Sharing Risk to Avoid Tragedy: Informal Insurance and Irrigation in Village Economies

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Abstract

I present a model of joint co-operation over irrigation and risk sharing in presence of limited commitment constraints. I estimate the model to the setting of three village economies in rural India. The implied dynamics are validated by non-targeted empirical evidence and show that if access to irrigation can be regulated by villagers, the two institutions reinforce each other. However, if irrigation is non-excludable (as is the case with provision by central authorities), such investments harm local co-operation. Counterfactual experiments quantify mutual reinforcement between the two institutions and gains attainable by replacing the government-owned irrigation.

Key words: Risk Sharing, Limited Commitment, Informal Institutions

JEL Codes: E20, O12, O11, O13, Q15

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1 Introduction

Farmers are exposed to a plethora of shocks affecting their crop yields, investment decisions and, ultimately, consumption. Some of these shocks are idiosyncratic in their nature such as pests, human, animal, crop diseases, machine breakdowns or unemployment. For the vast majority of farmers who are located in developing countries, self-insurance is usually very limited - either due to poverty or lack of formal credit markets. In order to mitigate these risks, rural societies have developed systems of informal insurance characterized by high repayment flexibility (Udry, 1990, 1994; Townsend, 1994). Surprisingly, however, although repayments in such arrangements are in principle completely voluntary, they have proved robust to excessive default rates. The main reason for this is arguably the repeated nature of interactions within these societies and the possibility of shutting off their access to credit in the future or applying other forms of exclusion and punishment.

At the same time, one of the major aggregate risks faced by many farmers is erratic rainfall resulting in droughts. Fortunately enough, the impact of such weather shocks can also be mitigated to some extent through the use of modern irrigation systems. Given their highly public nature, the best outcomes can be achieved either if the degree of co-operation between affected households is high, or if enough of the necessary infrastructure is provided by central authorities. Since such investments reduce the level of aggregate risks, they can also reduce the demand for informal insurance. However, also in this case, the repeated nature of interactions and various types of social norms may allow for eliciting better co-operation patterns, especially if the infrastructure is under management of the local community. Thus, these two institutions may be very interrelated. Investigating this cornerstone relationship is at the heart of this paper.

In particular, I extend the canonical model of risk sharing with limited commitment developed by Kehoe and Levine (1993), Kocherlakota (1996) and Ligon, Thomas and Worrall (2002) in order to study joint determination of risk sharing against idiosyncratic risks and co-operation over investments reducing aggregate risk in the presence of limited commitment constraints. I first argue that if villagers have a possibility to exclude non-cooperators both from the local informal insurance and irrigation networks, the two institutions are likely to reinforce each other. On one hand, compared to standard self-insurance, state-contingent risk sharing constitutes a more effective way of insuring distortionary idiosyncratic risks, and as such improves efficiency of irrigational investments (Arrow, 1971). On the other, co-ordinated investments into irrigation increase the value of co-operation for all households by improving their aggregate productivity process while maintaining the value of non-cooperating at a low level (due to the punishing deviators by exclusion from both institutions). Consequently, this dynamic implies that the extent of risk sharing transfers sustainable in equilibrium is enhanced by the irrigation margin. Interestingly, the fact that each institution provides an effective punishment for deviations on either margin of co-operation implies that both institutions not only reinforce, but also stabilize each other with respect to potential default.

Focusing on the empirical setting of three rural Indian villages, I structurally estimate the model using rich empirical variations in the first wave of the ICRISAT panel from years 1976-1984 combined with Minor Irrigation Censuses conducted by the Indian Ministry of Water Resources. I do so by employing methods of simulated moments and indirect inference for matching the empirical evidence on the degree of consumption smoothing, characteristics of the aggregate and idiosyncratic income shocks and the impact of bad weather and irrigation on income. Validating both the estimation strategy and modeling assumptions, I show that the estimated village economies fit both the targeted and non-targeted moments in the data well. Most importantly, I devise an extended consumption smoothing test taking into account the impact of irrigation and its ownership structure and compare its results from the data generated by the quantitative model and from a long-run panel made of the merged first and (not used for estimation) second waves of the ICRISAT panel. The implied economic effects are close to each other and confirm that while increases in the amount of irrigation improve risk sharing, increases in irrigation's government-ownership share crowd it out. I also discuss further studies supporting the mechanism.[1]

Using the estimated model, I conduct two counterfactual experiments. First, I investigate the interaction between the two margins of co-operation over risk sharing and irrigation. When the risk sharing co-operation is turned off, I find that although the self-insurance motives increase the mean level of irrigation investments by up to 87%, their volatility increases by up to 227%. At the same time, although the mean level of consumption does not change much, its variance goes up by up to 181%. This confirms importance of risk sharing both for providing better insurance against idiosyncratic shocks and enhancing efficiency of investments in rural areas. Consequently, households co-operating over irrigation value access to risk sharing by up to 10% of consumption in every period. On the other hand, as I turn off the co-operation over irrigation, irrigational investments decline by up to 12%, the aggregate productivity drops by up to 7% and its variance increases by up to 23%. Confirming results from the extended consumption smoothing test, risk sharing becomes less efficient as reflected by significant increases in the elasticity of consumption and reductions in the size of insurance transfers. As a result, households engaged only into risk sharing are willing to forgo up to 16% of consumption in every period in order to continue co-operating over irrigation. Interestingly, maintaining co-operation over irrigation turns out to be particularly important in Shirapur, as without it its villagers would not be able to sustain any co-operation over risk sharing either, demonstrating the mutual stabilization of endogenous institutions in rural economies.

