Risk-Sharing, Private Information, and the Use of Fertilizer

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Abstract

Insuring people's consumption can push them to cut their effort when it is difficult to monitor how hard they work. This effort reduction can go hand in hand with a decrease in the use of effort-complementary inputs. I use this mechanism to explain how risk-sharing may withhold fertilizer use in rural India. I study a model of risk-sharing with hidden action frictions and use the latest ICRISAT panel to estimate it. Median fertilizer use is 3.6 times higher under no sharing than under full insurance. A subsidy that halves the purchase prices of fertilizer would almost double farmers' welfare in consumption-equivalent terms.

Keywords: Risk-sharing, private information, effort, agriculture, fertilizer, complementarity.

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Every year, governments around the developing world spend billions of dollars on fertilizer subsidies. In India, for example, spending on fertilizer subsidies added up to 11 billion dollars (about 0.5% of GDP) in 2016 (Government of India, Ministry of Finance (2016)). Many agricultural experts bolster these policies arguing that increased fertilizer use leads to higher yields and therefore improved standards of living for rural households (Ellis (1992) and Sachs (2004)).[1] This argument suggests that farmers are missing opportunities for increased crop yields and has spurred economists' interest in uncovering which factors hold down the adoption of fertilizer in village economies.[2] In this paper, I analyze the role of risk-sharing arrangements in withholding fertilizer use.

Rural households in developing countries face severe income fluctuations due to weather conditions, illnesses, and pests, among other things. These households insure against random income shocks by relying on a variety of risk-sharing arrangements, such as gift exchange and personal loans (Bardhan and Udry (1999) and Fafchamps (2011)). There is a consensus in the literature that risk-sharing generally falls short of the full insurance benchmark; i.e., households are unable to insure completely against idiosyncratic risks (Townsend (1994), Udry (1994), and Conning and Udry (2007)). A leading explanation for imperfect risk-sharing is private effort (Fafchamps (1992) and Ligon (1998)).[3] The intuition is as follows: when it is hard to monitor how hard households work, consumption insurance can induce them to shirk (i.e., to work less and rely on others for their livelihood). Concurrently, effort and fertilizer are likely to be complementary inputs: the returns to fertilizer are higher when farmers apply it carefully and timely. Moreover, fertilizer application results in higher yields and weed growth, which require more labor for hand-weeding and harvesting.[4]

[1]See Duflo et al. (2008) for experimental evidence on the rates of return to fertilizer in Kenya.

[2]Possible explanations to low fertilizer use are credit constraints and risk (Dercon and Christiaensen (2011), Karlan et al. (2014), and Donovan (2020)), lack of complementary inputs (Beaman et al. (2013)), low quality (Bold et al. (2017)), and behavioral biases (Duflo et al. (2011)).

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

[4]I formalize the idea that fertilizer and effort are complements by assuming that

Given that fertilizer and effort can be complements, and insurance can decrease households' incentives to exert effort, I argue that risk-sharing may hold down fertilizer use through its discouraging effect on effort supply.[5]

In this paper, I study the connection between risk-sharing and fertilizer use. I provide a theoretical framework that relates the level of risk-sharing to households' effort supply and demand for fertilizer. Because of the private information (hidden action) friction, insurance leads farmers to lower the effort they exert, thereby decreasing their incentives to use inputs that are complementary to effort, like 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.[6] Empirically, I structurally estimate the model to quantify (1) the extent to which risk-sharing can hold down fertilizer use and (2) the effect of a fertilizer subsidy on recipients' welfare.

I outline a model of risk-sharing in which farmers insure against idiosyncratic productivity shocks by sharing the profits of agricultural production. Each household chooses how much effort to supply and how much fertilizer to buy to increase the expected yields of the fields it cultivates. 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. There is a trade-off between risk-sharing and productive efficiency: a higher level of insurance reduces the private marginal benefit of effort, thereby inducing households to shirk. Fertilizer and effort are complements; hence, higher insurance lowers fertilizer productivity, pushing farmers to decrease fertilizer use. 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,

the agricultural production function is strictly supermodular. I.e., effort increases the marginal product of fertilizer and vice versa. See Subsection 1.2.

[5]See Burchardi et al. (2019) for experimental evidence on the role of output-sharing on agricultural input choices when there are moral hazard frictions.

