The Dual Role of Insurance in Input Use: Mitigating Risk Versus Curtailing Incentives

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Abstract

Insurance can encourage the use of risk-increasing inputs, but it can also decrease people's incentives to exert effort when it is difficult to monitor how much they exert themselves. This effort reduction can go hand in hand with a decrease in the use of effort-complementary inputs. I study a model of risk-sharing that allows for both effects of insurance on input use and use the latest ICRISAT panel to structurally estimate it. Median fertilizer use is between 1.3 and 3.6 times higher under no sharing than under full insurance. A subsidy that halves the purchase prices of fertilizer increases farmers' welfare by 8% in consumption-equivalent terms.

Keywords: Insurance, risk, private information, effort, agriculture, fertilizer, complementarity.

JEL Classification: O12 O13 O33 Q16

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Economists have long been interested in the relationship between insurance and technology adoption. A common perspective is that incomplete insurance markets withhold the use of risk-increasing inputs (Foster and Rosenzweig (2010)). While the inability to insure may bias farmers' decisions towards low-risk and low-return technologies, insurance can also decrease incentives to work. If farmers' incomes tend to be higher when they exert themselves more, efficiency might require that they enjoy a higher consumption when they generate more earnings. In these contexts, insurance can push farmers to lower their effort. This effort reduction can go hand in hand with decreases in the use of effort-complementary inputs, such as fertilizer. I analyze the relationship between input use and insurance when the latter can create incentive problems. I use this relationship to shed light on how risk-sharing arrangements affect fertilizer use in rural India.

Insurance plays a vital role in the rural areas of developing countries. In these contexts, households face severe income fluctuations due to weather conditions, illnesses, and pests, among other things. Here, insurance usually comes from informal risk-sharing arrangements, such as gift exchange and personal loans (Bardhan and Udry (1999) and Fafchamps (2011)). Imperfections in these arrangements are pervasive; i.e., households are unable to insure completely against idiosyncratic risks (Townsend (1994), Udry (1994), and Conning and Udry (2007)). An important reason rural households only enjoy limited insurance is that they might need adequate incentives to work (Fafchamps (1992) and Ligon (1998)).[1] The intuition is as follows: when it is hard to monitor how hard households work, consumption insurance can induce them to exert themselves less (i.e., reduce their effort and rely on others for their livelihood). I argue that this mechanism can have important consequences on the relationship between insurance and the use of agricultural inputs, such as fertilizer. This input, which probably plays a key role in increasing the returns of many seeds (Foster and Rosenzweig (2010)), is likely effort-complementary. First, the returns to fertilizer are higher when farmers apply it carefully and timely. Second, fertilizer leads to higher yields and weed growth, which may increase the need for labor for hand-weeding and harvesting.[2]

[1] Other explanations include limited commitment (Ligon et al. (2002)), hidden income (Kinnan (2021)), and local information (Ambrus et al. (2020)).

[2] I formalize the idea that fertilizer and effort are complements by assuming that the agricultural production function is strictly supermodular. I.e., effort increases the marginal product of fertilizer and vice versa. See Subsection 1.2.

If fertilizer and effort are complements, and insurance can decrease households' incentives to exert effort, risk-sharing may reduce fertilizer use through its discouraging effect on effort supply. This effect of insurance on fertilizer use would go against its positive impact through the crowding in of risky inputs (Emerick et al. (2016)). In this case, the sign of the relationship between risk-sharing and fertilizer use (and any other risk-increasing and effort-complementary input) would be theoretically ambiguous.

In this paper, I study the connection between risk-sharing and fertilizer use when insurance can lead to incentive problems because of private information frictions in production decisions. I provide a theoretical framework that relates the level of risk-sharing to households' effort supply and demand for fertilizer. Insurance can have two contrasting effects on fertilizer use. First, if fertilizer is risk-increasing, insurance can induce farmers to intensify its use. However, because of the private information frictions, insurance can lead farmers to lower their effort, thereby decreasing their incentives to use inputs complementary to it, such as fertilizer. I also show that a subsidy that reduces the purchase prices of fertilizer (akin to the Indian government's Retention Price cum Subsidy Scheme) is welfare-enhancing for subsidy recipients.[3] Empirically, I structurally estimate the model to quantify (1) the extent to which risk-sharing can affect fertilizer use and (2) the effect of a fertilizer price subsidy on recipients' welfare.

I outline a model of risk-sharing in which farmers insure against idiosyncratic productivity shocks by sharing the incomes they generate from operating their farms. Each household chooses how much effort to supply and how much fertilizer to buy before the productivity shocks realize. Their choices are not verifiable; e.g., it is prohibitively costly to observe how hard villagers work or how much nutrients they supply to their fields. I characterize the constrained-efficient allocation of risk-sharing, effort, and fertilizer. Insurance has a positive effect on the take up of risky inputs, as conventional arguments suggest. However, the unverifiability of farmers' production decisions generates a second margin through which insurance affects effort supply and fertilizer use: a higher level of insurance reduces the private marginal benefit of effort, thereby inducing households to shirk. If fertilizer and effort are complements, the disincentive effect of insurance results in

[3]This argument does not take into account the possibility of misuse of overuse of fertilizer. See Subsection 1.4.

lower fertilizer productivity, which leads farmers to use less of this input. Then, I analyze how an exogenous reduction in fertilizer prices (a fertilizer subsidy) affects resource allocation and efficiency in the village economy. I decompose the effect of this policy on farmers' welfare into two parts. First, the subsidy reduces agricultural production costs, thereby increasing profits and consumption. Second, the policy manages to shrink the productive inefficiency generated by risk-sharing. Indeed, a decrease in the price of fertilizer induces households to buy more of it. Because effort and fertilizer are complements, the subsidy pushes farmers to exert more effort. In the constrained-efficient allocation, effort is underprovided; hence, the policy moves the effort allocation closer to the full information benchmark, increasing welfare.

I structurally estimate the model using the latest (2009-2014) ICRISAT monthly panel from the Indian semi-arid tropics, which provides high-quality information on households' farming activities and the prices paid for agricultural inputs. I use variation in the observed fertilizer prices to rationalize farmers' observed fertilizer-effort ratios as optimal choices given the assumed economic environment. The relationship between these ratios and the fertilizer prices in the data allows us to learn some of the primitives of the economy: the households' tastes (their disutilities of effort), the distortion in a second-best (constrained-efficient) allocation relative to its first-best counterpart (the wedge between the social and the private technical rate of substitution between effort and fertilizer), and the agricultural technology (the elasticity of substitution between fertilizer and effort). This empirical strategy only requires information on the distributions of households' fertilizer-effort ratios and the fertilizer prices they face. It provides a joint test of (1) the complementarity between effort and fertilizer and (2) the relationship between the ratio of fertilizer to effort and risk-sharing. I use the estimated elasticity of substitution between fertilizer and effort and marginal disutilities of effort to assess the effect of risk-sharing on effort supply and fertilizer use. Given their disutilities of effort, agricultural technology, and fertilizer prices, how would households' production decisions look like if they were to face different levels of risk-sharing? I simulate how effort supply and fertilizer use would change if farmers moved from a situation in which they have full insurance to one in which they do not share any risk under different levels of risk aversion. Median fertilizer use is between 1.3 (for extremely risk-averse farmers) and 3.6 (for risk-neutral farmers) times higher under no sharing than under full insurance. Median effort supply is between 4 (for extremely risk-averse farmers) to 12 (for risk-neutral farmers) times higher. Then, I simulate the effects of a fertilizer subsidy on recipients' welfare. I consider a policy that subsidizes the prices of fertilizer that farmers currently face so that they need to pay less for each unit of fertilizer they buy. The consumption-equivalent gain in farmers' welfare of halving the prices of fertilizer they currently face is 8%. This gain would be equal to 99% in a world where effort and fertilizer do not affect yield variability.

This paper makes four contributions. First, I analyze a mechanism that relates insurance to input use through the complementarity between the inputs and effort. I show that when there are private information frictions in production decisions, insurance can have a negative (positive) effect on the use of factors of production that complement (substitute) effort. In particular, more consumption insurance is isomorphic to a higher effort cost, which induces households to use smaller quantities of effort-complementary inputs (and higher amounts of effort-substitute inputs). This effect is independent of the positive impact of insurance on risk-increasing inputs. Hence, the overall influence of insurance on the use of an effort-complementary factor of production can be negative even if the latter is risk-increasing. I apply this idea to the context of risk-sharing in rural India and build a model to study how informal insurance affects fertilizer use.

Second, I show that the fertilizer-effort ratio and fertilizer price distributions are sufficient to identify a subset of the model parameters. These parameters include the elasticity of substitution between effort and fertilizer. Thus, I do not impose the assumption that effort and fertilizer are complements, letting the data discipline their complementarity instead. I show how to use the parameters identified by the fertilizer-effort ratio and fertilizer price distributions to conduct a counterfactual exercise that quantifies the extent to which risk-sharing arrangements can affect effort supply and fertilizer use for different levels of risk aversion. Then, I show how to calculate the welfare gain of a change in fertilizer prices on households' welfare. I propose a method to calibrate (or fix) the extra parameters needed to quantify this gain by minimizing the distance between the optimal level of risk-sharing implied by the model and an estimate of the average risk-sharing coefficient.

Third, I estimate the model with data from 18 villages in rural India. I use data from the surveys collected by ICRISAT, which provide high-quality information on farming activities for roughly 700 households. The estimated parameters satisfy the model's restrictions on the elasticity of substitution between effort and fertilizer and the marginal disutilities of effort without being imposed. Moreover, almost 70% of the estimated wedges between the social and the private technical rate of substitution between effort and fertilizer satisfy the model's restriction without being imposed.

Fourth, I use the estimated parameters to calculate the extent to which risk-sharing can affect effort supply and fertilizer use. I show that if farmers were in autarky, in median terms, they would use between 1.3 and 3.6 times as much fertilizer and supply between 4 and 12 times more effort than if they were fully insured, depending on how risk averse they are. Thus, my estimates suggest that risk-sharing can play a sizable role in shaping households' agricultural production decisions. Finally, I study the impact of a policy similar to the Retention Price cum Subsidy Scheme on welfare. My results suggest that there is room to improve households' welfare by reducing current fertilizer prices: a 50% reduction in these prices increases the farmers' consumption-equivalent welfare by 8% if input choices have a direct impact on yield variance.

Related literature

Uncovering the determinants of agricultural input use in developing countries is a top priority in academic and policy circles (Feder et al. (1985), Sunding and Zilberman (2001), Foster and Rosenzweig (2010), Udry (2010), and Jack (2013)). Low use of modern inputs, especially fertilizer and improved seeds, is a leading cause of reduced agricultural productivity in these countries. Economists have considered the interaction between insurance and technology adoption (e.g., Udry (2010), Dercon and Christiaensen (2011), and Donovan (2020)). This research focuses on the intuition that imperfect insurance induces risk-averse farmers to decrease their use of risky technologies. That is, these farmers may sacrifice the expected returns of risky-increasing inputs in exchange for less uncertain consumption. This paper advances the understanding of the constraints to agricultural input use in village economies. I focus on how insurance can discourage effort supply and show how this effect relates to fertilizer use through its complementarity with effort.

The mechanism I propose to link risk-sharing to fertilizer use relies on private information (hidden action) frictions. Private effort plays an important role in most of the sharecropping literature (Quibria and Rashid (1984), Singh (1991), and Sen (2016)). Ligon (1998) uses private effort to rationalize imperfect risk-sharing in village economies. While several papers provide evidence for private effort by testing models of imperfect insurance against each other (Ligon (1998), Ábrahám and Pavoni (2005), Kaplan (2006), Attanasio and Pavoni (2011), and Karaivanov and Townsend (2014)), this friction is hard to detect using observational data (Foster and Rosenzweig (2001)).[4] I contribute to this literature by quantifying the negative relationship between risk-sharing and effort.[5]

Foster and Rosenzweig (2010) argue that research on agricultural input use should focus on complementarities and substitutabilities between inputs. The relationships between labor and agricultural intermediates seem to be particularly important (Dorfman (1996) and Hornbeck and Naidu (2014)). By taking into account the complementarity between effort and fertilizer, my model directly speaks to this issue. In particular, the model explicitly recognizes that the profitability of an agricultural input (and hence its use) ultimately depends on a household's willingness to allocate its time to farm labor (which depends on how insured it is).

Finally, this paper relates to a growing literature focusing on how informal insurance affects different aspects of the village economy (Munshi and Rosenzweig (2006), Munshi and Rosenzweig (2016), Advani (2019), Morten (2019), and Mazur (2020)). I contribute to this literature by exploring yet another channel through which risk-sharing interacts with household behavior in village economies, i.e., agricultural input use.

1 Model

I analyze a static economy where households face productivity shocks and belong to a risk-sharing pool. The pool allows farmers to share their incomes to hedge against idiosyncratic risks. For consistency with the structural estimation performed below, I refer to the risk-sharing pool as a village, even though, at this

[4]There is experimental evidence showing that imperfect monitoring has a negative effect on risk-sharing (Jain (2020)).

[5]The literature on sharecropping has produced consistent evidence that better risk-sharing (in the form of a lower fraction of the agricultural output going to the tenant) leads to lower efficiency and effort provision (Laffont and Matoussi (1995) and Burchardi et al. (2019)).

point, we can think of it as a caste or kinship network. Each household chooses how much effort to supply and how much fertilizer to buy before the idiosyncratic shocks realize. These choices affect the distribution of the yields that the farm generates. In Subsection 1.1, I outline the setup of the model. I focus on two information structures: the full information regime, in which households' choices of effort and fertilizer are verifiable, and the private information regime, in which their choices are private. I characterize the efficient allocation of effort and fertilizer as a function of the sharing contract in Subsection 1.2 and solve for the efficient sharing contract in Subsection 1.3. In Subsection 1.4, I study the effect of a fertilizer price subsidy on farmers' welfare. In Subsection 1.5, I study a version of the model where input choices affect expected yields without affecting higher moments of the yield distribution. With this version of the model, I can obtain sharper theoretical predictions that are useful to illustrate the effect of insurance on input use through their complementarity with effort. In Subsection 1.6, I provide a discussion of the main modeling assumptions. Appendix A contains all the proofs.