As a second experiment, I quantify the welfare effects of replacing the government-

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[1] See work of Wade (1988) and Bardhan (2000) and their discussions in the literature review and in Section 5.1. Furthermore, Ostrom (1990) gives many examples of rural societies that both co-operated over the common resources/goods and various forms of risk sharing. In the case of Spanish societies co-operating over irrigation, the contract on the water use also contained water sharing rules in times of droughts. In particular, the crops in most need of water were given priority. In case of the Filipino farmers, the way of dividing land was symmetrical in the sense of everyone having some land closer to and some further away from the water source; and during dry periods all the farmers collectively decided how to share the burden and assign the water rights, again with priority for the crops in most need.

owned infrastructure with the community-owned one. Such a reform strengthens the within-village co-operation by improving both the informal insurance (achieving a reduction in consumption elasticity w.r.t. idiosyncratic shocks of up to 80% and an increase in the amount of insurance transfers of up to 52%) and the efficiency of irrigational investments (achieving a reduction in variance of aggregate productivity of up to 33% and an increase in its average level of up to 7%). As a result, it is valued by villagers by up to 9% of consumption in every year.

Given the trade-off associated with central ownership and management of public investments, policy makers should carefully consider the general equilibrium effects of their actions on the welfare of rural societies. This is especially so since any policy distorting co-operation over one margin may not only distort efficiency of other margins, but - in extreme cases - it may also result in domino effects leading to a complete collapse of co-operation in the community. Consequently, the research question pursued in this paper is particularly important for governments heavily supporting development of irrigation infrastructure - such as the government of India, where public spending on various irrigation projects in 2016 amounted to approx. 5.5 billion USD, or 8.5% of total budget expenditures. This paper seeks to guide such policies.

Literature review

Analysis in this paper is broadly motivated by the need to understand trade-offs associated with different ownership structures of public goods. Usual argument for decentralized ownership lies in superior information or higher valuation of local actors (Besley and Ghatak, 2001). In this paper, I provide a further argument for decentralized ownership of public infrastructure based on endogeneity of and inter-linkages between informal institutions in developing countries.

Methodologically, this paper is related to the literature on risk sharing with limited commitment and its interaction with other institutions. Banerjee and Newman (1998) build a model of a modernizing economy with information asymmetries to argue that the implied trade-off between informal lending and productivity choice may endogenously make some people stuck in the less productive sector. Focusing on the agricultural sector, I show that informal lending leads to welfare gains by reducing investment distortions due to uninsured risk. Furthermore, Attanasio and Rios-Rull (2000), Thomas and Worrall (2007), Kruger and Perri (2006) and Abraham and Laczo (2018) examine the impact of other public or private insurance programs on risk sharing against idiosyncratic shocks. Most related, the positive feedback of investments into excludable irrigation on the degree of risk sharing presented in this paper is similar to the one due to the existence of an excludable public-storage-like institution studied mostly theoretically in Abraham and Laczo (2018). However, the novelty of my work lies in (i) modeling intertemporal investments as productive ones, generating a reverse feedback mechanism where risk sharing improves efficiency of irrigational investments; and (ii) providing a quantifiable empirical application.

In Indian context, Wade (1988) and Bardhan (2000) provide extensive empirical analyses arguing that central provision and administration of irrigation in rural villages in South India has been associated with lower social co-operation in many dimensions as opposed to places with more of a community-based model of irrigation management. In what follows, I provide further empirical evidence consistent with their findings and develop a general equilibrium framework where these effects arise endogenously, allowing for a quantitative policy evaluation.[2]

The empirical application of this paper's quantitative model to the context of ICRISAT villages speaks to the risk sharing literature following seminal contribution of Ligon, Thomas and Worrall (2002).[3] By analyzing the case of irrigation, this paper is the first

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[2] These results are also consistent with Baldwin's (2016) analysis of informal institutions in Africa demonstrating that compared to democratically elected but distant politicians, traditional chiefs often fare much better in provision and management of local public goods.

[3] Other papers using the first wave of ICRISAT panel include Mazzoco and Saini (2012), Laczo (2015), Abraham and Laczo (2018), Morten (2019) and Bold and Broer (2020). There are also papers applying this class of models to rural settings in other countries, see for instance Dubois, Jullien and Magnac (2008) who estimate their model on the IFPRI dataset from Pakistani villages.

in the quantitative-strand of this literature to introduce a productive investment margin into the setting of rural villages. In the most related work, Morten (2019) studies joint determination of risk sharing in village and temporary migration to urban areas.[4] Although both her and my work share the feature of one institution having impact on the other and vice versa, I focus on an application to agricultural sector studying the interaction of risk sharing with investments into irrigation.

Last but not least, my work speaks to broader development literature studying interactions between productivity or investment decisions and the (access to insurance against) underlying risks.[5] Mobarak and Rosenzweig (2012), Cole, Gine and Vickery (2014), Karlan, Osei, Osei-Akoto and Udry (2014) and Cai, Chen, Fang and Zhou (2015) conduct experiments in India, Ghana and China showing that access to formal insurance products induces farmers to shift production towards more profitable but riskier methods. Finally, Fink, Jack and Masiye (2020) show in African context that liquidity constraints that are binding during "hungry seasons" (occurring since crop can be harvested only once or twice a year, e.g. due to lack of irrigation) result in inefficient labor supply decisions and lower agricultural output.[6] In what follows, I present a mechanism through which better consumption smoothing achieved through informal risk sharing increases efficiency of agricultural investments, and vice versa.

Structure

This paper is organized as follows. In Section 2, I introduce the model environment. Section 3 discusses the associated allocations with various degrees of co-operation over risk sharing and/or irrigation. In Section 4, I structurally estimate the model and I present results from the quantitative model in Section 5. Finally, Section 6 concludes with a policy discussion and future research outlook.