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

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 under-provided; 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 rural India, which provides high-quality information on households' farming activities and the prices paid for agricultural inputs. I use household- and month-level variation in fertilizer prices to rationalize their observed effort and fertilizer choices as optimal given their economic environment. The latter consists of households' tastes (their disutilities of effort), the market arrangements in the risk-sharing unit to which they belong (the level of sharing in each village and month), the economy-level technology (the elasticity of substitution between fertilizer and effort), and the prices of fertilizer. This empirical strategy only requires information on the distributions of households' effort and fertilizer choices and the fertilizer prices they face. It provides a joint test of (1) the relationship between risk-sharing and agricultural production decisions and (2) the complementarity between effort and fertilizer. I retrieve the elasticity of substitution between fertilizer and effort, the households' marginal disutilities of effort, and the level of sharing in each village and month. I use these parameters to quantitatively assess the impact of risk-sharing on effort supply and fertilizer use. Given the disutilities of effort, the agricultural technology, and the fertilizer prices, how would households' choices look like if they were to face different levels of risk-sharing? I simulate how effort supply and fertilizer use would change if farmers were to move from a situation in which they have full insurance to one in which they do not share any risk. Median fertilizer use is 3.6 times higher under no sharing than under full insurance. Median effort supply is 12 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 99%.

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 effort frictions, insurance has 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). 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 a subset of the model's parameters are identified just from the distributions of households' effort and fertilizer choices and of the prices of fertilizer they face. The parameters identified include the elasticity of substitution between effort and fertilizer. Thus, the model does not impose any assumption on the complementarity between fertilizer and effort, letting the data discipline this parameter instead. I show how to use these parameters to conduct counterfactual exercises that analyze the effect of changes on the prices of inputs (including the cost of effort, which is as if it was higher for more insured households) on households' production decisions. I also show that, up to three parameters, the distributions of effort and fertilizer choices and fertilizer prices are sufficient to identify and calculate the welfare gains of a change in fertilizer prices on households' welfare.

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 marginal benefit of effort 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 3.6 times as much fertilizer and supply 12 times more effort than if they were fully insured. 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 99%.

Related literature

Uncovering the determinants of agricultural input use in village economies 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 low- and middle-income countries. The literature has argued that it is important to uncover the impact of risk-sharing arrangements on technology adoption and agricultural input use, as these arrangements are ubiquitous in village economies.[7] This paper contributes to the understanding of the factors that constrain the use of modern agricultural inputs in village economies. I focus on how risk-sharing negatively affects effort supply and show how this effect relates to the use of fertilizer 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), Ka-

[7] According to Udry (2010), understanding "how [...] imperfect insurance influence[s] input choice and/or technology adoption in agriculture" is "a key research agenda" in agricultural and development economics.

plan (2006), Attanasio and Pavoni (2011), and Karaivanov and Townsend (2014)), this friction is hard to detect using observational data (Foster and Rosenzweig (2001)).[8] I contribute to this literature by quantifying the negative relationship between risk-sharing and effort.[9]

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 in which 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 point, we can think of it as a caste or kinship network. Every household chooses how much effort to supply and how much fertilizer to buy to increase the expected yields of the fields it cultivates. In Subsection 1.1, I outline the setup of the model. I focus on two informa-

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

[9]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)).

tion 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 subsidy on farmers' welfare. In Subsection 1.5, I provide a brief 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 $e_i \in \mathbb{R}_+$ and fertilizer $f_i \in \mathbb{R}_+$. Refer to $a_i = (e_i, f_i)$ as an action for household i. Let ε_i be a production shock with mean μ and variance η^2. Farmer i's production function is

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

where y is jointly concave in a_i, and strictly concave, strictly increasing, and twice-continuously differentiable in both e_i and f_i. The shocks are independently distributed across households.[10] Household i can only supply effort to its farm (there is no market for effort) and buy fertilizer at an exogenous price, that i takes as given, from a trader. Let $p_i \in \mathbb{R}_{++}$ be the particular price of fertilizer that i faces. Household i's agricultural profit (income) is

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

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

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

where $\alpha \in [0, 1]$ is a coefficient that fully characterizes the extent of risk-sharing and $\overline{\pi}$ is average income. The intuition is that each household consumes a fraction $1 - \alpha$ of its agricultural profit, and contributes the rest

[10] This assumption is convenient for exposition. My results are valid for more general specifications; e.g., $\varepsilon_i = \upsilon + \theta_i$, where υ is a village-level shock and θ_i is idiosyncratic risk.

to a common pool which farmers share equally. Risk-sharing is enforceable and households 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

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

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

An allocation is a sharing rule α together with an action profile $\boldsymbol{a} = \left(a_i\right)_i$. There is a utilitarian social planner who chooses an allocation to maximize welfare. 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 $\boldsymbol{a}^*$ for a given sharing rule α. Then, I find a welfare-maximizing sharing rule α^*.