1.1 Setup

There are n households, each producing agricultural output (yields) y_i, $i \in N = \{1, \ldots, n\}$. Output is uncertain, and depends on effort and fertilizer, $e_i, f_i \in \mathbb{R}_+$. Refer to $a_i = (e_i, f_i)$ as an action. Let ε_i be an idiosyncratic productivity shock such that $\mathbb{E}(\varepsilon_i) = 1$ and $\mathbb{V}\text{ar}(\varepsilon_i) = \eta^2$. Farmer i's production function is

$$y_i = y(a_i)\,\varepsilon_i, \tag{1}$$

where y is jointly concave in a_i, and strictly concave, strictly increasing, and twice-continuously differentiable in both e_i and f_i.[6] Household i can supply effort to its farm (there is no market for effort) and buy fertilizer at an exogenous price from a trader. Let $p_i \in \mathbb{R}_{++}$ be the price of fertilizer that i faces. Household i takes this price as given, and its agricultural profit (income) is

$$\pi_i = y_i - p_i f_i. \tag{2}$$

[6]Thus, effort and fertilizer affect the yield distribution but do not affect the distribution of the producitivy shock. See Just and Pope (1979), Traxler et al. (1995), and Donovan (2020) for further discussion on this assumption.

Households share incomes to smooth consumption risk. Household i's consumption is

$$c_i(\alpha) = (1-\alpha)\,\pi_i + \alpha\overline{\pi}, \tag{3}$$

where $\alpha \in [0,1]$ is a variable that characterizes the extent of risk-sharing and $\overline{\pi}$ is average income. Thus, each household consumes a fraction $1-\alpha$ of its income and contributes the rest to a communal pool that farmers share equally. Risk-sharing is enforceable, and farmers cannot hide income. Finally, while risk-sharing is determined endogenously (see Subsection 1.3), I assume that each household takes α as given.

Household i's expected utility is

$$U(c_i(\alpha), e_i) = \mathbb{E}(c_i(\alpha)) - \frac{\rho}{2}\mathbb{V}\mathrm{ar}(c_i(\alpha)) - \kappa_i e_i,$$

where ρ is the coefficient of absolute risk aversion and κ_i is household i's marginal disutility of effort.

I characterize a welfare-maximizing allocation in two information regimes: full information, in which the planner can verify each household's behavior, and private information, in which their choices of effort and fertilizer are not verifiable. I refer to a welfare-maximizing allocation under full information as efficient, and to a welfare-maximizing allocation under private information as constrained efficient. To solve the planner's problem, I proceed as follows. First, I find a welfare-maximizing action profile for a given sharing rule. Then, I find a welfare-maximizing sharing rule.

1.2 Optimal action profile

Full information. Assume that the planner can verify $\boldsymbol{a}$. The problem of finding a welfare-maximizing action profile for a given α is

$$\max_{\boldsymbol{a}} \sum_{i\in N} U(c_i(\alpha), e_i), \tag{4}$$

subject to Equations (3), (2), and (1). Let $\boldsymbol{a}^{\diamond}(\alpha)$ be a solution to Problem (4). The following claim pins down a welfare-maximizing action profile under full information.[7]

[7] Throughout the paper, I do not consider the corner solutions in which optimal effort or fertilizer is null. Inada conditions imposing $\lim_{e_i\to0^+} y_e(e_i,f_i) = \lim_{f_i\to0^+} y_f(e_i,f_i) = +\infty$ are sufficient to avoid these solutions if $\rho\eta^2$ is not too high.

Claim 1 (Efficient action profile)**.** *For a given α, an efficient action profile implies that*

$$\frac{y_e\left(a_i^{\diamond}\left(\alpha\right)\right)}{y_f\left(a_i^{\diamond}\left(\alpha\right)\right)} = \frac{\kappa_i}{p_i},$$

for each $i \in N$.

Thus, for each household, the technical rate of substitution between effort and fertilizer is equal to the relative unit costs of these inputs. This condition is identical to that implied by profit maximization for a competitive firm with production function $y\left(a_i\right)$ facing a price vector $\left(\kappa_i, p_i\right)$.

Private information. Assume that household i's action is private to i. To find a welfare-maximizing action profile for a given α, the planner must solve

$$\begin{aligned} &\max_{\boldsymbol{a}} \sum_{i\in N} U\left(c_i\left(\alpha\right), e_i\right), \\ &\text{subject to } a_i \in \arg\max_{\widehat{a}_i} U\left(c_i\left(\alpha\right), \widehat{e}_i\right),\ \forall i \in N, \end{aligned} \tag{5}$$

and Equations (3), (2), and (1). An optimal action profile must satisfy n incentive-compatibility (IC) constraints. These constraints say that the action the planner chooses for household i coincides with what the household would do on its own; otherwise, the household would have an incentive to deviate to another action. Let $\boldsymbol{a}^*\left(\alpha\right)$ be a solution to Problem (5). The following claim pins down a welfare-maximizing action profile under private information.

Claim 2 (Constrained-efficient action profile)**.** *Assume that each household takes as given the other households' actions. For a given α, a constrained-efficient action profile implies that*

$$\frac{y_e\left(a_i^*\left(\alpha\right)\right)}{y_f\left(a_i^*\left(\alpha\right)\right)} = \frac{\kappa_i}{\left(1 - \frac{n-1}{n}\alpha\right) p_i},$$

for each $i \in N$.

Claim 2 shows that when there are private information frictions in production decisions, risk-sharing induces a distortion in the technical rate of substitution between effort and fertilizer. In particular, $1 - \left(n-1\right) n^{-1}\alpha$ is the wedge between the social and the private technical rate of substitution, which summarizes the the distortions arising from the unverifiability of household i's choices.

What is the impact of insurance on effort supply and fertilizer use? First, suppose that there are no private information frictions in production decisions. In this case, insurance increases the (expected) social marginal benefits of effort and fertilizer without affecting their marginal costs. Hence, higher risk-sharing leads farmers to increase effort supply and fertilizer use. We might refer to this effect of insurance on input use as the risk channel. This mechanism suggests that more insured households should increase the utilization of risky inputs and underlies the classic argument that incomplete insurance can limit investment in risk-increasing inputs with high expected returns. What happens if we introduce private information frictions in production decisions? In this case, when farmers share more, each of them appropriates a smaller fraction of the marginal product of the effort they exert. Hence, the more risk-sharing there is, the smaller the private marginal benefit of this input. Thus, there is a new channel through which insurance can affect effort supply opposing the risk channel. We might refer to this effect of insurance on effort supply as the free-riding channel. Free-riding in effort also impacts fertilizer use through its complementarity with effort. If fertilizer and effort are complements (i.e., the marginal product of fertilizer increases in effort), then the free-riding channel implies that insurance can also decrease fertilizer use. Indeed, if people exert themselves less when they share more, and fertilizer is less productive in this case, then it is optimal for them to reduce their use of this input. Hence, the overall effect of risk-sharing on households' choices under private information frictions in production decisions is ambiguous. I formalize these intuitions in the following theorem.

Theorem 1 (Effort, fertilizer, and risk-sharing)**.** *Let $\boldsymbol{a}^{\diamond}(\alpha)$ be an optimal action profile under full information. Then,*

$$\frac{\partial e_i{}^{\diamond}(\alpha)}{\partial \alpha} > 0 \text{ and } \frac{\partial f_i{}^{\diamond}(\alpha)}{\partial \alpha} > 0.$$

Let $\boldsymbol{a}^{*}(\alpha)$ be an optimal action profile under private information. In this case, insurance decreases the fraction of the marginal product of own effort farmers appropriate, inducing them to free-ride on each others' efforts. Thus, the overall effect of insurance on effort supply is ambiguous. In particular, if the free-riding channel is strong enough then

$$\frac{\partial e_i{}^{*}(\alpha)}{\partial \alpha} < 0.$$

Moreover, suppose that e_i and f_i are complements, in the sense that y is strictly supermodular in (e_i, f_i). Then, provided that the free-riding channel is strong enough, it must be the case that

$$\frac{\partial f_i^* (\alpha)}{\partial \alpha} < 0.$$

1.3 Optimal sharing rule

We turn to the problem of finding a welfare-maximizing sharing contract.

Full information. Consider the problem of finding a welfare-maximizing sharing contract under full information; i.e.:

$$\max_{\alpha} \sum_{i \in N} U (c_i (\alpha), e_i),$$

subject to Equations (3), (2), (1), and $\boldsymbol{a} = \boldsymbol{a}^\diamond (\alpha) =: \boldsymbol{a}^\diamond$, where $\boldsymbol{a}^\diamond$ is the solution to Problem 4. The following claim shows that, under full information, risk-sharing is perfect.

Claim 3 (Efficient sharing). *Under full information, the welfare-maximizing sharing contract is full insurance.*

Insurance benefits farmers because it decreases the variance of consumption. Moreover, for given profiles of effort and fertilizer choices, a marginal increase in insurance increases the social marginal benefit of these inputs because it reduces their impact on output volatility. Since risk-sharing does not generate externalities under full information, the planner maximizes welfare by providing the households with as much insurance as possible.

Private information. Assume that households' choices are private. In this case, the problem of finding a welfare-maximizing sharing contract is

$$\max_{\alpha} \sum_{i \in N} U (c_i (\alpha), e_i),$$

subject to Equations (3), (2), (1), and $\boldsymbol{a} = \boldsymbol{a}^* (\alpha)$, where $\boldsymbol{a}^* (\alpha)$ is the solution to Problem 5. To solve this problem, I apply the first-order approach (Hölmstrom (1979), Rogerson (1985), and Abraham et al. (2011)); i.e., I replace the IC constraints in Problem (5) with the first-order conditions for $a_i^* (\alpha)$, for each $i \in N$.

In this case, we can safely apply this approach because i's objective function is strictly concave in $a_i(\alpha)$, for any choice of α.

Let $W(\alpha)$ denote welfare evaluated at $\boldsymbol{a}^*(\alpha)$. The next claim characterizes the welfare-maximizing sharing contract under private information, and highlights that, under this information regime, a marginal increase in α can generate a trade-off between decreasing consumption volatility and decreasing aggregate consumption.

Claim 4 (Constrained-efficient sharing)**.** *First, notice that*

$$\begin{aligned}\frac{\partial W(\alpha)}{\partial \alpha} &= \\ &\sum_{i\in N}\underbrace{\left\{\left[1-\rho\left(1-\frac{2(n-1)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)y(a_i^*(\alpha))\eta^2\right]y_e(a_i^*(\alpha))-\kappa_i\right\}}_{(+)}\underbrace{\frac{\partial e_i^*(\alpha)}{\partial \alpha}}_{?} \\ &+\sum_{i\in N}\underbrace{\left\{\left[1-\rho\left(1-\frac{2(n-1)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)y(a_i^*(\alpha))\eta^2\right]y_f(a_i^*(\alpha))-p_i\right\}}_{(+)}\underbrace{\frac{\partial f_i^*(\alpha)}{\partial \alpha}}_{?} \\ &\underbrace{+\rho(1-\alpha)\left(\frac{n-1}{n}\right)\eta^2\sum_{i\in N}[y(a_i)]^2}_{(+)}.\end{aligned} \tag{6}$$

Let α^* be a constrained-efficient sharing rule. It must be the case that

$$\begin{aligned}\tfrac{\partial W(\alpha^*)}{\partial \alpha} &= 0 \quad \textit{if } \alpha^* \in (0,1), \\ \tfrac{\partial W(\alpha^*)}{\partial \alpha} &\leq 0 \quad \textit{if } \alpha^* = 0, \\ \tfrac{\partial W(\alpha^*)}{\partial \alpha} &\geq 0 \quad \textit{if } \alpha^* = 1.\end{aligned}$$

To understand Equation (6), it is useful to compare it with the effect of risk-sharing on welfare under full information. From the proof of Claim 1, we can see that, under full information,

$$\left[1-\rho\left(1-\frac{2(n-1)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)y(a_i^\diamond(\alpha))\eta^2\right]y_e(a_i^\diamond(\alpha))=\kappa_i$$

and

$$\left[1-\rho\left(1-\frac{2(n-1)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)y(a_i^\diamond(\alpha))\eta^2\right]y_f(a_i^\diamond(\alpha))=p_i.$$

Hence, if households' choices of effort and fertilizer corresponded to their decisions under full information, Equation (6) would boil down to

$$\frac{\partial W(\alpha)}{\partial \alpha} = \rho (1-\alpha) \left(\frac{n-1}{n} \right) \eta^2 \sum_{i \in N} \left[y(a_i) \right]^2,$$

which is precisely equal to the effect of risk-sharing on welfare under full information (see the proof of Claim 3). The difference between the welfare effect of insurance under the two information regimes comes from the first two terms of Equation (6). In particular, under private information, the social marginal benefits of effort and fertilizer are higher than their private marginal costs, for any level of risk-sharing $\alpha \in [0, 1)$. Thus,

$$\left[1 - \rho \left(1 - \frac{2(n-1)}{n}\alpha + \frac{n-1}{n}\alpha^2 \right) y(a_i^*(\alpha)) \eta^2 \right] y_e(a_i^*(\alpha)) - \kappa_i \geq 0$$

and

$$\left[1 - \rho \left(1 - \frac{2(n-1)}{n}\alpha + \frac{n-1}{n}\alpha^2 \right) y(a_i^*(\alpha)) \eta^2 \right] y_f(a_i^*(\alpha)) - p_i \geq 0.$$

Theorem 1 tells us that the overall effect of insurance on effort supply and fertilizer use is ambiguous. Suppose that the free-riding channel is strong enough, so that insurance has a negative effect on effort supply and fertilizer use. In this case, Claim 4 shows that risk-sharing affects welfare in two opposing ways. In particular, insurance can generate a welfare cost through its effect on effort supply and fertilizer use. This cost comes about because insurance distorts the allocation of effort and fertilizer away from the full-information benchmark. The last term of Equation (6) is the welfare gain associated with a marginal reduction in consumption volatility. This gain is the marginal benefit of risk-sharing. An optimal sharing rule balances the trade-off between effort provision and consumption smoothing. Hence, under private information, we should not expect to observe full insurance, as it happens under full information.

1.4 Fertilizer subsidy

I analyze the effect of a fertilizer subsidy on households' welfare, which I model as an exogenous decrease in fertilizer prices.[8]

[8] See Subsection 2.2.4 for a description of a policy implemented by the Indian government that can be modeled in this way.