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[4] Meghir, Mobarak, Mommaerts and Morten (2019) introduce risky migration into the quantitative theory developed in Morten (2019) and apply it to the empirical setting in Bangladesh.

[5] See de Janvry, Sadoulet and Suri (2017) for a review of this literature.

[6] See also long literature cited in Fink, Jack and Masiye (2020).

2 Model economy

Preferences, production and investment

Consider a dynamic infinite-horizon village-economy with N ex-ante identical farming households. They are risk averse, discount future at the rate of β and enjoy consumption c according to a utility function $u(c)$ with $u_c, -u_{cc} > 0$. All information is publicly held and common knowledge.

In any period t, farmer i receives crop output according to:

$$y_{i,t} = \phi_t \cdot \theta_{i,t} \tag{1}$$

The output is a function of both idiosyncratic θ and aggregate ϕ productivity shocks. The random variable $\theta_{i,t} \in \Theta = \left(\theta^1, ..., \theta^{N_\theta}\right)$, $0 < \theta^1 < ... < \theta^{N_\theta} < \infty$ follows a Markov chain with transition matrix π_θ and the two first moments of $\mathrm{E}(\theta)$ and $\mathrm{Var}(\theta)$. These shocks should be interpreted as machine breakdowns, pests, human, animal, crop diseases or unemployment affecting the well-being of villagers in an idiosyncratic fashion.

The aggregate productivity $\phi_t \in \Phi = \left(\phi^1, ..., \phi^{N_\phi}\right)$, with $0 < \phi^1 < ... < \phi^{N_\phi} < \infty$ is distributed according to a mixture of two Markov processes: a "good" (G) and a "bad" (B) one, with transition matrices π_ϕ^G and π_ϕ^B and two first moments satisfying $\mathrm{E}\left(\phi^G\right) > \mathrm{E}\left(\phi^B\right)$ and $\mathrm{Var}\left(\phi^G\right) < \mathrm{Var}\left(\phi^B\right)$. Importantly, irrigational investments (e.g. pumps, wells, canals or tanks) done in period t help to ensure that the crop output will not be adversely affected by rainfall fluctuations between periods t and $t+1$, i.e. they increase the probability of drawing the aggregate productivity ϕ from the "good" distribution at the beginning of period $t+1$.

Moreover, these investments can be made either by villagers themselves or by central government. To this end, $\frac{1}{1-s_k}\mathbf{k}_t = \frac{1}{1-s_k} \cdot [k_{1,t}, \ldots, k_{N,t}]$ denotes a vector of irrigation owned by villagers being co-financed by a government agency at the rate of s_k (with $k_{i,0} = k_0 \ \forall i$). Since taxation in poor rural areas (such as the ones analyzed in this paper) is virtually non-existent, I assume that the subsidies for the village-owned investments $\frac{s_k}{1-s_k}\sum_{i=1}^{N} k_{i,t+1}\ \forall t$ are financed with resources external to the villages. Importantly, irrigation is modeled as a stock variable depreciating at the rate of δ and allowing also for self-insurance.[7] Furthermore, ω denotes the irrigation investment provided (i.e. subsidized at 100%) and owned by central authorities.[8] Thus, in any period t the total amount of irrigation available is given by $\frac{1}{1-s_k}\mathbf{k}_t + \omega$.[9]

Given the discussion above, the expected distribution from which ϕ is drawn at the beginning of period $t+1$ is modeled as follows:[10]

$$\pi_{\phi_{t+1}}\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}, \omega\right) = \begin{cases} \pi_\phi^G & \textit{with } P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}, \omega\right) \\ \pi_\phi^B & \textit{with } 1 - P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}, \omega\right) \end{cases} \tag{2}$$

where $P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}, \omega\right) = \frac{1}{N}\sum_{j=1}^{N} \bar{P}\left(\nu\left[\frac{1}{1-s_k}k_{j,t+1} + \frac{1}{N}\omega\right]\right)$ is the probability of drawing aggregate productivity from the "good" distribution, and ν is a parameter measuring efficiency of investments. I assume $\bar{P} : \mathrm{R}_+ \times \mathrm{R}_+ \to [0,1]$ to be twice continuously differentiable with its first two derivatives satisfying $\bar{P}_k, \bar{P}_\omega > 0$ and $\bar{P}_{kk}, \bar{P}_{\omega\omega} < 0$.

Intuitively, investments into irrigation infrastructure $\mathbf{k}_{t+1}$ and ω benefit the whole com-

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[7] This assumption implies that any irrigation equipment (such as a pump or a water tank) can be sold or that any product of irreversible irrigation investments (such as a well or a canal) can be leased out. In reality this reversibility need not always apply. The model can be easily extended to allow for irreversible irrigation investment, but this would significantly complicate the numerical solution of the quantitative model.

[8] Notice that while investments by villagers are chosen endogenously, I assume that the stream of government-owned irrigation is constant. Making ω_t stochastic would not change the qualitative nature of results below. Furthermore, if government was acting as a benevolent Stackelberg leader deciding about investments ω_t, they would clearly make choices such that the overall welfare is maximized, giving rise to no crowding out of risk sharing (see Section 3). This approach, however, would generate dynamics at odds with empirical evidence in Section 5.1.

[9] I ignore investments in private production capital, as these are usually very small among the smallholder farmers in developing countries. Nonetheless, the results derived generalize to a setting with a production function $y_{i,t} = \phi_t \cdot \theta_{i,t} \cdot \left(k_{i,t}^p\right)^\alpha$, with k^p standing for production capital and k^i standing for irrigation capital affecting distribution of shocks ϕ.