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

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

subject to Equations (3), (2), and (1). There are no participation constraints, without loss of generality, because the planner is benevolent, each household's Pareto weight is 1, and risk-sharing is enforceable. Let $\boldsymbol{a}^{\diamond}\left(\alpha\right)$ be a solution to Problem (4). The following claim nails down the welfare-maximizing action profile.[11]

[11]Throughout the paper, I do not consider the corner solutions in which optimal effort or fertilizer is null. Inada conditions imposing $\lim_{e_i \to 0^+} y_e\left(e_i, f_i\right) = \lim_{f_i \to 0^+} y_f\left(e_i, f_i\right) = +\infty$ are sufficient to avoid these solutions.

Claim 1 (Efficient action profile)**.** *Under full information, and for given α, the welfare-maximizing action profile is a solution to*

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

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.

Private information. Assume that household i's action is private to i. In this case, to find a welfare-maximizing action profile for a given α, the planner has to 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). The difference between Problems (4) and (5) is that, in the private information regime, an optimal action profile has to 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 identifies the solution to this problem.

Claim 2 (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, the welfare-maximizing action profile is a solution to*

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

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 if facing a higher cost of effort. Claim 2 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. The next theorem shows how effort supply and fertilizer use change when the sharing coefficient α moves.

Theorem 1 (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 1 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.

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.:

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

subject to Equations (3), (2), (1), and $\boldsymbol{a} = \boldsymbol{a}^{\diamond}\left(\alpha\right) =: \boldsymbol{a}^{\diamond}$, 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.*

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

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

subject to Equations (3), (2), (1), and $\boldsymbol{a} = \boldsymbol{a}^{*}\left(\alpha\right)$, where $\boldsymbol{a}^{*}\left(\alpha\right)$ 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 $a_i^{*}\left(\alpha\right)$, for each $i \in N$. In this case, we can safely apply this approach because i's objective function is strictly concave in $a_i\left(\alpha\right)$, for any choice of α.

Let $W\left(\alpha\right)$ denote social welfare evaluated at $\boldsymbol{a}^{*}\left(\alpha\right)$. 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 4 (Constrained-efficient sharing)**.** *First, notice that*

$$\frac{\partial W\left(\alpha\right)}{\partial \alpha} = \underbrace{\sum_{i \in N}\left(\kappa\left(\frac{1}{1-\frac{n-1}{n}\alpha} - 1\right)\frac{\partial e_i^{*}\left(\alpha\right)}{\partial \alpha}\right)}_{(-)} \underbrace{-\frac{n\rho}{2}\frac{\partial \mathbb{V}\mathrm{ar}\left(c_i\left(\alpha\right)\right)}{\partial \alpha}}_{(+)}. \tag{6}$$

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

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

The first term of Equation (6) is the loss in aggregate production that the planner generates by increasing risk-sharing. This loss is the marginal cost of risk-sharing. The cost comes about because insurance distorts the allocation of effort and fertilizer away from the full-information benchmark. In particular, Equation (6) shows that the reduction in effort associated with a marginal increase in risk-sharing has a first-order effect on welfare.[12] The second term of Equation (6) is the 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.[13]

Notice that welfare can be written as

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

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

[12] 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.

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

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

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

Hence, besides reducing the monetary costs of production, the subsidy affects effort supply. Recall that $y_e\left(a_i^*\left(\alpha\right)\right) - \kappa_i > 0$ (see Claim 2): since effort is underprovided under private information, its marginal product is greater than its marginal cost. When fertilizer and effort are complements (which implies $\partial e_i^*\left(\alpha\right)/\partial p < 0$), the subsidy induces households to exert more effort, thus shrinking the negative externality generated by risk-sharing. I call this the *direct* effort 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.

To determine 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 $\partial^2 W(\alpha^*)/\partial\alpha^2 < 0$.[14] 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 $\partial^2 e_i^*(\alpha^*)/\partial\alpha\partial p > 0$

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

then the slope of the effort supply function with respect to risk-sharing becomes more negative when the price of fertilizer is 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.

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 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.

In the production function in Equation (1), shocks are additive. Hence, supplying more effort or using more fertilizer increases expected output without affecting its higher moments. This assumption implies that risk does not have a direct effect on input choice. I make this strong assumption for two reasons. First, it isolates the negative effect of risk-sharing on fertilizer use through the complementarity between effort and fertilizer. This effect contrasts with work highlighting how insurance affects input choices directly through the inputs' risk factors (Braverman and Stiglitz (1986) and Donovan (2020)). Section E of the Online Appendix compares the two approaches and discusses how my results change if input choices have an impact on output volatility. In particular, fertilizer may be risk increasing (Just and Pope (1979)). Hence, we could expect better-insured households to use more of it. However, 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 the second reason for assuming additive shocks: it considerably simplifies the analysis of the model while still being consistent with the evidence that risk-sharing is negatively correlated with fertilizer use.

