epa-will-ban-a-farming-pesticide-linked-to-health-problems-in-children.

Saha, Atanu, C. Richard Shumway, and Arthur Havenner. 1997. “The Economics and Econometrics of Damage Control.” *American Journal of Agricultural Economics* 79(3): 773–85. https://doi.org/10.2307/1244419

Shirangi, A., Mark Nieuwenhuijsen, Danielle Vienneau, and CD’Arcy J. Holman. 2011. “Living near Agricultural Pesticide Applications and the Risk of Adverse Reproductive Outcomes: A Review of the Literature.” *Paediatric and Perinatal Epidemiology* 25(2): 172–91. https://doi.org/10.1111/j.1365-3016.2010.01165.x

Stout, Daniel M., Karen D. Bradham, Peter P. Egeghy, Paul A. Jones, Carry W. Croghan, Peter A. Ashley, Eugene Pinzer, et al. 2009. “American Healthy Homes Survey: A National Study of Residential Pesticides Measured from Floor Wipes.” *Environmental Science and Technology* 43(12): 4294–300. https://doi.org/10.1021/es8030243

Tilman, David, Kenneth G. Cassman, Pamela A. Matson, Rosamond Naylor, and Stephen Polasky. 2002. “Agricultural Sustainability and Intensive Production Practices.” *Nature* 418: 671–7. https://doi.org/10.1038/nature01014

Warnick, James C.E., Javier Escobal, and Sonia C. Laszlo. 2011. “Ambiguity Aversion and Portfolio Choice in Small-Scale Peruvian Farming.” *B.E. Journal of Economic Analysis and Policy* 11(1): 1–54. https://doi.org/10.2202/1935-1682.2331

Wechsler, Seth, and David Smith. 2018. “Has Resistance Taken Root in U.S. Corn Fields? Demand for Insect Control.” *American Journal of Agricultural Economics* 100(4): 1136–50. https://doi.org/10.1093/ajae/aay016

Wilson, Clevo, and Clem Tisdell. 2001. “Why Farmers Continue to Use Pesticides despite Environmental, Health and Sustainability Costs.” *Ecological Economics* 39(3): 449–62. https://doi.org/10.1016/S0921-8009(01)00238-5

World Health Organization. 2015. “IARC Monographs Volume 112: Evaluation of Five Organophosphate Insecticides and Herbicides.” *International Agency for Research on Cancer*. https://www.iarc.fr/wp-content/uploads/2018/07/MonographVolume112-1.pdf.

Ye, Ming, Jeremy Beach, Jonathan W. Martin, and Ambikaipakan Senthilselvan. 2013. “Occupational Pesticide Exposures and Respiratory Health.” *International Journal of Environmental Research and Public Health* 10(12): 6442–71. https://doi.org/10.3390/ijerph10126442

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher’s website.

How to cite this article: Voica, Daniel C., Troy G. Schmitz. 2022. “Trading risk for ambiguity: Production versus health under pesticide application.” *American Journal of Agricultural Economics* 104(4): 1327–1342. https://doi.org/10.1111/ajae.12266