[10] Due to the Markov property of shocks we have that for every state-dependent variable S the realization in period $t+1$ depends only on the period-t state of the world (and not the whole history), i.e. $S\left(x^{t+1}\right) = S\left(x_{t+1}|x_t\right)$.

munity by reducing the risk of bad aggregate shocks, if they co-operate over irrigation (see below).[11] Their public nature is a proxy for multiple dimensions of irrigation structures over which farmers may find it beneficial to co-operate with each other (such as construction, maintenance, operation or allocation of water).[12]

Co-operation in the village

Given the nature of idiosyncratic and aggregate shocks affecting the economy, villagers have two motives for co-operation over: (i) mutual insurance against idiosyncratic shocks; and (ii) irrigational investments. To this end, this co-operation has to be individually rational at any instance as villagers are assumed to be free to walk away from such agreements. In particular, conditional on any state of the world, the associated equilibrium allocations are constrained to be such that farmers are voluntarily participating in the agreement on either risk sharing and/or irrigational investments co-operation. This means that the expected value of remaining in the agreement at any instance and state of the world has to exceed the corresponding expected value of deviation.

As far as the benefits of such deviations are concerned, after defaulting on their risk sharing or irrigational investment promises agents can (i) consume as much of their output as they want in the current and in all future periods (i.e. not sharing it with others); and (ii) invest into irrigation without internalizing positive externalities on others.

The first margin of deviations on risk sharing promises is well understood as it has been analyzed in the literature following Kehoe and Levine (1993), Kocherlakota (1996) and Ligon et al. (2002). In line with it, I assume that deviators will be prohibited from accessing the local risk sharing arrangement in all future periods. This means that from the current

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[11] Interpreted more broadly, they can also be thought of, to some extent, as constructions preventing floods (field bunds, drainage canals etc.).

[12] Such co-operations may be beneficial due to attaining some economies of scale. For instance, Wade (1988, p. 6, 75) discusses an institution of "common irrigators" who are appointed by local village councils. They are paid using contributions from all benefiting farmers and are responsible for watering fields, ensuring fair allocations, organizing groups for repairing infrastructure and (together with village councils) fining households abusing common resources.

period onwards a farmer that defaults on his irrigation or risk sharing promises would be able to rely on self-insurance only, i.e. he would be able to consume his own production and savings (in the form of depreciated irrigation capital) only.

Furthermore, I assume that the community has access to technology allowing them to exclude deviators from the part of irrigation provided and managed by other villagers (but not by government, see below). This excludability technology can be thought of as e.g. the village council forbidding deviators to draw water from common water sources, neighbours refusing to sell water from resources on their plots, or pump owners refusing to provide services when needed. Moreover, it can be also thought of as a proxy for public shaming or ostracism imposed upon deviators.[13]

Crucially, the government-owned investments ω are shared by *all* community members, i.e. they are non-excludable. This means that the central agency is unable to condition access to their part of irrigation based on other private informal contracts in the village (such as risk sharing). The reason for this is either that doing so simply does not lie in the agency's domain or it lacks information (or expertise) necessary for such a form of management.[14]

The two ways of providing irrigation discussed above imply that deviating or non-cooperating households are able to maintain access only to their own and the government-provided part of the irrigation units. Strictly speaking, the irrigation provided by villagers is a club good, whereas the part provided by government is a public good.

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[13] As is well understood in the literature studying endogenously incomplete markets generated by the limited commitment friction, it is possible to support a continuum of equilibria with different welfare properties depending on the exact specification of the outside option. By assuming that any deviation is punished by exclusion from both the local insurance and the village-owned part of the irrigation infrastructure, I effectively focus the analysis on equilibria with the highest supportable degree of risk sharing and most efficient public good provision. This assumption regarding the deviation on risk sharing is standard in the literature following Kehoe and Levine (1993), Kocherlakota (1996) and Ligon et al. (2002). Thus, in the case of irrigation systems being provided by villagers, assuming excludability and focusing on the best equilibrium attainable is in line with this literature. While a permanent exclusion from credit markets or irrigation infrastructure may be seen as far-fetched, these assumptions are a proxy for very strong social norms present in rural villages.

[14] See Bardhan (1993) for a further discussion of these issues from both conceptual and empirical perspectives.

Finally, I will consider all possible allocations of no co-operation, joint co-operation over risk sharing and irrigation, and also co-operation separately over the former and over the latter. In the case of co-operation over irrigation investments only, I assume that households internalize the associated externalities without engaging in state-contingent risk sharing. In the alternative case, I assume that households engage in informal insurance arrangement, but do not share their irrigation units and so do not internalize irrigation externalities on others when investing.

Discussion of modeling assumptions

Access to irrigation. Figure 4 in Appendix D shows that although households with both small and large landholdings were able to access some irrigation in all the three empirical settings of this paper, there were also some households who did not use irrigation at all. The latter can reflect either unequal access to irrigation or heterogeneous irrigation demand due to differential crop choices. While it is true that farmers in rural India often invest in private irrigation units (e.g. dugwells), owners of such private resources usually sell water or rent pumps to other members of their communities (Bliss and Stern, 1982; Anderson, 2011). While one could argue that possession of such resources may generate monopoly power to irrigation suppliers, this does not seem to happen in practice (Bliss and Stern, 1982; Dubash, 2000).

However, it is usually much more economically sensible to invest into common irrigation infrastructure, such as large water tanks, canals, tubewells or shared water pumps (Dubash, 2000). This is seen particularly often in dry and semi-arid South India (regions of the ICRISAT villages), where the motives for co-operation are particularly strong and so the local communities organize informal bodies aimed at co-ordinating development, maintenance and monitoring of village-wide irrigation systems (see e.g. Wade, 1988 and Bardhan, 2000). Studying two villages in the state of Gujarat, Dubash (2000) finds that the informal system of social norms, rules and moral judgment not only maintains irrigation charges at "fair" levels, but that it is also used for regulating access to irrigation water and eliciting good co-operative patterns - in line with the excludability assumed in case of community-owned irrigation (see more on this in Section 5.1). Thus, the model developed here is a proxy for the wide array of centralized or decentralized (in the sense of Coase, 1960) co-operation patterns possible.