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,[15] 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 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 specif. 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.[16]

[15] In the data, more than 90% of the households in the full sample supply labor to their farm.

[16] See Jensen (2007), Svensson and Yanagizawa (2009), Aker (2010), Nakasone (2014),

However, my theoretical results do not depend on the presence of price dispersion.

In the model, I assume that this contract is linear.[17] 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 production 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 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 and estimate the model outlined above to retrieve some of its structural parameters. I use these parameters

Aker and Fafchamps (2015), Mitra et al. (2018).

[17]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)).

to (1) quantify the extent to which risk-sharing can decrease effort supply and fertilizer use, and (2) calculate the welfare gain from a fertilizer subsidy for subsidy recipients.

2.1 Background and data

I use a 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 comes from detailed survey interviews conducted at a monthly frequency from 2009 to 2014 and covers households in 18 villages in the Indian semi-arid tropics. For each village, 40 households were randomly selected stratifying by landholding classes (10 are landless laborers, 10 are small farmers, 10 are medium farmers, and 10 are large farmers). My empirical strategy requires information on the distributions of households' effort and fertilizer choices and of the fertilizer prices they face. This data fits 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.[18] Moreover, researches have widely used this 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.[19]

[18]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.

[19]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

For the estimation, I need information on how much effort the households exert, how much fertilizer they use, and the prices of fertilizer they face. Effort is proxied by the per capita total hours of work supplied by family members in the fields they cultivate. Fertilizer is the per capita total value of fertilizers used by family members in the fields they cultivate. Fertilizer price is the average price of fertilizer payed by the household for all fertilizer it bought. 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.

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
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.

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.

This claim characterizes the households' optimal choices of effort and fertilizer as functions of the technology (the production function), the households' preferences (their disutilities of effort), the market arrangements (risk-sharing) in which they operate,[20] and the prices of fertilizer 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 in which the households operate, which they take as given. This strategy allows me to retrieve (1) the elasticity of substitution between effort and fertilizer, (2) the households' marginal disutilities of effort, and (3) the levels of risk-sharing that they face, as explained below. I use these 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 were to move 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 who are treated by this policy. To do so, I compute the consumption-equivalent gain in farmers' welfare 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 the model is that it greatly simplifies strategic interactions between the 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 give rise to more convoluted strategic interactions, hence making identification and estimation more complex. While my model is parsimonious, most of its estimated parameters satisfy the theoret-

[20]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.

ical 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

$$y\left(a_i\right) = \ell_i^{1-\chi}\left[e_i^{\frac{\sigma-1}{\sigma}} + f_i^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\chi\sigma}{\sigma-1}}, \tag{7}$$

where $\sigma \in (0,\infty)$ is the elasticity of substitution between effort and fertilizer, ℓ_i is land, which I assume to be fixed,[21] 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 and fertilizer for household i), the first-order conditions for effort and fertilizer given in Claim 2 read as follows:

$$\ell_i^{1-\chi}\chi\left[e_i^{*\frac{\sigma-1}{\sigma}} + f_i^{*\frac{\sigma-1}{\sigma}}\right]^{\frac{\chi\sigma}{\sigma-1}-1} e_i^{*-\frac{1}{\sigma}} = \frac{\kappa_i}{\left(1-\frac{n-1}{n}\alpha\right)}$$

and

$$\ell_i^{1-\chi}\chi\left[e_i^{*\frac{\sigma-1}{\sigma}} + f_i^{*\frac{\sigma-1}{\sigma}}\right]^{\frac{\chi\sigma}{\sigma-1}-1} f_i^{*-\frac{1}{\sigma}} = p_i.$$

Dividing the second equation by the first one, rearranging, and taking logs, I 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 environment. The latter consists of the elasticity of substitution between fertilizer and effort (σ), i's disutility of effort (κ_i), the risk-sharing pool (α and n), and the price of fertilizer i faces (p_i).