Notice that welfare can be written as

$$\sum_{i\in N}\left[y\left(a_i\right)-p_if_i-\kappa_ie_i\right]-\frac{\rho\eta^2}{2}\left(1-\frac{2\left(n-1\right)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)\sum_{i\in N}\left[y\left(a_i\right)\right]^2.$$

For simplicity, assume that $p_i = p_j = \widetilde{p}$, for each i, j. The results are the same if we consider that $p_i := \tau_i\widetilde{p}$, where τ_i parametrizes the additional (e.g., shipping) costs that i incurs to buy a unit of fertilizer. We can analyze the effect of a marginal subsidy on the price of fertilizer on welfare by computing the effect of a marginal *decrease* in the price of fertilizer on welfare. For example, let $1-s$ be the fraction of the fertilizer price subsidized, so that the price of fertilizer faced by the households is $p = s\widetilde{p}$. Then, by the chain rule, the effect of a marginal increase in the fraction of the fertilizer price subsidized (i.e., a marginal decrease in s) on welfare is proportional to the effect of a marginal decrease in the price of fertilizer on welfare.

Under full information, the welfare-maximizing sharing rule is full insurance, irrespective of the price of fertilizer (Claim 3). Thus, by the envelope theorem, the effect of a marginal *decrease* in the price of fertilizer on welfare under full information is given by

$$\sum_{i\in N} f_i^{\diamond}.$$

The subsidy increases profits by mechanically reducing the monetary costs of agricultural production. I call this the price effect. On the other hand, under private information, insurance responds to changes in the price of fertilizer. This response comes about because, by affecting the households' incentives to exert effort, the subsidy affects the marginal cost of risk-sharing; i.e., the reduction in effort supply given rise by a marginal increase in insurance. Since α^* is chosen by the planner to maximize welfare, the effect of a marginal decrease in the price of fertilizer on welfare is

$$-\frac{\mathrm{d}W\left(\alpha^*\right)}{\mathrm{d}p} = -\frac{\partial W\left(\alpha^*\right)}{\partial p}-\underbrace{\frac{\partial W\left(\alpha^*\right)}{\partial \alpha}}_{=0}\frac{\partial \alpha^*}{\partial p}.$$

This expression boils down to

$$-\frac{\mathrm{d}W(\alpha^*)}{\mathrm{d}p} =$$

$$-\sum_{i\in N}\left\{\underbrace{\left\{\left[1-\rho\left(1-\frac{2(n-1)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)y(a_i^*(\alpha))\eta^2\right]y_e(a_i^*(\alpha))-\kappa_i\right\}}_{(+)}\underbrace{\frac{\partial e_i^*(\alpha)}{\partial p}}_{(-)}\right.$$

$$\left.\underbrace{\left\{\left[1-\rho\left(1-\frac{2(n-1)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)y(a_i^*(\alpha))\eta^2\right]y_e(a_i^*(\alpha))-\kappa_i\right\}}_{(+)}\underbrace{\frac{\partial f_i^*(\alpha)}{\partial p}}_{(-)}-f_i^*(\alpha)\right\}.$$

Hence, besides reducing the monetary costs of production, the subsidy affects effort supply and fertilizer use. Recall that

$$\left[1-\rho\left(1-\frac{2(n-1)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)y(a_i^*(\alpha))\eta^2\right]y_e(a_i^*(\alpha))-\kappa_i\geq 0$$

and

$$\left[1-\rho\left(1-\frac{2(n-1)}{n}\alpha+\frac{n-1}{n}\alpha^2\right)y(a_i^*(\alpha))\eta^2\right]y_f(a_i^*(\alpha))-p_i\geq 0.$$

(see Claim 4). When fertilizer and effort are complements (which implies $\partial e_i^*(\alpha)/\partial p < 0$), the subsidy induces households to exert more effort besides using more fertilizer, thus shrinking the negative externality generated by risk-sharing. I call this the input effect. While this argument holds for a marginal reduction in the price of fertilizer, it shows that, under private information, welfare is an increasing function of the subsidy. Thus, it is always welfare-enhancing to decrease fertilizer prices. However, we should not expect the effect of a change in risk-sharing on welfare to be zero for discrete changes in p.

The argument that a fertilizer price subsidy increases welfare rests on the assumption that fertilizer only impacts agricultural production and this effect is positive. While the model abstracts from this possibility, there is a literature documenting that excessive fertilizer application can have negative consequences on soil, water, and air quality (see, e.g., Sainju et al. (2019)). This possibility would make fertilizer use induce a trade-off between increasing current yields and degrading the environment. In this case, a fertilizer price subsidy need not always be welfare-enhancing.

1.5 A model of risk-sharing with additive productivity shocks

In this subsection, I re-derive the results obtained above in a setting in which I can obtain sharper theoretical results. In particular, I assume that the productivity shocks are additive. In this case, farmer i's production function is

$$y_i = y(a_i) + \varepsilon_i, \tag{7}$$

where ε_i is an idiosyncratic productivity shock such that $\mathbb{E}(\varepsilon_i) = 0$ and $\mathbb{V}\text{ar}(\varepsilon_i) = \eta^2$. With this specification, supplying more effort or using more fertilizer increases expected output without affecting its higher moments. Risk-sharing does not affect inputs through their effect on output volatility. Hence, the additive shock specification allows me to isolate the negative effect of risk-sharing on fertilizer use through the complementarity between effort and fertilizer. This effect contrasts the positive impact of insurance on input choices through their risk factors (see Subsection 1.2).[9] Some authors argue that fertilizer may be risk increasing (Just and Pope (1979)), which could imply that better-insured households should use more of it. If this is the case, one may doubt the usefulness of the additive shock specification. However, this specification is useful for several reasons. First, in Section C of the Online Appendix, I show that there is a negative correlation between average fertilizer use and the elasticity of consumption to idiosyncratic income shocks. If the risk factor channel were dominating, this correlation should have been positive. Hence, this assumption considerably simplifies the analysis of the model while still being consistent with the evidence that risk-sharing is negatively correlated with fertilizer use.[10] Second, it turns out that the trade-off between insurance and input use that obtains under additive productivity shocks is a limiting case of the one that obtains under multiplicative productivity shocks. Finally, we can more easily generalize the model in several dimensions when productivity shocks are additive.

Let us first analyze an optimal allocation of effort and fertilizer for a given level of risk-sharing α under full information.

[9] See also Braverman and Stiglitz (1986) and Donovan (2020).

[10] To be sure, we could imagine other explanations for the negative correlation between average fertilizer use and the elasticity of consumption to idiosyncratic income shocks found in the data. While this correlation does not demonstrate that risk-sharing only affects fertilizer use through the complementarity between effort and fertilizer, its presence is inconsistent with explaining the relationship between risk-sharing and fertilizer use based solely on the risk factor channel.

Claim 5 (Efficient action profile). *Under full information and for a given α, a welfare-maximizing action profile implies that*

$$y_e\left(a_i^{\diamond}\left(\alpha\right)\right) = \kappa_i,$$
$$y_f\left(a_i^{\diamond}\left(\alpha\right)\right) = p_i,$$

for each $i \in N$.

The intuition behind this claim is as follows: under full information, risk-sharing does not generate externalities; hence, the optimal action profile is independent of α. In particular, the planner equates for each household the marginal product of effort to its marginal utility cost and the marginal product of fertilizer to its price.

Next, consider what happens to an optimal allocation of effort and fertilizer for a given level of risk-sharing α under private information.

Claim 6 (Constrained-efficient action profile). *Assume each household maximizes its objective taking as given the actions of the other households. Under private information, and for given α, a welfare-maximizing action profile implies that*

$$y_e\left(a_i^{*}\left(\alpha\right)\right) = \frac{\kappa_i}{\left(1 - \frac{n-1}{n}\alpha\right)} = p_i^e,$$
$$y_f\left(a_i^{*}\left(\alpha\right)\right) = p_i,$$

for each $i \in N$.

Refer to p_i^e as the 'effective cost' of effort for household i. Thus, we can think of better-insured households as facing a higher cost of effort. Claim 6 shows that risk-sharing induces a direct negative externality on effort provision, as it increases the effective cost of effort. On the other hand, risk-sharing has no direct impact on fertilizer use because it does not affect its marginal benefit or cost. This asymmetry between fertilizer and effort arises because households share profits; hence, they share both the revenues and the costs of fertilizer (since there are no labor markets, work effort does not enter the monetary costs of production). Thus, the impact of the sharing contract on the private marginal benefit and the marginal cost of fertilizer cancel out. Moreover, from the proof of Claim 2, we can see that the first-order conditions for effort and fertilizer in Claim 6 can be obtained as a limiting case for the multiplicative shock specification when ρ or η are small. The next theorem shows how effort supply and fertilizer use change when the sharing coefficient α moves.

Theorem 2 (Effort, fertilizer, and risk-sharing)**.** *Let $\boldsymbol{a}^*(\alpha)$ be a constrained-efficient action profile. Then,*

$$\frac{\partial e_i{}^*(\alpha)}{\partial \alpha} < 0.$$

Moreover, suppose that e_i and f_i are complements, in the sense that y is strictly supermodular in (e_i, f_i). Then,

$$\frac{\partial f_i{}^*(\alpha)}{\partial \alpha} < 0.$$

The sign of the latter inequality reverses if y is strictly submodular in (e_i, f_i).

Theorem 2 shows that if risk-sharing increases, then households exert less effort, and decrease the use of fertilizer as long as effort and fertilizer are complements.The intuition is as follows. Because of private information, more insurance induces households to shirk. This reduction in effort pushes farmers to decrease fertilizer use, as it decreases its marginal product, thereby making it less profitable.

Now, in order to complete the characterization of an optimal allocation of resources, let us consider an optimal choice of risk-sharing. The following claim shows that, under full information, risk-sharing is perfect, as it is the case with multiplicative productivity shocks.

Claim 7 (Efficient sharing)**.** *Under full information, the welfare-maximizing sharing contract is full insurance.*

As before, the intuition is that since risk-sharing does not generate externalities under full information, the planner maximizes welfare by providing the households with as much insurance as possible.

Next, re-define $W(\alpha)$ as welfare evaluated at $\boldsymbol{a}^*(\alpha)$. The next claim characterizes the welfare-maximizing sharing contract under private information, and highlights that, under this information regime, a marginal increase in α generates a trade-off between decreasing consumption volatility and decreasing aggregate consumption.

Claim 8 (Constrained-efficient sharing)**.** *First, notice that*

$$\frac{\partial W(\alpha)}{\partial \alpha} = \underbrace{\sum_{i \in N} \left(\kappa_i \left(\frac{1}{1 - \frac{n-1}{n}\alpha} - 1 \right) \frac{\partial e_i^*(\alpha)}{\partial \alpha} \right)}_{(-)} \underbrace{- \frac{n\rho}{2} \frac{\partial \mathbb{V}\text{ar}(c_i(\alpha))}{\partial \alpha}}_{(+)}. \tag{8}$$

Let α^* be an optimal sharing rule under private information. It must be the case that

$$\frac{\partial W(\alpha^*)}{\partial \alpha} = 0 \quad \textit{if } \alpha^* \in (0,1)\,,$$
$$\frac{\partial W(\alpha^*)}{\partial \alpha} \leq 0 \quad \textit{if } \alpha^* = 0,$$
$$\frac{\partial W(\alpha^*)}{\partial \alpha} \geq 0 \quad \textit{if } \alpha^* = 1.$$

The first term of Equation (8) is the loss in aggregate production that the planner generates by increasing risk-sharing. The reduction in effort associated with a marginal increase in risk-sharing has a first-order effect on welfare.[11] The second term of Equation (8) is the gain associated with a marginal reduction in consumption volatility.

Finally, let us consider the effect of a fertilizer subsidy on households' welfare. With additive productivity shocks, welfare can be written as

$$\sum_{i \in N} \left[y\left(a_i\right) - p_i f_i - \kappa e_i - \frac{\rho}{2} \left(\left(1-\alpha\right)^2 + \frac{\alpha^2}{n} + \frac{2\alpha\left(1-\alpha\right)}{n} \right) \eta^2 \right].$$

Again, for simplicity, assume that $p_i = p_j = \widetilde{p}$, for each i, j. As it happens with the multiplicative productivity shocks, under full information, the effect of a marginal *decrease* in the price of fertilizer on welfare under full information is given by

$$\sum_{i \in N} f_i^{\diamond}.$$

The intuition for this result is that optimal risk-sharing is full insurance irrespective of the price of fertilizer. Instead, under private information, the effect of a marginal decrease in the price of fertilizer on welfare is

$$\begin{aligned} -\frac{\mathrm{d}W\left(\alpha^*\right)}{\mathrm{d}p} &= -\frac{\partial W\left(\alpha^*\right)}{\partial p} - \underbrace{\frac{\partial W\left(\alpha^*\right)}{\partial \alpha}}_{=0} \frac{\partial \alpha^*}{\partial p} \\ &= \sum_{i \in N} \left[-\left(y_e\left(a_i^*\left(\alpha^*\right)\right) - \kappa_i\right) \frac{\partial e_i^*\left(\alpha^*\right)}{\partial p} + f_i^*\left(\alpha^*\right) \right]. \end{aligned}$$

Recall that $y_e\left(a_i^*\left(\alpha\right)\right) - \kappa_i > 0$ (see Claim 6): since effort is underprovided under private information, its marginal product is greater than its marginal cost. When

[11] The partial effect of a marginal increase in risk-sharing on fertilizer use can be ignored because the decrease in the marginal product of fertilizer is exactly offset by the decrease in its marginal cost. This result follows from the assumption that households share the profits of agricultural production.

fertilizer and effort are complements (which implies $\partial e_i^* (\alpha) / \partial p < 0$), the subsidy induces households to exert more effort, thus shrinking the negative externality generated by risk-sharing.

We might be interested in determining how insurance responds to the subsidy (i.e., $\partial \alpha^* / \partial p$), notice that the first-order condition $\partial W (\alpha^*) / \partial \alpha = 0$ implicitly defines an interior optimal sharing rule under private information (see Claim 6). Assuming that $\partial^2 W (\alpha^*) / \partial \alpha^2 \neq 0$, by the implicit function theorem, the effect of a marginal decrease in the price of fertilizer on optimal insurance is

$$-\frac{\partial \alpha^*}{\partial p} = \frac{\frac{\partial^2 W(\alpha^*)}{\partial \alpha \partial p}}{\frac{\partial^2 W(\alpha^*)}{\partial \alpha^2}}.$$

A local maximum requires that $\partial^2 W (\alpha^*) / \partial \alpha^2 < 0$.[12] Moreover,

$$\frac{\partial^2 W (\alpha^*)}{\partial \alpha \partial p} = \sum_{i \in N} \left[\kappa_i \underbrace{\left(\frac{1}{1 - \frac{n-1}{n} \alpha} - 1 \right)}_{(+)} \frac{\partial^2 e_i^* (\alpha^*)}{\partial \alpha \partial p} \right].$$

Hence,

- if $\partial^2 e_i^* (\alpha^*) / \partial \alpha \partial p > 0$, the subsidy decreases insurance;
- if $\partial^2 e_i^* (\alpha^*) / \partial \alpha \partial p = 0$, the subsidy does not affect insurance;
- if $\partial^2 e_i^* (\alpha^*) / \partial \alpha \partial p < 0$, the subsidy increases insurance.