Informal co-operation and limited commitment. I subject the village co-operation to limited commitment constraints as in the long literature following Ligon et al. (2002). Foster and Rosenzweig (2001) show empirically that this friction plays an important role in determining the degree of risk sharing in rural settings from three independent data sets from South Asia (including ICRISAT). Similarly, Bubb, Kaur and Mullainathan (2018) show that limited commitment is also constraining efficient irrigation through enforcement problems in water markets of 21 villages in central Uttar Pradesh, India.

3 Allocations with various degrees of co-operation

In this section, I discuss properties of equilibria associated with various degrees of co-operation. I start with the non-cooperative and first best allocations. Afterwards, I discuss the allocation of joint co-operation subject to limited commitment. In Appendix A, I analyze limited commitment allocations with risk sharing only and irrigation co-operation only.

3.1 Non-cooperative allocation

The non-cooperative allocation ("nc") is characterized by farmers consuming only their own production and savings (self-insurance) and not sharing irrigational investments. Conditional on state $x_t = \left(\phi_t, \theta_{i,t}, k^{nc}_{i,t}, \omega\right)$, the value achieved by farmer i in this allocation is given by solution to the following recursive problem:

$$V^{nc}_{i,t}\left(x_t\right)=\max_{c^{nc}_{i,t},k^{nc}_{i,t+1}} u\left(c^{nc}_{i,t}\right)+\beta \mathrm{E}_{\phi,\theta} V^{nc}_{i,t}\left(x_{t+1}|x_t\right) \tag{3}$$

subject to:

$$\left(\zeta^{nc}_{i,t}\left(x_t\right)\right)\ c^{nc}_{i,t}+k^{nc}_{i,t+1}\leq \phi_t\cdot\theta_{i,t}+\left(1-\delta\right)k^{nc}_{i,t}\ \forall t,x_t \tag{4}$$

where ϕ_{t+1} is drawn from the "good" distribution with probability $P\left(\frac{1}{1-s_k}\mathbf{k}^{nc}_{t+1},\omega\right)=P\left(\frac{1}{1-s_k}k^{nc}_{i,t+1},\omega\right)=\frac{1}{N}\bar{P}\left(\nu\left[\frac{1}{1-s_k}k^{nc}_{i,t+1}+\frac{1}{N}\omega\right]\right)+\frac{N-1}{N}\sum_{j\neq i}\bar{P}\left(\nu\frac{1}{N}\omega\right)$. Furthermore, $\zeta^{nc}_{i,t}\left(x_t\right)$ here (and in allocations below) stands for the Lagrange multiplier on the relevant budget (or resource) constraint.

The associated optimality conditions with respect to c and k read:

$$c:\ \zeta^{nc}_{i,t}=\ u_{i,c_t} \tag{5}$$

$$\begin{aligned} k:\ u_{i,c_t}=\beta&\left[P_k\left(\frac{1}{1-s_k}k^{nc}_{i,t+1},\omega\right)\left\{\mathrm{E}^G_\theta V^{nc}_{i,t+1}-\mathrm{E}^B_\theta V^{nc}_{i,t+1}\right\}\right. \\ &\left.+\left(1-\delta\right)\left\{P\left(\frac{1}{1-s_k}k^{nc}_{i,t+1},\omega\right)\mathrm{E}^G_\theta u_{i,c_{t+1}}+\left(1-P\left(\frac{1}{1-s_k}k^{nc}_{i,t+1},\omega\right)\right)\mathrm{E}^B_\theta u_{i,c_{t+1}}\right\}\right] \end{aligned} \tag{6}$$

where (i) I abuse notation by dropping dependance of $\zeta^{nc}_{i,t},c^{nc}_{i,t},k^{nc}_{i,t+1}$ on x_t (here and in what follows); and (ii) $\mathrm{E}^j\left[\cdot\right]$, $j\in\{B,G\}$ is an expectation operator under the "bad" or "good" aggregate productivity (or risk) distribution.

First, each household consumes what is available to them from their own crop output and the depreciated and unsubsidized part of own investments made in the previous period, net of new investments made.

Second, the irrigation investment is done at the point where the cost in terms of consuming marginally less today is equalized to (i) the expected value gain tomorrow weighted by the marginal increase in probability of good distribution realization; and (ii) the value of an additional unit of depreciated irrigation capital invested out of farmers' pockets (both in marginal utility terms).

Third, since (i) an additional unit of a centrally owned irrigation benefits everyone; and (ii) these resources come at no cost to the community, we have that:

Proposition 1. *In the non-cooperative allocation, an additional unit of centrally-owned irrigation strictly improves expected utility of every villager, i.e.* $\frac{\partial \mathrm{E} V_{i,t+1}^{nc}(x_{t+1})}{\partial \omega} > 0 \; \forall i, t$.