In the data, I observe for each household in each month (1) how much effort it supplied, (2) how much fertilizer it used, and (3) the price of fertilizer it paid. The parameters of interest are the elasticity of substitution between

[21] 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).

effort and fertilizer, the marginal disutility of effort, and the wedge between the social and the private marginal benefit of effort $\left(1-(n-1)\, n^{-1}\alpha\right)$. To take the model to the data, I need to specify how these parameters vary across households and time. I assume that the marginal disutility of effort is household specific and constant in time, and that village size and risk-sharing are time varying and village specific. Then, assuming that the model is correctly specified, if there is an error in the measurement of fertilizer or effort, I can estimate

$$\log\left(\frac{f_{it}}{e_{it}}\right)=\sigma\log\left(\kappa_i\right)-\sigma\log\left(1-\frac{n_{vt}-1}{n_{vt}}\alpha_{vt}\right)-\sigma\log\left(p_{it}\right)+\epsilon_{it}. \tag{8}$$

The assumption that village size and risk-sharing are time varying and village specific allows me to rationalize variation in village-month heterogeneity as coming from changes in either the size of the sharing pool 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.[22] In this case, I can use OLS to estimate the following regression equation:

$$\log\left(\frac{f_{it}}{e_{it}}\right)=\varphi_i+\phi_{vt}-\sigma\log\left(p_{it}\right)+\epsilon_{it}, \tag{9}$$

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 village size and risk-sharing are time varying and village specific, I need both cross-sectional and time variation in fertilizer prices or I would not be able to identify σ separately from the fixed

[22] A random measurement error in fertilizer prices, which is likely to exist, would imply a downward bias in the OLS estimate of σ.

effects.[23] I do observe dispersion in fertilizer prices across households and time, consistently with the literature on price dispersion in agricultural markets (Jensen (2010)). Finally, to accommodate the sparsity of the data in some village-month pairs, I focus on village-month pairs that contain at least 10 observations. This restriction does not entail the loss of any village and increases the precision of the estimated village-month fixed effects.[24] Table 2 reports the results of running the regression specified in Equation (9).

Table 2: Structural regression

Dep. variable: $\log\left(\frac{f_{it}}{e_{it}}\right)$	$\widehat{\beta}$ (s.e.)
$\log(p_{it})$	$-.3499^{***}$
	(.0.2326)
Household fixed effects	Yes
Village-month fixed effects	Yes
R-squared	0.629
Observations	9,881

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, $\widehat{\sigma}$,

[23] We can come up with different strategies to estimate the parameters of interest. For example, I could assume that village size and risk-sharing are village specific and constant in time, and use monthly variation in international fertilizer prices to instrument the prices of fertilizer faced by the households.

[24] As robustness checks, I re-estimate the model under different restrictions on the minimum number of observations that each village-month pair has to contain. I also estimate the model under no restriction, using all village-month pairs available. These different options have virtually no effect on the estimates of the elasticity of substitution between effort and fertilizer and the marginal disutilities of effort. On the other hand, dropping the village-month pairs that contain less than 10 observations slightly improves the ability of the estimated risk-sharing coefficients to satisfy the model's restriction without being imposed, as explained below.

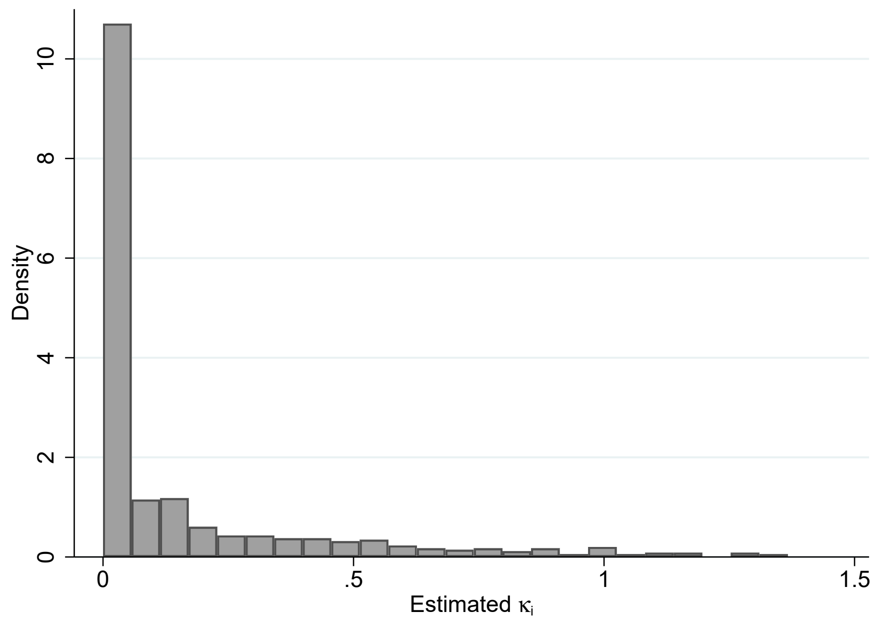
is about 0.35. As it lies between 0 and 1, this elasticity confirms that effort and fertilizer are complements.