To gain intuition, notice that $\partial e_i^* (\alpha^*) / \partial \alpha$ is the decrease in effort supply associated with a marginal increase in the sharing rule; i.e., the slope of the effort supply function with respect to risk-sharing. This is the marginal cost of insurance: the more negative this slope, the more costly insurance is in terms of reducing effort provision. Recall that the marginal benefit of insurance (i.e., the marginal increase in consumption smoothing) is independent of the price of fertilizer (see Equation (6)). If $\partial^2 e_i^* (\alpha^*) / \partial \alpha \partial p > 0$ then the slope of the effort supply function with respect to risk-sharing becomes more negative when the price of fertilizer is

[12] To see why, notice that $W (\alpha)$ is twice-continuously differentiable. By assumption, $(\partial \alpha^2)^{-1} \partial^2 W (\alpha^*) \neq 0$. Hence, either $(\partial \alpha^2)^{-1} \partial^2 W (\alpha^*) < 0$ or $(\partial \alpha^2)^{-1} \partial^2 W (\alpha^*) > 0$. However, $(\partial \alpha^2)^{-1} \partial^2 W (\alpha^*) > 0$ is a sufficient condition for α^* being a local minimum, not a maximum.

lower. Hence, a fertilizer subsidy increases the marginal cost of insurance, making it bigger than its marginal benefit. Because of the concavity of the welfare function around α^*, the planner decreases α to reestablish the equality between the marginal benefit and the marginal cost of risk-sharing.

1.6 Brief discussion of modeling assumptions

Before turning to the empirical evidence, I briefly discuss some modeling choices. I examine many of these choices in more detail in the Online Appendix. The appendix focuses on the additive shock specification (as implied by Equation (1)) because it is simpler to analyze analytically. A theoretical argument for focusing on this specification is advanced in Section E of the Online Appendix, which compares the additive and multiplicative shock specifications and discusses how my results change if input choices have an impact on output volatility. In particular, this section shows that if the marginal impact of inputs on output volatility is sufficiently small, then the qualitative results on the effect of insurance on input use that we obtain with the additive and multiplicative shock specifications coincide. Thus, the extension results I present in the Online Appendix should also apply the multiplicative shock specification, provided that the risk channel effect of insurance on input use is not too large.

Equation (2) implies that there are no labor (effort) markets in the village economy. In fact, agricultural labor markets might be important in the context where I focus the empirical part of the paper (Skoufias (1994) and Lamb (2003)). The assumption of no labor markets is only made for clarity: we can introduce hired labor as a third input in the production function; i.e., $y(a_i) = y\left(e_i, e_i^h, f_i\right)$, where e_i^h is hired labor. The crucial assumptions to maintain the results is that households still supply effort to their farm,[13] and there is a complementarity between this effort and fertilizer.

Equation (2) captures the assumption that households share their incomes to insure against consumption risk. Hence, what is shared is the value of output less the cost of fertilizer, but not less the cost of effort. This assumption is consistent with risk-sharing being an ex-post consumption smoothing mechanism together with the temporal sequencing of agricultural decisions (in which intermediates are chosen before the realization of shocks, as in Donovan (2020)). However, it

[13] In the data, more than 99% of the households supply labor to their farm.

could be the case that households commit to sharing agricultural yields instead of incomes. My theoretical results are valid also when assuming that farmers share outputs instead of profits (see Section F of the Online Appendix). Intuitively, if households share yields instead of profits, they stop sharing the cost of fertilizer. Hence, insurance decreases the marginal product of both effort and fertilizer.

In Equation (2), I allow fertilizer prices to be household specific. This assumption allows me to account for the fact that households may purchase fertilizer from different traders who apply different mark-ups, or farmers that live in different places may face different costs for the shipment of fertilizer. In the data, I document substantial price dispersion for fertilizer across households. This evidence is consistent with a large literature.[14] However, my theoretical results do not depend on the presence of price dispersion.

In the model, I assume that this contract is linear.[15] However, the result that risk-sharing decreases the use of fertilizer (Theorem 1) does not depend on this assumption. In particular, the same result can be obtained if the optimal sharing contract is differentiable and the first-order approach is valid (see Section D of the Online Appendix).

In Subsection 1.1, I assume that the households' expected benefit of consumption admits a mean-variance representation. This assumption simplifies strategic interactions between households (see Section D of the Online Appendix). A *linear* trade-off between expected consumption and the variance of consumption arises from the assumptions that the households' von Neumann-Morgensten utility functions are CARA (i.e., $u(c_i(\alpha)) = -\exp\{-\rho c_i(\alpha)\}$ and the productivity shocks are normally distributed. Separability in consumption and effort is a standard assumption in the moral hazard literature. Assuming that the marginal disutility of effort is constant allows me to treat it as a price and apply standard results in producer theory (Arcand et al. (2007) and Conlon (2009)).

Finally, as explained in Subsections 2.2 and 2.2.2, the assumptions that the

[14]See Jensen (2007), Svensson and Yanagizawa (2009), Aker (2010), Nakasone (2014), Aker and Fafchamps (2015), Mitra et al. (2018).

[15]In general, linear contracts are not optimal when there is private information. Yet, linearity simplifies the analysis considerably, and we can motivate it by empirical evidence (Dutta and Prasad (2002)). Indeed, explaining why linear contracts are so frequent is a longstanding problem in contract theory, since most models predict more complicated contracts (Holmström and Milgrom (1987) and Carroll (2015)).

households' expected benefit of consumption admits a mean-variance representation do not play a crucial role in the identification of the parameters of the model that use to conduct the counterfactual exercise. These assumptions do allow me to *compute* the counterfactual exercise (in a particularly simple way).

2 Empirical evidence

In this section, I first describe the data. Then, I estimate the model above to retrieve some of its structural parameters. I use the estimates to quantify the extent to which risk-sharing can decrease effort supply and fertilizer use. Finally, I calculate the welfare gain from a fertilizer price subsidy for subsidy recipients.

2.1 Background and data

I use household panel data collected under the Village Dynamics in South Asia (VDSA) project by the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT). The data come from detailed survey interviews conducted monthly from 2009 to 2014 and covers households in 18 villages in the Indian semi-arid tropics. For each village, there are 40 households randomly selected stratifying by landholding classes (10 are landless laborers, 10 are small farmers, 10 are medium farmers, and 10 are large farmers[16]). My empirical strategy requires information on the distributions of households' effort and fertilizer choices and the distribution of the fertilizer prices they face. These data fit my need because it provides information on households' farming activities and the prices they pay for agricultural inputs. An advantage of the data is that the information on farming is detailed: for each plot and each operation performed in a plot, the data reports the quantity and value of all inputs used by the household cultivating the plot. This information allows me to construct an aggregate measure of the fertilizer used by each household in each month.[17] Moreover, researchers have widely used

[16]This classification is based on operational landholdings, which equals the size of own land plus that of land leased/shared in and minus that of land of leased/shared out.

[17]A second advantage of the data is that it also contains information on households' expenditures and incomes, which allows me to analyze the correlations between reduced-form tests of risk-sharing and agricultural production decisions, as explained in Section C of the Online Appendix. There, I provide suggestive evidence that more insured households tend to supply less effort and use less fertilizer.

these data to test models of risk-sharing, making my results directly comparable with the findings of previous papers. I refer to Townsend (1994), Mazzocco and Saini (2012), and Morten (2019) for more detailed descriptions of the data.[18]

For the estimation, I need information on how much effort the households exert, how much fertilizer they use, and the fertilizer prices they face. I measure effort through the per capita total hours of work supplied by family members in the fields they cultivate in a given month. Fertilizer is the per capita total quantity (in kilograms) of fertilizers used by family members in their plots in a given month. Fertilizer price is the average fertilizer price paid by the household for all fertilizer it bought in a given month. All money values are converted to 1975 rupees for comparability with Townsend (1994). In Section B of the Online Appendix, I discuss in detail how I build all the variables I use.

Table 1 reports summary statistics for the sample.

[18] As pointed out by Mazzocco and Saini (2012), it can be difficult to compare some of the information contained in the data (e.g., expenditures) across households and over time, since (1) the frequency of the interviews varies, and (2) the interview dates differ across respondents. Some recall periods can be longer than a month (e.g., a household in Aurepalle reported the amount spent on rice from July 1 to November 8 in 2009). Hence, it is impossible to determine how the information provided distributes over the months that make up recall periods longer than a month. Fortunately, from 2010 onward, the survey gives information on the month to which every piece of information refers. Therefore, I drop the observations that pertain to the year 2009.

Table 1: Summary statistics

Variable	Average	Std. Dev.
Household size	5.17	2.24
Number of infants	0.05	0.23
Average adult age	40.76	8.57
Age-sex weight	4.48	1.77
Monthly consumption	151.18	410.38
Monthly income	105.27	1384.07
Monthly effort (hr)	20.57	22.76
Monthly fertilizer (kg)	22.51	62.06
Fertilizer per hectare (kg/ha)	73.33	184.25
Number of households	698	
Observations	11234	

Notes: All money values in 1975 rupees. Consumption, income, effort, and fertilizer expressed in adult-equivalent terms. Household-month observations.

2.2 Structural estimation

I now take the model outlined in Section 1 to the data. My strategy is to estimate the relative demand for fertilizer to effort, making use of Claim 2. This claim characterizes the households' optimal choices of effort and fertilizer as functions of their technology (production function), their preferences (disutilities of effort), the market arrangements (risk-sharing) where they operate,[19] and fertilizer prices they face. By estimating the relative demand of fertilizer to effort, I rationalize the observed ratios of fertilizer used to effort supplied as utility-maximizing choices given the economic environment where the households operate, which they take as given. This strategy allows me to retrieve the elasticity of substitution between effort and fertilizer and the households' marginal disutilities of effort. Moreover,

[19]The model in Section 1 assumes that insurance is endogenous and corresponds to a welfare-maximizing sharing rule. However, notice that Claim 2 (and hence the relative demand for fertilizer and effort that I estimate) holds for any α. My empirical strategy thus allows me to retrieve some of the parameters while being agnostic about the optimality of the risk-sharing coefficients. In Subsection 2.2.3, I use the retrieved parameters to compute the welfare-maximizing sharing rules that my model predicts.

if we are willing to make some additional assumptions, we can also identify and estimate the levels of risk-sharing that the households face, as explained below. I use the technology and preference parameter estimates to conduct a counterfactual exercise and a policy simulation. With the first exercise, I aim to quantify the extent to which risk-sharing can affect effort supply and fertilizer use. To do so, I simulate how the choices of effort and fertilizer would change if the households moved from a situation in which no one shares any risk to one in which each of them has full insurance. With the policy simulation, I aim to calculate how much a fertilizer subsidy can increase welfare for the farmers treated by this policy. To do so, I compute the welfare-equivalent gain in farmers' aggregate consumption generated by halving the prices of fertilizer that they currently face.

This subsection begins by describing the identification and estimation of the model. An advantage of this model is that it simplifies strategic interactions between households. This simplification follows from the assumptions of mean-variance expected utility and linear sharing contract (see Section D.1 of the Online Appendix), which together imply that each household's choices are independent of what others do. Relaxing these assumptions would typically generate more complicated strategic interactions, making identification and estimation more complex. While my model is parsimonious, most of its estimated parameters satisfy the theoretical restrictions on those parameters without being imposed, as explained below.

To take the model to the data, I first impose a functional form to the production function. I assume that

$$y\left(a_i\right) = \ell_i^{1-\chi}\left[e_i^{\frac{\sigma-1}{\sigma}} + f_i^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\chi\sigma}{\sigma-1}}, \tag{9}$$

where $\sigma \in (0,\infty)$ is the elasticity of substitution between effort and fertilizer, ℓ_i is land, which I assume to be fixed,[20] and $1-\chi \in [0,1)$ is the land share. With this production function (and denoting by e_i^* and f_i^* the optimal choices of effort

[20]This production function exhibits non-increasing returns to scale in a_i. The estimation of the model and the counterfactual exercise do not require decreasing returns to scale in a_i (i.e., $\chi \in (0,1)$). On the other hand, computing the welfare-maximizing sharing rule, which I need to calculate the welfare gain from a fertilizer subsidy, does require decreasing returns in a_i, as explained below. The assumption that land is a fixed factor of production is reasonable, as the data shows that the vast majority of households did not transact land in the period under analysis. See also Donovan (2020).

and fertilizer for household i), the equation in Claim 2 reads as follows:

$$\left(\frac{e_i^*}{f_i^*}\right)^{-\frac{1}{\sigma}} = \frac{\kappa_i}{\left(1 - \frac{n-1}{n}\alpha\right) p_i}.$$

Rearrange and take logs to obtain

$$\log\left(\frac{f_i^*}{e_i^*}\right) = \sigma \log\left(\kappa_i\right) - \sigma \log\left(1 - \frac{n-1}{n}\alpha\right) - \sigma \log\left(p_i\right).$$

This equation is household i's relative demand for fertilizer to effort. This demand relates i's optimal choices of effort and fertilizer to its economic environment. The latter consists of the elasticity of substitution between fertilizer and effort (σ), i's disutility of effort (κ_i), the wedge between the social and the private technical rate of substitution between effort and fertilizer ($1 - (n-1)\, n^{-1}\alpha$), and fertilizer price i faces (p_i).