3.2 First best allocation

For the first best allocation ("FB"), I consider a benevolent planner attaching equal Pareto weights to each household and maximizing utilitarian social welfare function (SWF) in each state of the world $x_t = \left(\phi_t, \{\theta_{i,t}\}, \mathbf{k}_t^{FB}, \omega\right)$:

$$V_t^{FB}(x_t) = \max_{\left\{c_{i,t}^{FB}, k_{i,t+1}^{FB}\right\}_i} \sum_{i=1}^{N} u\left(c_{i,t}^{FB}\right) + \beta \mathrm{E}_{\phi,\theta} V_{i,t}^{FB}\left(x_{t+1} | x_t\right) \tag{7}$$

The ensuing efficient allocation where the planner is free to move resources around, i.e. faces the resource constraint of:

$$\left(\zeta_t^{FB}(x_t)\right) \sum_{i=1}^{N} \left(c_{i,t}^{FB} + k_{i,t+1}^{FB}\right) \leq \phi_t \cdot \sum_{i=1}^{N} \theta_{i,t} + (1-\delta) \sum_{i=1}^{N} k_{i,t}^{FB} \; \forall t, x_t \tag{8}$$

with ϕ_{t+1} being drawn from the "good" distribution with probability $P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{FB}, \omega\right) = \frac{1}{N}\sum_{j=1}^{N} \bar{P}\left(\nu\left[\frac{1}{1-s_k}k_{j,t+1}^{FB} + \frac{1}{N}\omega\right]\right)$.

The allocation can be characterized using the following first order conditions:

$$c: \; \zeta_t^{FB} = \; u_{i,c_t} \; \Rightarrow \; \frac{u_{i,c_t}}{u_{j,c_t}} = 1 \; \forall i, j \tag{9}$$

$$\begin{aligned} k: \; u_{i,c_t} = \beta \Bigg[& P_k\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{FB}, \omega\right) \sum_{j=1}^{N} \left\{ \mathrm{E}_\theta^G V_{j,t+1}^{FB} - \mathrm{E}_\theta^B V_{j,t+1}^{FB} \right\} \\ & + (1-\delta)\left\{ P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{FB}, \omega\right) \mathrm{E}_\theta^G u_{i,c_{t+1}} + \left(1 - P\left(\mathbf{k}_{t+1}^{FB}, \omega\right)\right) \mathrm{E}_\theta^B u_{i,c_{t+1}} \right\} \Bigg] \end{aligned} \tag{10}$$

First of all, the planner internalizes now all the positive externalities associated with irrigational investments. In particular, the marginal benefit in the first best irrigation capital investment rule (10) includes the impact of marginal increase in irrigational investment not only on the investing household but also on all the other households in the village.

Secondly, comparing the consumption sharing rules (5) and (9) shows that in the first best with equal Pareto weights, consumption smoothing of all farmer households will be improved and, in particular, households' consumption will fluctuate only in response to aggregate shocks and endogenous adjustments in irrigation investments.

Related to the above, the self-insuring agents in the non-cooperative allocation above went on to smooth their (current and expected) variations in the marginal utility of consumption due to idiosyncratic shocks through inefficient adjustments in investments. Since the insurance of villagers against all relevant shocks in the first best allocation is improved, the efficiency of investment decisions is restored (Arrow, 1971).[15] Given all these observations, the expected life-time utility of all agents will be higher than in the non-cooperative allocation..

Finally, the equivalent of Proposition 1 applies in this allocation as well.

3.3 Co-operation over irrigation and risk sharing with limited commitment

The allocation of joint co-operation over irrigation and risk sharing ("IRS"), where households are free to walk away from the agreement at any instance, is a solution to the planner maximizing the following SWF:

$$V_t^{IRS}\left(x_t\right) = \max_{\left\{c_{i,t}^{IRS}, k_{i,t+1}^{IRS}\right\}_i} \sum_{i=1}^{N} \lambda_{i,t-1}^{IRS} \cdot u\left(c_{i,t}^{IRS}\right) + \beta \mathrm{E}_{\phi,\theta} V_{i,t}^{IRS}\left(x_{t+1}|x_t\right) \tag{11}$$

subject to the resource constraint equivalent of (8) and the following set of limited commitment constraints:

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[15] Notice that the excessive idiosyncratic risk may push households to increase their investments for precautionary saving reasons, potentially in the direction of internalizing the true social marginal benefits of investments. Nonetheless, this will in general not ensure socially efficient internalization of externalities (both in the non-cooperative and other allocations below).

$$\left(\mu_{i,t}^{IRS}\left(x_t\right)\right)\ \mathrm{E_t}\left[\sum_{t'=t}^{\infty}\beta^{t'-t}u\left(c_{i,t'}^{IRS}\right)\right]\geq V_{i,t}^{nc}\left(\tilde{x}_t\right)\ \forall i,x_t \tag{12}$$

where:

1. the current state is $x_t=\left(\phi_t,\left\{\theta_{j,t}\right\}_j,\mathbf{k}_t^{IRS},\omega,\left\{\lambda_{j,t-1}^{IRS}\right\}_j\right)$;
2. following the methodology developed by Marcet and Marimon (2019), the Pareto weights are updated according to $\lambda_{i,t}^{IRS}\left(x_t\right)=\lambda_{i,t-1}^{IRS}\left(x_{t-1}\right)+\mu_{i,t}^{IRS}\left(x_t\right)$ for $t\geq 1$ and, as in the first best allocation, I assume that $\lambda_{i,0}^{IRS}\left(x_0\right)=1\ \forall i$;
3. the value of the outside option is given by the value of non-cooperating, with the current state given by $\tilde{x}_t=\left(\phi_t,\theta_{i,t},k_{i,t}^{IRS},\omega\right)$. As explained in Section 2, this means that after deviating on one's risk sharing or investment promises, the deviator will be excluded in the current and all future periods from (i) the local informal insurance arrangement; and (ii) the benefits of investments made by other households (while maintaining access to the government-managed part of the irrigation system);
4. as in the first best, ϕ_{t+1} is drawn from the "good" distribution with probability $P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{IRS},\omega\right)=\frac{1}{N}\sum_{j=1}^{N}\bar{P}\left(\nu\left[\frac{1}{1-s_k}k_{j,t+1}^{IRS}+\frac{1}{N}\omega\right]\right)$.