To back out the marginal disutilities of effort, I compute

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

which I obtain by dividing the household fixed effects by $\widehat{\sigma}$. Figure 1 shows the histogram of the marginal disutility of effort.[25]

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

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

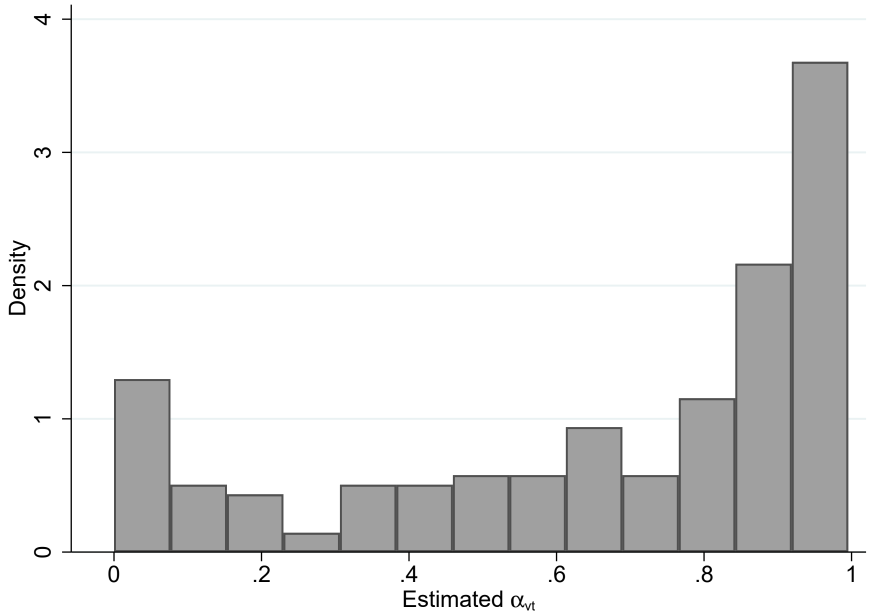
an increase in consumption of $0.047\rho^{-1}$ rupees. According to the estimates provided by the Indian Government (Indian Labour Bureau (2010)), in 2009, the daily wage rate for an adult male agricultural worker fell in the range of 50 to 120 2009 rupees, which roughly correspond to an hourly wage 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 marginal benefit of effort using the same procedure employed to obtain the marginal disutilities of effort. I cannot separately identify n_{vt} and α_{vt}. Nevertheless, following the standard practice in the literature (Ligon et al. (2002), Laczó (2015), Bold and Broer (2020)), I set village size equal to the number of households sampled by ICRISAT and back out a structural estimate of risk-sharing at the village-month level, $\widehat{\alpha}_{vt}$, by computing

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

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 0.67 with a standard deviation equal to 0.33.

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 and the optimal risk-sharing contract is differentiable, 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

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

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

$$\log\left(\frac{f_i^*}{e_i^*}\right) = \sigma\log\left(\kappa_i\right) - \sigma\log\left(\int u'\left(c_i^*\left(\boldsymbol{\pi}\right)\right)\frac{\partial c_i^*\left(\boldsymbol{\pi}\right)}{\partial \pi_i}\mathrm{d}\Phi^{\varepsilon}\left(\boldsymbol{\varepsilon}\right)\right) - \sigma\log\left(p_i\right). \tag{10}$$

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 (9) to estimate the κ_i's and σ.[26]

2.2.2 Counterfactual

How do fertilizer use and effort supply change when risk-sharing changes? Consider Equation (8). 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).