In the data, I observe, for each household in each month, (1) the quantity of effort supplied, (2) the quantity of fertilizer used, and (3) the price of fertilizer paid. The parameters of interest are the elasticity of substitution between effort and fertilizer, the marginal disutility of effort, and the wedge between the social and the private technical rate of substitution between effort and fertilizer ($1 - (n-1)\, n^{-1}\alpha$). To take the model to the data, I need to specify how these parameters vary across households, villages, and time. I assume that (1) the marginal disutility of effort is household-specific and constant in time, and (2) the wedge between the social and the private technical rate of substitution is time-varying and village-specific. If there is a random measurement error in fertilizer over effort, we end up with the following regression equation:

$$\log\left(\frac{f_{it}}{e_{it}}\right) = \sigma \log\left(\kappa_i\right) - \sigma \log\left(1 - \frac{n_{vt}-1}{n_{vt}}\alpha_{vt}\right) - \sigma \log\left(p_{it}\right) + \epsilon_{it}. \tag{10}$$

Differences in wedges across villages and time may come from changes in the size of the risk-sharing pools (n), the level of risk-sharing (α), or both. In principle, we do not need to take a stance on this issue. However, for notational consistency with the exercise that I perform below, in writing Equation (10), I assume that both village size and risk-sharing are time-varying and village-specific. This assumption allows me to rationalize variation in village-month heterogeneity as coming from changes in the sharing pool size or the level of insurance.

2.2.1 Estimation

Under the premise that the model is correctly specified, the underlying assumptions for the consistent estimation of σ, κ_i, and $\left(1-(n_{vt}-1)\,n_{vt}^{-1}\alpha_{vt}\right)$ are that (1) the measurement error in fertilizer or effort is uncorrelated with any of the independent variables, and (2) there is no measurement error in fertilizer prices.[21] In this case, I can use OLS to estimate the following regression equation:

$$\log\left(\frac{f_{it}}{e_{it}}\right)=\varphi_i+\phi_{vt}-\sigma\log\left(p_{it}\right)+\epsilon_{it}, \tag{11}$$

where φ_i are household fixed effects and ϕ_{vt} are village-month fixed effects, which estimate $\sigma\log\left(\kappa_i\right)$ and $-\sigma\log\left(1-(n_{vt}-1)\,n_{vt}^{-1}\alpha_{vt}\right)$, respectively. The identification of κ_i relies on the assumption that risk-sharing is not household-specific and constant in time; otherwise, φ_i would also be capturing variation in risk-sharing at the household level. Notice that, under the assumption that the wedges between the social and the private technical rate of substitution between effort and fertilizer are time-varying and village specific, I need cross-sectional *and* time variation in fertilizer prices to identify σ separately from the fixed effects.[22] I do observe dispersion in fertilizer prices across households and time, consistently with the literature on price dispersion in agricultural markets (Jensen (2010)). Table 2 reports the results of running the regression specified in Equation (11).

[21] A random measurement error in fertilizer prices would imply a downward bias in the OLS estimate of σ.

[22] Different assumptions on how the parameters vary across households, villages, and time require different structural equations to identify those parameters. For example, I could assume that the wedges between the social and the private technical rates of substitution are village-specific and constant in time. In this case, Equation (11) should only have household fixed effects. When I run this regression specification, I obtain a significant estimate for σ equal to 0.21. Notice that if the wedges are village-specific and constant in time, then I do not need both cross-sectional and time variation in fertilizer prices to identify σ separately from the fixed effects. Specifically, I could rely on variation in fertilizer prices across villages and months. If I regress the $\log\left(f_{it}/e_{it}\right)$ on median or average fertilizer prices at village and month level (while controlling for household fixed effects), I obtain a significant estimate for σ equal to 0.15.

Table 2: Structural regression

Dep. variable: $\log\left(\frac{f_{it}}{e_{it}}\right)$	$\widehat{\beta}$ (s.e.)
$\log(p_{it})$	-0.3499^{***} (0.0241)
Household fixed effects	Yes
Village-month fixed effects	Yes
R-squared	0.640
Observations	9,941

Notes: OLS regressions of log fertilizer used per worked hours on log fertilizer prices. Standard errors are clustered at the village-month level.

The estimated elasticity of substitution between effort and fertilizer, $\widehat{\sigma}$, is about 0.35. As it lies between 0 and 1, this elasticity confirms that effort and fertilizer are complements.

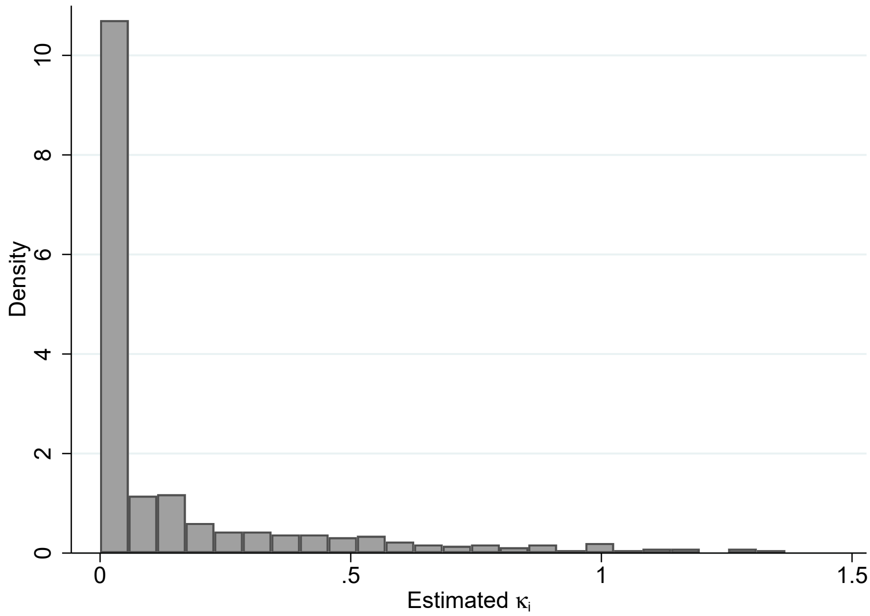
We can use the estimates of the elasticity of substitution between effort and fertilizer ($\widehat{\sigma}$) and the household fixed effects ($\widehat{\varphi}_i$) to retrieve $\widehat{\log(\kappa_i)} = (\widehat{\sigma})^{-1}\widehat{\varphi}_i$. Then, we can compute

$$\widehat{k}_i = \exp\left\{\widehat{\log(\kappa_i)}\right\}$$

to obtain estimates of the household-specific marginal disutilities of effort. Figure 1 shows the histogram of the marginal disutility of effort.[23]

[23]For readability, I trim the top 15% of the distribution.

Figure 1: Histogram of $\widehat{k}_i$



The average marginal disutility of effort is approximately 7. To get a sense of this number, assume that households have quadratic utility. Then, the increase in consumption that would exactly compensate the average household for an increase in one hour of work (i.e., the marginal rate of substitution of effort for consumption) is pinned down by the following equation:

$$\frac{\mathrm{d}c_i(\alpha)}{\mathrm{d}e_i} = \frac{7}{\rho c_i(\alpha)}.$$

Average household consumption is approximately 150 rupees. Hence, compensating the average household for an additional hour of work requires an increase in consumption of $0.047\rho^{-1}$ rupees. According to the estimates provided by the Indian Government (Indian Labour Bureau (2010)), in 2009, the daily wage rate for an adult male agricultural worker fell in the range of 50 to 120 2009 rupees, which roughly correspond to an hourly wage rate (assuming eight hours of work per day) of 0.5 to 1.2 1975 rupees. If the labor market were competitive, then the marginal rate of substitution of effort for consumption would be equal to the hourly wage rate. This equality, together with an average marginal disutility of effort equal to 7, implies a coefficient of absolute risk aversion between 0.04 and 0.09 for the average household.

I can back out the wedges between the social and the private technical rates of substitution between effort and fertilizer using the same procedure employed to obtain the marginal disutilities of effort. In particular, I can use the estimates of the elasticity of substitution between effort and fertilizer ($\widehat{\sigma}$) and the village-month fixed effects ($\widehat{\varphi}_i$) to retrieve (the log of) the wedges from $(\widehat{\sigma})^{-1}\widehat{\phi}_{vt}$. While this exercise may be valuable, we might be more interested in doing more than this. In particular, if we are willing to believe that both n and α vary across villages and months, we could try to back out the level of risk-sharing in each village and month. Unfortunately, the estimated village-month fixed effects do not allow me to separately identify n_{vt} and α_{vt}. However, we can do something to retrieve values for the village- and month-specific risk-sharing coefficients. Following the standard practice in the literature (Ligon et al. (2002), Laczó (2015), Bold and Broer (2020)), I set the village size in each village and month (n_{vt}) equal to the number of households sampled by ICRISAT in that village and month. Conditional on this imputation, I can back out a structural estimate of risk-sharing at the village-month level, $\widehat{\alpha}_{vt}$. To obtain this estimate, let

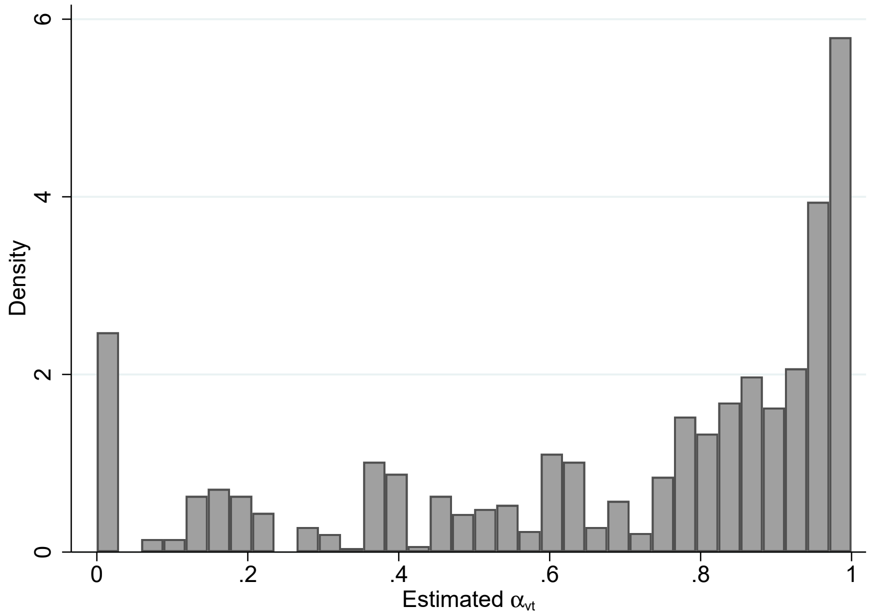
$$\widehat{\zeta}_{vt} = \exp\left\{\log\left(1 - \widehat{\frac{n_{vt}-1}{n_{vt}}\alpha_{vt}}\right)\right\}.$$

Then, compute

$$\widehat{\alpha}_{vt} = \left(1 - \widehat{\zeta}_{vt}\right)\frac{\widetilde{n}_{vt}}{\widetilde{n}_{vt}-1},$$

where $\widetilde{n}_{vt}$ is the imputed number of households sampled by ICRISAT. According to the theory, $\widehat{\zeta}_{vt} \in [0,1]$, for each v, t. Without any restriction being imposed, almost 70% of the $\widehat{\zeta}_{vt}$ fall within the expected 0-1 range. The histogram of $\widehat{\alpha}_{vt}$ I obtain after dropping the estimates of that do not fall within the expected 0-1 range is given in Figure 2.

Figure 2: Histogram of $\widehat{\alpha}_{vt}$



On average, $\widehat{\alpha}_{vt}$ equals 0.69 with a standard deviation equal to 0.32.

Brief discussion of identifying assumptions. It is worth noting that the identification of the κ_i's and σ does not rely on the linearity of the risk-sharing contract (Equation (3)), nor on the assumption that the expected benefit of consumption admits a mean-variance representation. In particular, Section D of the Online Appendix (specifically, Claim D.2) shows that if the first-order approach is valid, the optimal risk-sharing contract is differentiable, and the productivity shocks are additive, then household i's problem is equivalent to that of a competitive firm facing a real price of fertilizer equal to p_i and a real price of effort equal to $p_i\left(c_i^*\left(\boldsymbol{\pi}\right)\right)$, where

$$p_i^e\left(c_i^*\left(\boldsymbol{\pi}\right)\right) := \frac{k_i}{\int u'\left(c_i^*\left(\boldsymbol{\pi}\right)\right) \frac{\partial c_i^*\left(\boldsymbol{\pi}\right)}{\partial \pi_i} \mathrm{d}\Phi^{\varepsilon}\left(\boldsymbol{\varepsilon}\right)}.$$

In this expression, u is the von Neumann-Morgensten utility of consumption and $\partial c_i^*\left(\boldsymbol{\pi}\right)/\partial \pi_i$ is the slope of the contract, which measures the responsiveness of consumption to income. In this case, household i's relative demand for fertilizer to effort would be

$$\log\left(\frac{f_i^*}{e_i^*}\right) = \sigma \log\left(\kappa_i\right) - \sigma \log\left(\int u'\left(c_i^*\left(\boldsymbol{\pi}\right)\right) \frac{\partial c_i^*\left(\boldsymbol{\pi}\right)}{\partial \pi_i} \mathrm{d}\Phi^{\varepsilon}\left(\boldsymbol{\varepsilon}\right)\right) - \sigma \log\left(p_i\right). \quad (12)$$

Under the assumption that the risk-sharing contract is village and month specific, and u is the same across households and periods, we can still use Equation (11) to estimate the κ_i's and σ.[24]

2.2.2 Counterfactual

How do fertilizer use and effort supply change when risk-sharing changes? Consider Equation (10). Given parameters σ, κ_i, and n_{vt}, I can move the sharing coefficients, α_{vt}, to quantify the effect of risk-sharing on fertilizer used per hours worked. To get a more precise estimate of the elasticity of substitution σ and the disutilities of effort κ_i, I estimate the model on the whole sample of observations. Then, I use the structural estimates obtained to pin down σ and κ_i. As for n_{vt}, I set village size equal to the number of households sampled by ICRISAT. Formally, I compute

$$\widetilde{x}_{it}\left(\widetilde{\alpha}_{vt}\right) = \widetilde{\log\left(\frac{f_{it}}{e_{it}}\right)} = \widehat{\sigma}\widehat{\log\left(\kappa_i\right)} - \widehat{\sigma}\log\left(1 - \frac{\widetilde{n}_{vt} - 1}{\widetilde{n}_{vt}}\widetilde{\alpha}_{vt}\right) - \widehat{\sigma}\log\left(p_{it}\right),$$

where $\widetilde{n}_{vt}$ is the number of households sampled by ICRISAT, I impute $\widetilde{\alpha}_{vt}$ using the estimated levels of risk-sharing, and $\widetilde{x}_{it}$ is the resulting choice of fertilizer over effort (i.e., fertilizer use per hours of work), in logs. Figure 3 shows the kernel density estimate of fertilizer used per hours worked when setting $\widetilde{\alpha}_{vt} = 0$ (black) and $\widetilde{\alpha}_{vt} = 1$ (grey).