This allocation can be characterized using the following set of optimality conditions:

$$c:\ \zeta_t^{IRS}=u_{i,c_t}\cdot\left(\lambda_{i,t-1}^{IRS}+\mu_{i,t}^{IRS}\right)\ \forall i\ \Rightarrow\ \frac{u_{i,c_t}}{u_{j,c_t}}=\frac{\lambda_{j,t-1}^{IRS}+\mu_{j,t}^{IRS}}{\lambda_{i,t-1}^{IRS}+\mu_{i,t}^{IRS}}\ \forall i\neq j \tag{13}$$

$$\begin{aligned}
k:\ u_{i,c_t}=&\beta\left[P_k\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{IRS},\omega\right)\sum_{j=1}^{N}\left\{\mathrm{E}_\theta^G\frac{\lambda_{j,t}^{IRS}+\mu_{j,t+1}^{IRS}}{\lambda_{j,t}^{IRS}}V_{j,t+1}^{IRS}-\mathrm{E}_\theta^B\frac{\lambda_{j,t}^{IRS}+\mu_{j,t+1}^{IRS}}{\lambda_{j,t}^{IRS}}V_{j,t+1}^{IRS}\right\}\right.\\
&-\frac{\mu_{i,t}^{IRS}}{\lambda_{i,t}^{IRS}}P_k\left(\frac{1}{1-s_k}k_{i,t+1}^{IRS},\omega\right)\left\{\mathrm{E}_\theta^G V_{i,t+1}^{nc}-\mathrm{E}_\theta^B V_{i,t+1}^{nc}\right\}\\
&+P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{IRS},\omega\right)\mathrm{E}_\theta^G\left[u_{i,c_{t+1}}\frac{\lambda_{i,t}^{IRS}+\mu_{i,t+1}^{IRS}}{\lambda_{i,t}^{IRS}}\left(1-\delta\right)-\frac{\mu_{i,t+1}^{IRS}}{\lambda_{i,t}^{IRS}}\frac{\partial V_{i,t+1}^{nc}}{\partial k_{i,t+1}^{IRS}}\right]\\
&\left.+\left(1-P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{IRS},\omega\right)\right)\mathrm{E}_\theta^B\left[u_{i,c_{t+1}}\frac{\lambda_{i,t}^{IRS}+\mu_{i,t+1}^{IRS}}{\lambda_{i,t}^{IRS}}\left(1-\delta\right)-\frac{\mu_{i,t+1}^{IRS}}{\lambda_{i,t}^{IRS}}\frac{\partial V_{i,t+1}^{nc}}{\partial k_{i,t+1}^{IRS}}\right]\right]
\end{aligned} \tag{14}$$

First of all, notice the modified consumption sharing rule: consumption in period t is determined by Pareto weights inherited from previous period, adjusted for potentially binding limited commitment constraints (which becomes known right after the aggregate and idiosyncratic shocks are realized). This is done in such a way that in equilibrium no agent defaults on the contract and so that the co-operation is sustainable in the long-run. Moreover, the extent of efficient risk sharing is pinned down by "how slack" are the limited commitment constraints of all the agents. In particular, the amount of resources the planner is able to transfer from agent i to others is an increasing function of distance between the household i's (inside) value of co-operation and the (outside) value of deviating in the enforcement constraint (12).

Furthermore, whenever the equilibrium is characterized by binding limited commitment, the insurance markets become endogenously incomplete. These frictions have implications not only for consumption smoothing, but - through uninsured risk - also for the efficiency of investments. Because the government-owned irrigation excessively affects the slackness of limited commitment constraints, its welfare-improving effects exposed in Proposition 1 are unlikely to hold here. I discuss these effects in what follows.

Village-owned irrigation and risk sharing. Similarly as in the first best, the planner accounts for all the benefits accruing to farmers when deciding about irrigation investments (up to the endogenous Pareto weights). Apart from improving the aggregate risk process for everyone, the second most important benefit of investments done by villagers is that they relax future participation constraints, allowing for more insurance transfers between community members (i.e. for improving risk sharing). This effect can be seen in (14) as whenever $\mu_{i,t+1}^{IRS}$ is positive in some states, the effective return on investment is pushed up.

However, decisions made within co-operation will generally also affect the value of deviation. As higher irrigation investments today increase the probability of ending up in the "good" aggregate state tomorrow (both inside and outside of the contract), the planner needs to account for it by shading investments in case of binding enforcement constraints *today* for household i.[16] What is more, she also needs to take into account the negative effect of increasing the irrigation investment of household i on their value of the outside option (coming through improved self-insurance in the form of higher next period's savings).[17] In general, these corrective adjustments will be larger in states of the world when the enforcement constraints are "more binding", i.e. when the associated Lagrange multipliers μ have higher values. Nonetheless, these adverse effects are likely to be minor compared to the benefits of providing insurance against aggregate shocks and relaxing limited commitment constraints.[18]

Government-owned irrigation and risk sharing. Different from the village-owned irrigation and due to being non-excludable, increasing the amount of government-owned investments to $\omega' > \omega$ is likely to decrease the extent of efficient risk sharing. These crowding out effects will be especially strong whenever the elasticity of consumption w.r.t. aggregate shocks is low enough (i.e. the overall insurance against aggregate shocks in place is already good enough). In such a case the economic benefit of providing additional government-owned irrigation becomes low, and so hikes in ω increase the inside value function on the LHS of the limited commitment constraint (12) at a significantly lower rate than that of the outside one on the RHS, leading to tightening of limited commitment constraints and so crowding out of risk sharing.