[26] 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

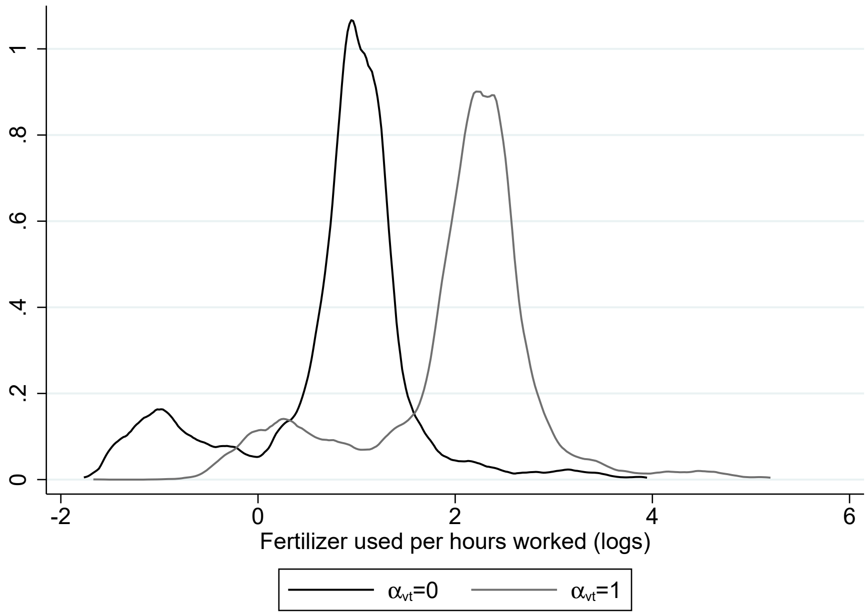


Table 3 reports the summary statistics of $\widetilde{x}_{it}\,(0)$ and $\widetilde{x}_{it}\,(1)$.

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. Next, I disentangle the impact of risk-sharing on effort supply and fertilizer use (see Section G of the Online Appendix). Table 4 reports the summary statistics of the percentage changes of effort supply and fertilizer use when going from full insurance to no sharing.

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 importance of risk-sharing in shaping households' effort supply and fertilizer use.

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 (10) 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? To answer this question, I compute the welfare-maximizing sharing rule, solving Equation (6). This sharing rule is the one that a utilitarian planner would choose in a private information regime. 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.

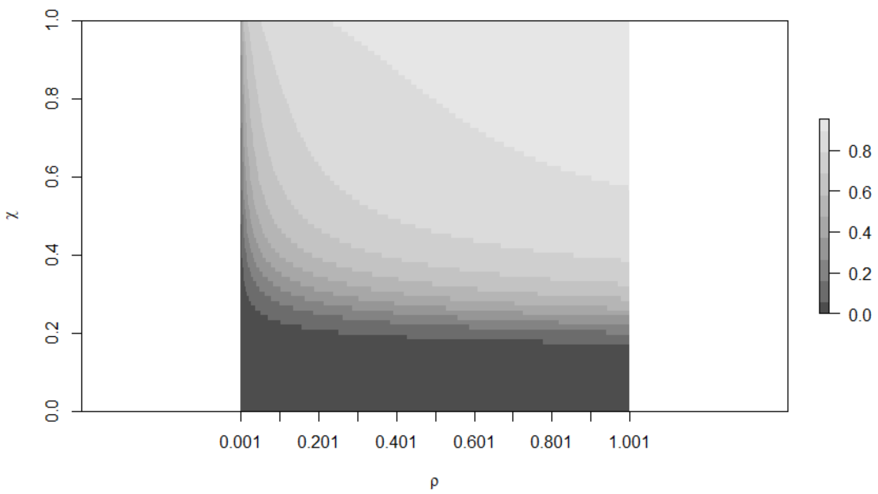
Computing the optimal sharing rule (by solving Equation (6)) requires to calculate the marginal benefit and the marginal cost of risk-sharing. These benefits and costs are the decrease in consumption volatility and the reduction in effort supply that arise when increasing risk-sharing. Computing the 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 (7)). To see why notice that 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 $\kappa_i \left(1 + (n-1)\, n^{-1}\alpha\right)^{-1}$ (see the proof of Theorem 1). 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 (6), 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 $\rho \in [0.001, 1.000]$.[27] I set $\eta = 0.75$,

[27]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). 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 in-

following Morten (2019)'s estimate. Figure 5 shows the optimal sharing rule as a function of χ and ρ.

Figure 4: Welfare-maximizing sharing rule



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 effect happens because the responsiveness of effort to the effective cost of effort is decreasing in χ.[28]

come (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 $(\rho h)^{-1} \log(0.5(\exp\{-\rho h\} + \exp\{\rho h\}))$. Thus, $\rho \in [0.001, 1.000]$ corresponds to risk premia between 1% and 99% of the standard deviation of household income.

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

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,[29] the Government was exogenously lowering the prices of fertilizer.