[24] Howeover, we would need to readdress the counterfactual exercise and policy simulation highlighted below. See the last paragraph of the following subsection.

Figure 3: Comparative statics

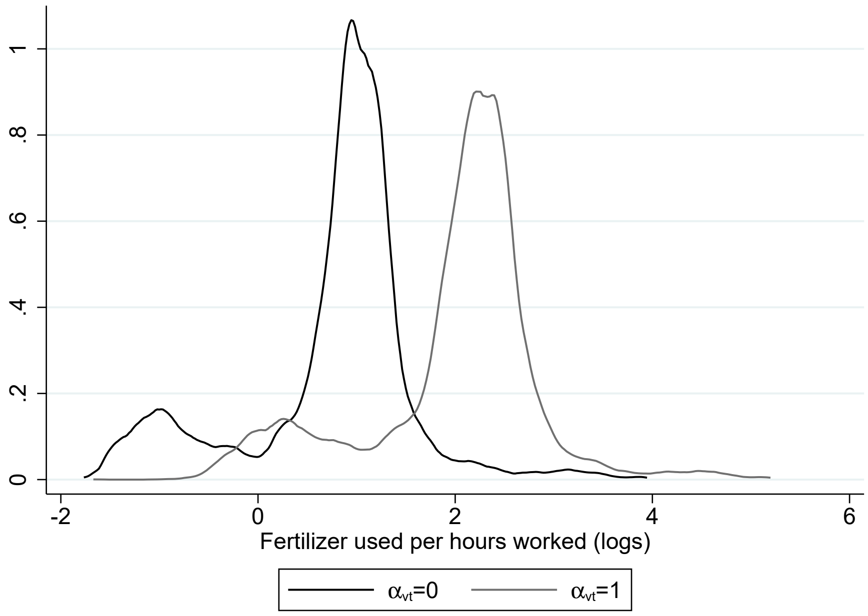


Table 3 reports the summary statistics of $\widetilde{x}_{it}(0)$ and $\widetilde{x}_{it}(1)$.

Table 3: Summary statistics for $\widetilde{\log\left(\frac{f_{it}}{e_{it}}\right)}$

	Average	S.d.	Min	Max
$\widetilde{\alpha}_{vt}=0$	2.4541	14.0909	-1.7666	387.3596
$\widetilde{\alpha}_{vt}=1$	3.6874	14.0827	-1.6697	388.5255

On average, when going from full insurance to no sharing, the median fertilizer over effort goes from 2.21 kilograms per hours worked to 0.97 kilograms per hours worked. It is interesting to disentangle the impact of risk-sharing on effort supply and fertilizer use. With additive productivity shocks, we can write down an expression for the effect of risk-sharing on effort supply and fertilizer use (see Section G of the Online Appendix). This expression only depends on the parameters estimated by running regression (11). Table 4 reports the summary statistics of the percentage changes of effort supply and fertilizer use when going from full insurance to no sharing when the productivity shocks are additive.

Table 4: Summary statistics for percentage changes of effort and fertilizer use (from $\widetilde{\alpha}_{vt} = 0$ to $\widetilde{\alpha}_{vt} = 1$)

	Average	S.d.	Min	Max
$e_{it}(0)/e_{it}(1)$	17.6330	15.6046	1	69.7501
$f_{it}(0)/f_{it}(1)$	4.8080	3.8009	1	15.6967

Median fertilizer use increased by 3.6 times, and median effort supply increases by 12 times. Hence, the intuition behind the result presented in Table 3 is that both effort supply and fertilizer use increase when moving from full insurance to autarky; however, effort supply is more responsive to changes in risk-sharing than fertilizer use, and hence increases more than what fertilizer use does.

This simple calculation quantifies the possible importance of risk-sharing for shaping households' effort supply and fertilizer use. The results in Table 4 are the same that would obtain when the productivity shocks are multiplicative in the limiting case in which either $\rho \to 0$ or $\eta \to 0$. In this case, the effect of insurance on input use boils down to the free-riding channel. However, as discussed in Section 1, there might be a risk-channel effect of insurance by which risk-sharing should positively affect the use of risky inputs. What would the results in Table 4 look like if we assumed that the productivity shocks were multiplicative? In this case, there is no closed-form solution for the relationship between risk-sharing, effort supply, and fertilizer use. Hence, to answer this question, I numerically solve for the optimal choices of effort and fertilizer using the first-order conditions outlined in the proof of Claim 2 and analyze how the solutions change when we move the level of risk-sharing α. These first-order conditions depend on ρ and η, two parameters that we cannot estimate by simply running regression (11). Instead of estimating these two parameters, I solve the first-order conditions for effort and fertilizer for different values of the parameters. In particular, I set the standard deviation of the productivity shock η to 0.75, following Morten (2019)'s estimate. As for the coefficient of absolute risk aversion, I take $\rho \in [0, 1]$. Under a CARA utility specification, these values of risk aversion correspond to a very wide range of risk attitudes, going from risk neutrality to extreme risk aversion. One way to see this is to follow Babcock et al. (1993). Consider a fair coin toss that delivers a gain h is the result is head and imposes a loss $-h$ if the result if tail. Refer to h as the gamble size and let it be equal to the standard deviation of household income (see Table 1). If the households' utilities of consumption are CARA then the risk premium of this gamble, expressed as a fraction of the size of the gamble h, is $(\rho h)^{-1}\log\left(0.5\left(\exp\left\{-\rho h\right\}+\exp\left\{\rho h\right\}\right)\right)$. Thus, $\rho\in[0,1]$ corresponds to risk premia between 1% and approximately 99% of the standard deviation of household income.

Figures 4 and 5 show the median change in effort supply and fertilizer use when going from full insurance to no sharing when the productivity shocks are multiplicative under different levels of risk aversion.

Figure 4: Median change in effort supply when going from full insurance to no sharing

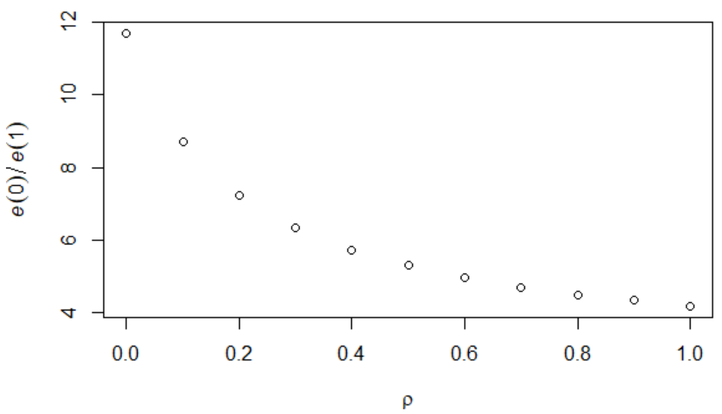
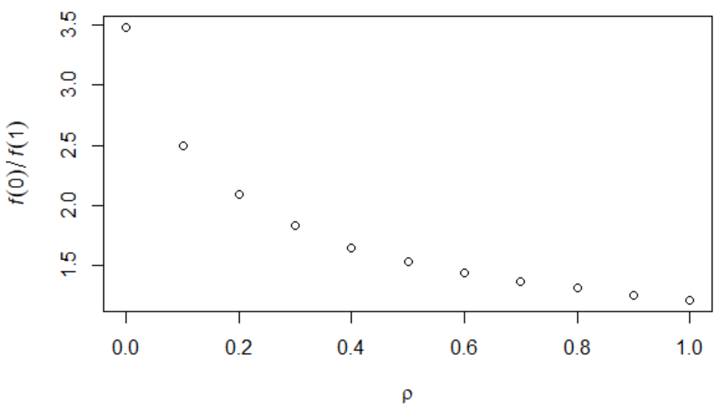


Figure 5: Median change in fertilizer use when going from full insurance to no sharing



As we can see, even for extremely high levels of risk aversion, effort supply and fertilizer use are higher under no sharing than full insurance. This evidence suggests that the free-riding channel dominates the risk factor channel for any reasonable level of risk aversion. The risk factor channel starts dominating the free-riding one for fertilizer use (i.e., there is a positive relationship between insurance and fertilizer use) around $rho = 2$, which would imply a risk premia equal to almost 100% of the standard deviation of household income. Thus, for the structural parameters obtained, my model suggests that we should expect a positive relationship between insurance and fertilizer use only for unrealistically risk-averse farmers. Specifically, the two figures above show that when moving from full insurance to no sharing, median fertilizer use is between 1.3 (for extremely risk-averse farmers) and 3.6 (for risk-neutral farmers) times higher. Median effort supply decreases by 4 to 12 times, depending on their assumed risk aversion.

Brief discussion of functional form assumptions. The estimates that I use to conduct the counterfactual exercise are the $\widehat{\kappa}_i$'s and $\widehat{\sigma}$. As explained above, these estimates do not depend on the linearity of the risk-sharing contract. However, the counterfactual exercise relies on this assumption to compute the effect of a change in risk-sharing of farmers' input choices. Alternatively, we could drop the assumption that the sharing contract is linear and use Equation (12) to calculate how different levels of insurance affect input use. In particular, under no sharing;

$$\log\left(\int u'\left(c_i^*\left(\boldsymbol{\pi}\right)\right)\frac{\partial c_i^*\left(\boldsymbol{\pi}\right)}{\partial \pi_i}\mathrm{d}\Phi^{\varepsilon}\left(\boldsymbol{\varepsilon}\right)\right)=\log\left(\int u'\left(\pi_i\right)\mathrm{d}\Phi^{\varepsilon}\left(\boldsymbol{\varepsilon}\right)\right),$$

and under full insurance,

$$\log\left(\int u'\left(c_i^*\left(\boldsymbol{\pi}\right)\right)\frac{\partial c_i^*\left(\boldsymbol{\pi}\right)}{\partial \pi_i}\mathrm{d}\Phi^{\varepsilon}\left(\boldsymbol{\varepsilon}\right)\right)=\log\left(\int u'\left(\frac{\sum_{j\in N}\pi_j}{n}\right)\frac{1}{n}\mathrm{d}\Phi^{\varepsilon}\left(\boldsymbol{\varepsilon}\right)\right).$$

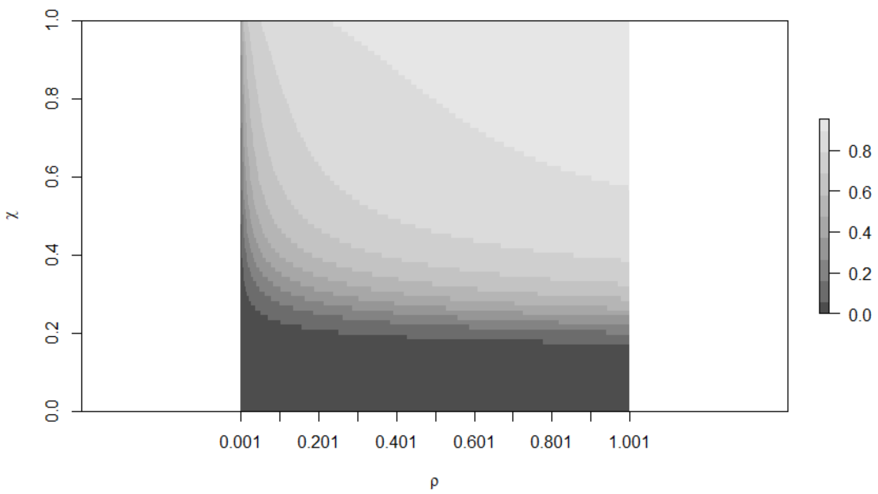
2.2.3 Welfare-maximizing sharing rule

Given the parameters I estimate, how much risk-sharing does my model predict? In the case of additive productivity shocks, I can answer this question by computing the welfare-maximizing sharing rule; i.e., solving Equation (8). This equation implicitly defines the sharing rule that a utilitarian planner would choose in a private information regime when the productivity shocks are additive. Besides being interesting to see how much risk-sharing my model predicts, I also need to compute the welfare-maximizing sharing rule to calculate how a fertilizer subsidy affects welfare. The reason is that a reduction in fertilizer prices affects the level of risk-sharing in each village and month. This change in risk-sharing affects households' choices and utilities.

Computing the optimal sharing rule with additive productivity shocks (by solving Equation (8)) requires to calculate the marginal benefit and the marginal cost of risk-sharing. These benefits and costs are the decrease in consumption volatility and the reduction in effort supply that arise when increasing risk-sharing. Computing the responsiveness of effort supply to changes in risk-sharing (i.e., the cost of risk-sharing) requires the assumption that there are decreasing returns in households' choices of effort and fertilizer (i.e., $\chi < 1$ in Equation (9)). To see why notice that, with additive productivity shocks, the household's problem of choosing effort and fertilizer is equivalent to that of a competitive firm facing a real price of fertilizer equal to p_i and a real price of effort equal to $\kappa_i\left(1+\left(n-1\right)n^{-1}\alpha\right)^{-1}$ (see the proof of Theorem 2). Under constant returns, the profit-maximizing choices of inputs by a competitive firm are indeterminate; hence, I cannot compute the decrease in effort supply brought about by an increase in risk-sharing. On the other hand, under decreasing returns, the choices of effort and fertilizer are uniquely determined; hence, I can compute $\partial e_i\left(\alpha\right)/\partial\alpha$.

Section H of the Online Appendix reports the algebraic steps to solve Equation (8), and shows that I need values for the land share $(1-\chi)$, the coefficient of absolute risk-aversion (ρ), and the variance of the idiosyncratic shock (η^2). The land share parametrizes the responsiveness of the effort supply to changes in risk-sharing (i.e., the marginal cost of risk-sharing); ρ and η^2 parametrize the welfare gain of reducing consumption volatility (i.e., the marginal benefit of risk-sharing). Notice that my empirical strategy does not allow to retrieve these parameters. Hence, I proceed as follows. I build a grid of possible values for χ and ρ. In principle, $\chi \in [0, 1]$; however, for computational reasons, I take $\chi \in (0.1, 0.9)$. As for the coefficient of absolute risk aversion, I assume that $\rho \in [0.001, 1.000]$.[25] I set $\eta = 0.75$, following Morten (2019)'s estimate. Figure 6 shows the optimal sharing rule under additive productivity shocks as a function of χ and ρ.

Figure 6: Welfare-maximizing sharing rule with additive productivity shocks



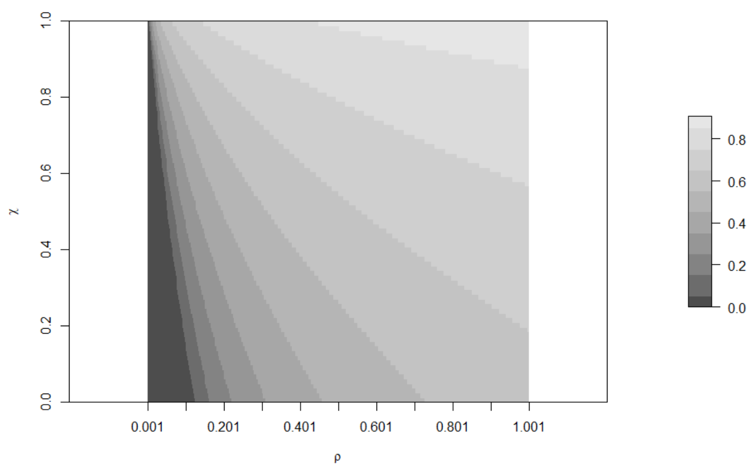
The rows represent different values of ρ, and the columns represent different values of χ. The colors in the box represent different values of the optimal sharing rule: the darker a point, the closer to autarky. A first intuition is that when households are more risk averse it is optimal to give them more insurance: for a given χ, optimal sharing increases when moving to the right. In the same way, when the land share coefficient increases, it is optimal to give the households more insurance: for a given ρ, optimal sharing increases when moving up. This

[25] The range $[0.001, 1.000]$ for ρ corresponds to a wide range of risk aversions. One way to see this is to follow Babcock et al. (1993). See the discussion at the end of Subsection 2.2.2.

effect happens because the responsiveness of effort to the effective cost of effort is decreasing in χ.[26]

We can also compute the welfare-maximizing sharing rule when the productivity shocks are multiplicative. To speed up the previous exercise in the case of multiplicative productivity shocks, I focus on computing the welfare-maximizing sharing rule for the median household only; i.e., I numerically solve Equation (6) assuming that there is only one household whose observable characteristics coincide with those of the median household.[27] As before, I solve for the welfare-maximizing sharing rule for different values of χ and ρ. Again, I take $\chi \in (0.1, 0.9)$ and $\rho \in [0.001, 1.000]$. Figure 7 shows the optimal sharing rule under multiplicative productivity shocks as a function of χ and ρ.

Figure 7: Welfare-maximizing sharing rule with multiplicative productivity shocks



As with the additive shock specification, when households are more risk averse

[26]In particular, if $\chi = 1$ then risk-sharing has no effect on the households' production decisions.

[27]Specifically, I set the village size, the marginal disutility of effort, and the fertilizer price equal to the median village size, the median marginal disutility of effort, and the median fertilizer price.

and the land share coefficient increases it is optimal to give them more insurance.

2.2.4 Fertilizer subsidy

Promoting fertilizer use is an objective for most governments in the developing world. Starting from 1977, the Indian Government introduced the Retention Price cum Subsidy Scheme (RPS), which stayed in place until 2003. Initially, the RPS was aimed at nitrogen-release fertilizer only, but the Government later extended it to other fertilizers. The RPS worked by setting a so-called retention price to fertilizers. The retention price was the price at which farmers should have been able to buy a unit of fertilizer (net of shipping costs and traders' mark-ups). This price was lower than the cost of production of fertilizer and fixed (i.e., independent of the quantity of fertilizer bought and sold in the market). The Government paid the difference between retention price and cost of production to fertilizer manufacturers for each unit sold. From the standpoint of poor households self-employed in agriculture, which paid no income tax,[28] the Government was exogenously lowering the prices of fertilizer.

I use the structural estimates obtained above to calculate how reintroducing an RPS would affect farmers' welfare. The model shows that a fertilizer subsidy increases welfare. To quantify this increase, I compute the consumption-equivalent gain in welfare of a fertilizer subsidy; i.e., the percentage increase in aggregate consumption that would make the planner indifferent to switching back from the subsidized fertilizer price to the actual price. Formally, let $\mathrm{W}\left(\sum_{i\in N} c_i\left(\boldsymbol{p}\right), \left(\boldsymbol{p}\right)\right)$ be the welfare that obtains when the households face the price vector $\boldsymbol{p} = \left(p_i\right)_i$, which implies that expected aggregate consumption is equal to $\sum_i c_i\left(\boldsymbol{p}\right)$. Then, we can define the consumption-equivalent gain in welfare of a fertilizer price subsidy as the number Δ such that

$$\mathrm{W}\left(\sum_{i\in N} c_i\left(\boldsymbol{p}\right) + \Delta, \boldsymbol{p}\right) = \mathrm{W}\left(\sum_{i\in N} c_i\left(\boldsymbol{p}^s\right), \boldsymbol{p}^s\right),$$

where $\boldsymbol{p}^s$ are the subsidized fertilizer prices. I focus on a subsidy that decreases the observed prices of fertilizer by 50%. To solve the previous equation, I need values for ρ (the coefficient of absolute risk aversion) and $1-\chi$ (the land share in the agricultural production function), two parameters that we cannot estimate

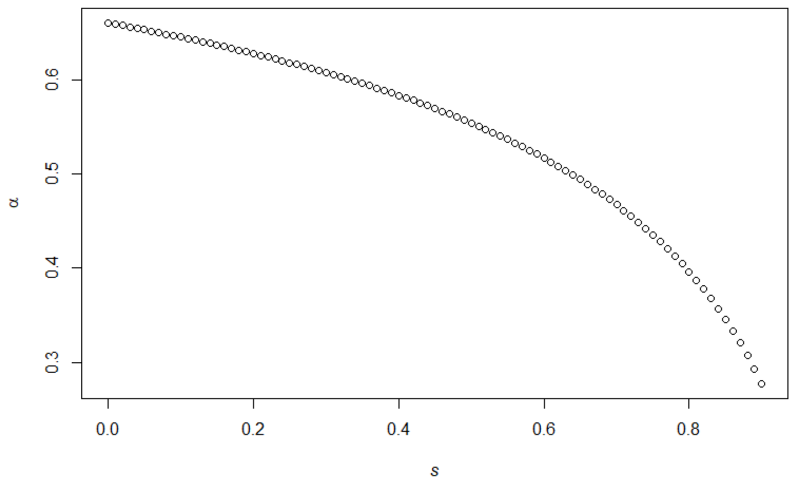
[28] Since 1886, according to the Indian Income Tax Act, Section 10(1), agricultural income is tax exempt.

by running regression (11). To solve this problem, I calibrate ρ and χ so that the optimal sharing rule implied by my model (in the absence of a fertilizer price subsidy) matches 0.67, which is the average level of risk-sharing I estimated in Subsection 2.2.1. This calibration implies that $\rho = 0.36$ and $\chi = 0.58$ for the multiplicative shock specification and $\rho = 0.01$ and $\chi = 0.53$ for the additive shock one.

In the case of multiplicative productivity shocks, I find that the consumption-equivalent gain in welfare from this cut in the prices of fertilizer is 8%. In the case of additive productivity shocks, this gain goes up to 99%.

As explained in Section 1, a fertilizer subsidy also affects optimal risk-sharing. We might be interested in understanding how risk-sharing reacts to changes in fertilizer prices. Figure 8 plots the optimal risk-sharing rule (on the y-axis) against $s \in (0, 1]$ (on the x-axis) when the productivity shocks are additive. Here, s is the fraction of fertilizer prices that are subsidized, so that the price of fertilizer faced by household i in month t is $(1 - s)\, p_{it}$.

Figure 8: Welfare-maximizing sharing rule and fertilizer subsidy (additive shocks)

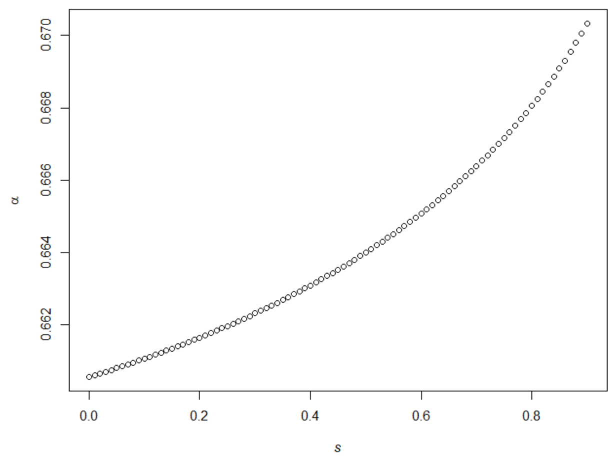


Hence, we can see that higher fertilizer price leads to more risk-sharing. For example, if the fertilizer subsidy is set cut fertilizer price in half, my model predicts that risk-sharing would decrease by 16%. The intuition is that, for the set of parameters estimated and calibrated, the slope of the effort supply function with respect to risk-sharing becomes more negative when the price of fertilizer is lower.

Thus, the subsidy increases the marginal cost of insurance, making it bigger than its marginal benefit. Because of the concavity of the welfare function around α^*, the planner decreases α to reestablish the equality between the marginal benefit and the marginal cost of risk-sharing.

Figure 9 plots the optimal risk-sharing rule (on the y-axis) against $s \in (0, 1]$ (on the x-axis) when the productivity shocks are multiplicative.

Figure 9: Welfare-maximizing sharing rule and fertilizer subsidy (multiplicative shocks)



In this case, a lower fertilizer price leads to more risk-sharing. This effect obtains because, in this case, when farmers buy more fertilizer and exert more effort, they also increase consumption volatility through the inputs' impact on yield variance. Hence, it becomes optimal for the planner to insure farmers more when they face cheaper inputs.

3 Conclusions

While rural households in developing countries face sizable random fluctuations in income, they often lack access to formal insurance. Despite this shortfall, these households manage to smooth their consumption, albeit imperfectly, by relying on informal insurance arrangements. These arrangements are pervasive and may be relevant drivers of technology adoption and agricultural input use. Most studies relating risk-sharing to agricultural input use argue that insurance should increase the take up of risky input. In this paper, I suggest that the disincentive effect of insurance can induce a trade-off between insurance and the use of effort-complementary inputs. I use this mechanism to study the relationship between informal insurance arrangements and fertilizer in rural India.

The paper makes use of the following two insights. First, risk-sharing can decrease households' incentives to exert effort. Second, fertilizer and effort are complementary inputs. The paper outlines a model of risk-sharing that combines these two insights and demonstrates theoretically that better-insured households may reduce their effort supply and fertilizer use. This "free-riding channel" relating insurance and fertilizer may reduce or even reverse the positive effect of insurance on the use of risky inputs.

I structurally estimate the model using the last ICRISAT panel from rural India. I obtain estimates for the elasticity of substitution between effort and fertilizer and the household-specific marginal disutilities of effort. I use these estimates to quantify the effect of risk-sharing on fertilizer use and effort supply. I find that when moving from full insurance to no sharing, median fertilizer use is between 1.3 and 3.6 times higher, depending on how risk averse the farmers are supposed to be. Median effort supply decreases by 4 to 12 times, depending on their assumed risk aversion. I also analyze the effect of a fertilizer subsidy on risk-sharing and recipients' welfare. If households' input choices increase yield variance, a 50% reduction in the observed prices of fertilizer would generate a 8% consumption-equivalent gain in welfare. In a world where effort and fertilizer do not affect yield variability, this gain would be equal to 99%.

My results show that considering the effect of insurance on fertilizer use through the complementarity between fertilizer and effort reverses the common perspective that insurance should foster fertilizer use for any reasonable level of risk aversion that Indian farmers might have. These results can play an important role in shaping our understanding of the relationship between insurance and technology adoption.

A Proofs

Proof of Claim 1. Problem (4) is equivalent to

$$\max_{\boldsymbol{a}} \sum_{i\in N} \left[y\left(a_i\right) - p_i f_i - \kappa_i e_i\right] - \frac{\rho\eta^2}{2}\left(1 - \frac{2\left(n-1\right)}{n}\alpha + \frac{n-1}{n}\alpha^2\right)\sum_{i\in N}\left[y\left(a_i\right)\right]^2.$$

If $\boldsymbol{a}^{\diamond}\left(\alpha\right)$ is an interior solution to this problem then

$$y_e\left(a_k^{\diamond}\left(\alpha\right)\right)\left[1 - \rho\left(1 - \frac{2\left(n-1\right)}{n}\alpha + \frac{n-1}{n}\alpha^2\right)y\left(a_k^{\diamond}\left(\alpha\right)\right)\eta^2\right] = \kappa_k,$$
$$y_f\left(a_k^{\diamond}\left(\alpha\right)\right)\left[1 - \rho\left(1 - \frac{2\left(n-1\right)}{n}\alpha + \frac{n-1}{n}\alpha^2\right)y\left(a_k^{\diamond}\left(\alpha\right)\right)\eta^2\right] = p_k,$$

for each $k \in N$. □

Proof of Claim 2. Problem (5) is equivalent to

$$\max_{a_i}\left(1 - \frac{n-1}{n}\alpha\right)\left(y\left(a_i\right) - p_i f_i\right) - \frac{\rho}{2}\left[\left(1 - \frac{n-1}{n}\alpha\right)y\left(a_i\right)\eta\right]^2 - \kappa_i e_i,$$

for each $i \in N$. If $a_i^*\left(\alpha\right)$ is an interior solution to the previous problem, then

$$\left\{\left(1 - \frac{n-1}{n}\alpha\right)\left[1 - \rho\left(1 - \frac{n-1}{n}\alpha\right)y\left(a_i^*\left(\alpha\right)\right)\eta^2\right]\right\}y_e\left(a_i^*\left(\alpha\right)\right) = \kappa_i,$$
$$\left[1 - \rho\left(1 - \frac{n-1}{n}\alpha\right)y\left(a_i^*\left(\alpha\right)\right)\eta^2\right]y_f\left(a_i^*\left(\alpha\right)\right) = p_i,$$

for each $i \in N$. □

Proof of Theorem 1. Consider the first-order conditions for effort and fertilizer under full information derived in the proof of Claim 1. The partial effects of a marginal increase in α on the marginal benefits of effort and fertilizer are equal to

$$y_e\left(a_i^{\diamond}\left(\alpha\right)\right)\rho\left(\frac{2\left(n-1\right)}{n}\right)\left(1-\alpha\right)y\left(a_i^{\diamond}\left(\alpha\right)\right)\eta^2$$

and

$$y_f\left(a_i^{\diamond}\left(\alpha\right)\right)\rho\left(\frac{2\left(n-1\right)}{n}\right)\left(1-\alpha\right)y\left(a_i^{\diamond}\left(\alpha\right)\right)\eta^2.$$

These quantities are positive. On the other hand, insurance does not affect the marginal costs of effort and fertilizer. It follows from standard convex programming techniques that $\left(e_i^{\diamond}\left(\alpha\right), f_i^{\diamond}\left(\alpha\right)\right)$ is an increasing function of α.