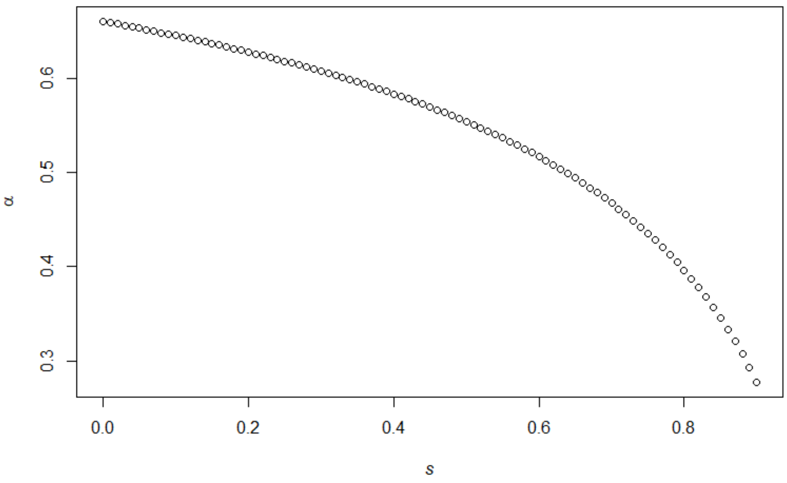
I use the structural estimates obtained above to calculate how reintroducing an RPS would affect farmers' welfare. The model shows that a fertilizer subsidy increases welfare (Subsection 1.4). To quantify this increase, I compute the consumption-equivalent gain in welfare of a fertilizer subsidy; i.e., the percentage increase in aggregate consumption that would make the planner indifferent to switching back from the subsidized fertilizer price to the actual price. I focus on a subsidy that decreases the observed prices of fertilizer by 50%. I find that the consumption-equivalent gain in welfare from this cut in the prices of fertilizer is 99%.

My model implies that a fertilizer subsidy affects risk-sharing and welfare (see Subsection 1.4). Figure **??** plots the optimal risk-sharing rule (on the y-axis) against $s \in (0, 1]$ (on the x-axis), where s is the fraction of the price of fertilizer that is subsidized, so that the price of fertilizer faced by household i in month t is $(1 - s)\, p_{it}$.[30]

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

[30]To draw this graph, I calibrate ρ and χ so that the optimal sharing rule matches 0.67, which is the average level of risk-sharing I estimated in Subsection 2.2.1. This calibration implies that $\rho = 0.01$ and $\chi = 0.53$.

Figure 5: Welfare-maximizing sharing rule and fertilizer subsidy



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.

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 they might have an impact on technology adoption and agricultural input use. Studies on risk-sharing abound, but few of them try to relate risk-sharing to agricultural input use. In this paper, I analyze the effect of informal insurance arrangements on fertilizer use when there are private information frictions in production decisions.

The paper makes use of the following two insights. First, risk-sharing can have a discouraging effect on 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 decrease effort provision and fertilizer use.

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, the household-specific marginal disutility of effort, and the village- and month-specific constrained-efficient sharing rule. 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 3.6 times higher, and median effort supply decreases by 12 times. I also analyze the effect of a fertilizer subsidy on risk-sharing and recipients' welfare. My model predicts that a 50% reduction in the observed prices of fertilizer would generate a 16% drop in risk-sharing and a 99% consumption-equivalent gain in welfare.

In principle, risk-sharing could affect fertilizer use through channels different from the one I study in this paper. For example, better-insured households should be more willing to increase their use of riskier inputs. The fact that fertilizer might increase output volatility implies that risk-sharing could also have a positive effect on fertilizer use. I do not find evidence of a positive relationship between insurance and fertilizer use in the data. Moreover, while my model strips away from the possibility that fertilizer could increase yield volatility, if this effect is not too high, then my qualitative results remain valid. Other explanations can rationalize farmers' decisions to use low levels of fertilizer (Dercon and Christiaensen (2011), Bold et al. (2017), and Duflo et al. (2011)). The view I propose here complement these explanations and together deepen our knowledge of the reasons leading poor farmers to under-utilize fertilizer.

A Proofs

Proof of Claim 1. Problem (4) 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 2. Problem (5) is equivalent to

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

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 1. 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 2. 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 $(e_i, f_i, -p_i^e)$. Summon Topkis' monotonicity theorem to show that $(e_i^*(\alpha), f_i^*(\alpha))$ is strictly antitone in p_i^e. To complete the proof, notice that p_i^e is strictly increasing in α. $\square$

Proof of Claim 3. 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 1 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 $\alpha = 1$. $\square$

Proof of Claim 4. 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

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

Derivate 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

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

From the IC constraints given in Claim 2, the previous expression boils down to

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

Notice that $\left(\frac{1}{1-\frac{n-1}{n}\alpha}-1\right)>0$, $\partial e_i^*\left(\alpha\right)/\partial\alpha<0$ by the law of supply (see the proof of Theorem 1), and $\partial\mathbb{V}\mathrm{ar}\left(c_i\left(\alpha\right)\right)/\partial\alpha<0$ (see the proof of Claim 3). □

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