Next, consider the first-order conditions for effort and fertilizer under private information derived in the proof of Claim 2. The partial effect of a marginal increase in α on the marginal benefit of effort is proportional to

$$\left(-\frac{n-1}{n}\right)\left\{\left[1-\rho\left(1-\frac{n-1}{n}\alpha\right)y\left(a_i^*\left(\alpha\right)\right)\eta^2\right]-\rho y\left(a_i^*\left(\alpha\right)\right)\eta^2\right\}.$$

The sign of this quantity is ambiguous. The partial effect of a marginal increase in α on the marginal utility of fertilizer is proportional to

$$\rho\left(\frac{n-1}{n}\right)y\left(a_i^*\right)\eta^2,$$

a positive quantity. Suppose that y is strictly supermodular in (e_i, f_i). Since y is twice-continuously differentiable in e_i and f_i, strict supermodularity of y is equivalent to saying that $y_{ef}\left(a_i\right) > 0$. Standard lattice programming techniques imply that $f_i^*\left(\alpha\right)$ is strictly increasing in $e_i^*\left(\alpha\right)$ (Quah (2004)). Hence, if the free-riding channel is strong enough, so that $e_i^*\left(\alpha\right)$ is strictly decreasing in α, then so is $f_i^*\left(\alpha\right)$. □

Proof of Claim 3. Let $\mathcal{W}\left(\boldsymbol{a},\alpha\right) = \sum_{i\in N} U\left(c_i\left(\alpha\right), e_i\right)$ subject to Equations (3), (2), and (1). Notice that

$$\frac{\mathrm{d}\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right)}{\mathrm{d}\alpha} = \sum_{i\in N}\left[\frac{\partial\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right)}{\partial e_i^\diamond\left(\alpha\right)}\frac{\partial e_i^\diamond\left(\alpha\right)}{\partial\alpha}+\frac{\partial\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right)}{\partial f_i^\diamond\left(\alpha\right)}\frac{\partial f_i^\diamond\left(\alpha\right)}{\partial\alpha}\right]+\frac{\partial\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right)}{\partial\alpha}.$$

Since the planner is choosing $\boldsymbol{a}^\diamond\left(\alpha\right)$ so as to maximize welfare, we know that

$$\frac{\partial\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right)}{\partial e_i^\diamond\left(\alpha\right)} = \frac{\partial\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right)}{\partial f_i^\diamond\left(\alpha\right)} = 0.$$

Hence, at an efficient action profile,

$$\frac{\mathrm{d}\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right)}{\mathrm{d}\alpha} = \frac{\partial\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right)}{\partial\alpha}.$$

Notice that

$$\mathcal{W}\left(\boldsymbol{a}^\diamond\left(\alpha\right),\alpha\right) = \sum_{i\in N}\left[y\left(a_i^\diamond\left(\alpha\right)\right) - p_i f_i^\diamond - \frac{\rho}{2}\mathbb{V}\mathrm{ar}\left(c_i\left(\alpha\right)\right)\right],$$

where

$$\mathbb{V}\text{ar}\left(c_i\left(\alpha\right)\right) = \\ \mathbb{V}\text{ar}\left\{\left(1-\alpha\right)\left[y\left(a_i^{\diamond}\left(\alpha\right)\right)\varepsilon_i - p_i f_i^{\diamond}\right] + \alpha\frac{\sum_{j\in N}\left[y\left(a_j^{\diamond}\left(\alpha\right)\right)\varepsilon_j - p_j f_j^{\diamond}\right]}{n}\right\}.$$

From the previous equation, we can calculate that

$$\sum_{i\in N} -\frac{\rho}{2}\mathbb{V}\text{ar}\left(c_i\left(\alpha\right)\right) = -\frac{\rho}{2}\left\{\sum_{i\in N}\left[y\left(a_i^{\diamond}\left(\alpha\right)\right]^2\right]\right\}\left[1-\frac{2\left(n-1\right)}{n}\alpha + \frac{n-1}{n}\alpha^2\right]\eta^2.$$

Since $\left[1-2\left(n-1\right)n^{-1}\alpha + \left(n-1\right)n^{-1}\alpha^2\right]$ is decreasing over $[0,1]$, the partial effect of a marginal increase in insurance on welfare is positive. Finally, since the total effect of a marginal chance in insurance is equal to its partial effect, welfare is highest when $\alpha = 1$. □

Proof of Claim 4. The problem of finding a welfare-maximizing sharing contract under private information can be written as

$$\max_{\alpha}\sum_{i\in N}\left[y\left(a_i^*\left(\alpha\right)\right) - p_i f_i^*\left(\alpha\right) - \kappa_i e_i^*\left(\alpha\right) - \frac{\rho}{2}\mathbb{V}\text{ar}\left(c_i\left(\alpha\right)\right)\right].$$

Notice that, under private information, the planner is not choosing $\boldsymbol{a}\left(\alpha\right)$ to maximize welfare, which implies that we cannot use the implicit function theorem, as we did in the proof of Claim 3. Hence, compute the total derivative of the planner's objective function with respect to α to obtain

$$\sum_{i\in N}\left[y_e\left(a_i^*\left(\alpha\right)\right)\frac{\partial e_i^*\left(\alpha\right)}{\partial\alpha} + y_f\left(a_i^*\left(\alpha\right)\right)\frac{\partial f_i^*\left(\alpha\right)}{\partial\alpha} - p_i\frac{\partial f_i^*\left(\alpha\right)}{\partial\alpha} - \kappa_i\frac{\partial e_i^*\left(\alpha\right)}{\partial\alpha} \right. \\ \left. -\frac{\rho}{2}\frac{\partial\mathbb{V}\text{ar}\left(c_i\left(\alpha\right)\right)}{\partial\alpha}\right].$$

Rearranging, I get

$$\sum_{i\in N}\left[\left(y_e\left(a_i^*\left(\alpha\right)\right) - \kappa_i\right)\frac{\partial e_i^*\left(\alpha\right)}{\partial\alpha} + \left(y_f\left(a_i^*\left(\alpha\right)\right) - p_i\right)\frac{\partial f_i^*\left(\alpha\right)}{\partial\alpha} - \frac{\rho}{2}\frac{\partial\mathbb{V}\text{ar}\left(c_i\left(\alpha\right)\right)}{\partial\alpha}\right].$$

Combine the IC constraints given in Claim 2 to the previous expression to obtain Equation (6). Notice that

$$\left[1-\rho\left(1-\frac{n-1}{n}\alpha\right)y\left(a_i^*\left(\alpha\right)\right)\eta^2\right] \in (0,1].$$

To establish this result, notice that this quantity must be positive because otherwise the households would be better off supplying zero effort and purchasing no fertilizer. At the same time, $\rho\left(\left(n-1\right)n^{-1}\alpha\right)y\left(a_i^*\left(\alpha\right)\right)\eta^2 \geq 0$. □

Proof of Claim 5. With additive productivity shocks, maximizing welfare for a given level of risk-sharing under full information is equivalent to

$$\max_{\boldsymbol{a}} \sum_{i\in N} \left((1-\alpha)\left(y\left(a_i\right) - p_i f_i\right) + \alpha \frac{\sum_{j\in N} y\left(a_j\right) - p_j f_j}{n} - \kappa_i e_i \right);$$

i.e.,

$$\max_{\boldsymbol{a}} \sum_{i\in N} \left((1-\alpha)\left(y\left(a_i\right) - p_i f_i\right)\right) + \alpha \sum_{j\in N} \left(y\left(a_j\right) - p_j z_j\right) - \sum_{i\in N} \kappa_i e_i.$$

If $\boldsymbol{a}^{\diamond}(\alpha)$ is an interior solution, then

$$(1-\alpha)\, y_e\left(a_k^{\diamond}(\alpha)\right) + \alpha y_e\left(a_k^{\diamond}(\alpha)\right) - \kappa_i = 0,$$

for each $k \in N$; i.e., the marginal product of effort equals its marginal utility cost. The same argument holds for fertilizer. □

Proof of Claim 6. With additive productivity shocks, maximizing welfare for a given level of risk-sharing under private information is equivalent to

$$\max_{a_i} \left(1 - \frac{n-1}{n}\alpha\right)\left(y\left(a_i\right) - p_i f_i\right) - \kappa_i e_i, \;\; \forall i \in N.$$

If $\boldsymbol{a}^{*}(\alpha)$ is an interior solution, then

$$\left(1 - \frac{n-1}{n}\alpha\right) y_e\left(a_i^{*}(\alpha)\right) - \kappa_i = 0$$

and

$$\left(1 - \frac{n-1}{n}\alpha\right)\left(y_f\left(a_i^{*}(\alpha)\right) - p_i\right) = 0,$$

for each $i \in N$. □

Proof of Theorem 2. Notice that household i's IC constraint is equivalent to the problem of a competitive firm with production function $y\left(a_i\right)$ facing a real price of fertilizer equal to p_i and a real price of effort equal to p_i^e. This is easily checked by considering the problem of such a firm and noticing that the profit-maximizing choices of effort and fertilizer coincide with the first-order conditions given in Claim 6. Hence, $\partial e_i^{*}(\alpha) / \partial \alpha < 0$ is an immediate consequence of the law of supply. Since y is increasing and strictly supermodular, the objective function

$$y\left(a_i\right) - p_i^e e_i - p_i f_i$$

is strictly supermodular in $\left(e_i, f_i, -p_i^e\right)$. Summon Topkis' monotonicity theorem to show that $\left(e_i^{*}(\alpha), f_i^{*}(\alpha)\right)$ is strictly antitone in p_i^e. To complete the proof, notice that p_i^e is strictly increasing in α. □

Proof of Claim 7. The problem of finding a welfare-maximizing sharing contract under full information is equivalent to

$$\max_{\alpha} \sum_{i \in N} \Bigg((1-\alpha)\left(y\left(a_i^{\diamond}(\alpha)\right) - p_i f_i^{\diamond}(\alpha)\right) + \alpha \frac{\sum_{j \in N} y\left(a_i j^{\diamond}(\alpha)\right) - p_j f_j^{\diamond}(\alpha)}{n} \\ - \frac{\rho}{2} \mathbb{V}\mathrm{ar}\left(c_i(\alpha)\right) - \kappa_i e_i^{\diamond}(\alpha) \Bigg),$$

where

$$\mathbb{V}\mathrm{ar}\left(c_i(\alpha)\right) = \left((1-\alpha)^2 + \frac{\alpha^2}{n} + \frac{2\alpha(1-\alpha)}{n} \right) \eta^2.$$

Claim 5 implies that, under full information, $\boldsymbol{a}^{\diamond}(\alpha)$ is independent of α. Hence, the problem is equivalent to minimizing $\mathbb{V}\mathrm{ar}\left(c_i(\alpha)\right)$. It is easy to check that $\mathbb{V}\mathrm{ar}\left(c_i(\alpha)\right)$ is minimized when $\alpha = 1$. □

Proof of Claim 8. The problem of finding a welfare-maximizing sharing contract under private information is equivalent to

$$\max_{\alpha} \sum_{i \in N} \left(\mathbb{E}\left(c_i(\alpha)\right) - \frac{\rho}{2} \mathbb{V}\mathrm{ar}\left(c_i(\alpha)\right) - \kappa_i e_i^{*}(\alpha) \right)$$

subject to

$$\left(1 - \frac{n-1}{n}\alpha\right) y_e\left(a_i^{*}(\alpha)\right) = \kappa_i,$$
$$y_f\left(a_i^{*}(\alpha)\right) = p_i,$$

for each $i \in N$. This problem can be written as

$$\max_{\alpha} \sum_{i \in N} \left(y\left(a_i^{*}(\alpha)\right) - p_i f_i^{*}(\alpha) + \mu - \kappa_i e_i^{*}(\alpha) \right) - \frac{n\rho}{2} \mathbb{V}\mathrm{ar}\left(c_i(\alpha)\right).$$

Differentiate the planner's objective function with with respect to α to obtain

$$\sum_{i \in N} \left(y_e\left(a_i^{*}(\alpha)\right) \frac{\partial e_i^{*}(\alpha)}{\partial \alpha} + y_f\left(a_i^{*}(\alpha)\right) \frac{\partial f_i^{*}(\alpha)}{\partial \alpha} - p_i \frac{\partial f_i^{*}(\alpha)}{\partial \alpha} - \kappa_i \frac{\partial e_i^{*}(\alpha)}{\partial \alpha} \right) \\ - \frac{n\rho}{2} \frac{\partial \mathbb{V}\mathrm{ar}\left(c_i(\alpha)\right)}{\partial \alpha}.$$

Rearranging, I get

$$\sum_{i \in N} \left(\left(y_e\left(a_i^{*}(\alpha)\right) - \kappa_i\right) \frac{\partial e_i^{*}(\alpha)}{\partial \alpha} + \left(y_f\left(a_i^{*}(\alpha)\right) - p_i\right) \frac{\partial f_i^{*}(\alpha)}{\partial \alpha} \right) - \frac{n\rho}{2} \frac{\partial \mathbb{V}\mathrm{ar}\left(c_i(\alpha)\right)}{\partial \alpha}.$$

From the IC constraints given in Claim 6, the previous expression boils down to

$$\sum_{i\in N}\left(\kappa_i\left(\frac{1}{1-\frac{n-1}{n}\alpha}-1\right)\frac{\partial e_i^*(\alpha)}{\partial\alpha}\right)-\frac{n\rho}{2}\frac{\partial\mathbb{V}\mathrm{ar}(c_i(\alpha))}{\partial\alpha}.$$

Notice that $\left(\left(1-\alpha(n-1)n^{-1}\right)^{-1}-1\right)>0$, $\partial e_i^*(\alpha)(\partial\alpha)^{-1}<0$ by the law of supply (see the proof of Theorem 2), and $\partial\mathbb{V}\mathrm{ar}(c_i(\alpha))(\partial\alpha)^{-1}<0$ (see the proof of Claim 7). □

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