Risk sharing and efficiency of investments. As uninsured consumption risks distort efficiency of investments (Arrow, 1971), the relationship between risk sharing and irrigation is likely to be characterized by mutual feedback. While the co-operation over irrigation may likely improve risk sharing through channels described above, the co-operation over risk sharing will generally reduce distortions to efficiency of irrigational investments.

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[16] The planner does not need to account for the impact of i's investments on others's value of deviation due to the assumed exclusion from village-owned part of irrigation.

[17] More precisely, the planner marginally shades the investment decisions in order to account for all the possible *next period's* states in which these limited commitment constraints are binding. This self-insurance effect is similar to the one present in Kehoe and Perri (2002) and Ligon et al. (2002).

[18] The negative effects of additional village-owned investments on outside option disappear as the depreciation rate approaches 1 and the size of population living in the village grows.

This is so as state-contingent risk sharing is a superior technology of insuring distortionary idiosyncratic shocks compared to simple self-insurance. See more on this in Appendix A, where I discuss the co-operation over irrigation only.

Mutual reinforcement and stabilization. The discussion above suggests that risk sharing and irrigational investments can be complementary to each other. In presence of limited commitment constraints, however, this complementarity implies that both institutions not only reinforce, but also stabilize each other. On one hand, each institution creates additional economic surplus (risk sharing improves efficiency of investments, and investments increase extent of risk sharing). On the other, each institution provides an effective punishment for deviating on either margin of co-operation. As a consequence, any policy distorting co-operation over one margin may not only distort efficiency of the other margin, but - in extreme cases - it may also result in domino effects leading to a complete collapse of co-operation in the community.

In Section 5, I demonstrate that the above intuition holds both in the data and in the quantitative experiments performed.

4 Estimation of the model

In this section, I structurally estimate the model. I first describe the data sources used. Then, I describe the estimation method based on simulated moments and indirect inference. Finally, I show that the estimated model performs well along both the targeted and non-targeted margins.

4.1 Data description

In order to estimate the model, I use the first wave of the ICRISAT Village Level Studies panel on households living in rural South India.[19] Following the literature, I focus the

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[19] The first wave of the ICRISAT's dataset is one of the most commonly used datasets in the macro-development literature, see e.g. Townsend (1994), Ligon et al. (2002), Mazzocco and Saini (2012), Laczo

analysis on the three villages of Aurepalle, Kanzara and Shirapur in years 1976-1984.[20] Furthermore, although not used in the estimation, I use the second wave of the ICRISAT panel covering period 2001-2004 in order to validate both the model and estimation strategy.[21] Both waves contain detailed data on households' demographics and economic decisions.[22]

First of all, I drop households which do not cultivate any land (owned or rented) in any period of the merged dataset and, in case of the first wave (where missing data is much more common), households with fewer than 80 household-month observations. Because the periodicity of the second wave is annual, I aggregate the monthly data in the first wave so that the two waves constitute comparable data sets.[23] When pooling the two waves, I match households that have not split over the 16 years gap between the two waves and treat households that have split as independent ones. This implies that I am left with 97 and 189 households in the first and second waves respectively.[24]

For the analysis of consumption smoothing, I need data on household income, consumption expenditures and household demographics. The income data in both waves is constructed as a sum of farm and non-farm income, profits from agriculture, caste occupations, livestock, capital and interest income (net of remittances and stock of savings). The non-durable consumption in both waves is equal to the sum of expenditures on milled grain, oil, animal products, fruits and vegetables, and on other non-durable goods such as electricity, water charges, cooking fuels for household use, and expenses for domestic work. In order to control for the household's age and size composition, the consumption and income variables are transformed into per-capita using the age-gender weight as in

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(2015) or Abraham and Laczo (2018).

[20] Other villages from the first wave of ICRISAT panel cannot be used due to very noisy consumption and income data.

[21] See Dercon, Krishnan and Krutikova (2013) for comparison of changes in the analyzed here villages between the first and second waves of the ICRISAT dataset. The second wave is also used by Morten (2019) to study joint determination of risk sharing and migration.

[22] Townsend (1994) gives a detailed description of the data in the first wave.

[23] Strictly speaking, the data in the first wave of ICRISAT is collected approximately every month. In order to obtain first a monthly dataset, I follow procedures as in Mazzocco and Saini (2012).

[24] I exclude outliers by trimming the data at the top and bottom percentiles.

	1976-1984		**2001-2004**	
Variable	Average	Std. Dev.	Average	Std. Dev.
Household size	7.75	3.44	4.72	2.06
Age-gender weight	6.34	2.87	4.20	1.63
log Cons. (real, per cap.)	6.85	0.94	7.06	0.49
log Income (real, per cap.)	7.18	0.75	7.53	0.73
% of small farm HHs	36%	-	46%	-
% of medium farm HHs	33%	-	38%	-
% of large farm HHs	31%	-	16%	-
Number of HHs	97	-	189	-
Observations	828	-	739	-

Table 1: Data summary statistics

Townsend (1994).[25] Finally, both the income and consumption variables are deflated to the 1975 price level using the consumer price index for agricultural laborers published by the Labour Bureau of India. Table 1 reports summary statistics of the ICRISAT panel.

Estimating the parameters related to irrigation investments requires data on the amount of irrigation used in each village, its ownership and management structure, and rainfall. While the ICRISAT panel contains precise data on household-level irrigated land, it does not contain any records on the ownership-management structure of irrigation units in place. To address this issue, I use the first and fourth Minor Irrigation Censuses conducted in 1986 and 2006, both being recorded 2 years after the end of the respective waves of the ICRISAT panel. This census contains district-level data[26] on the number, ownership-management structure, the irrigated area and financing of irrigation units. In particular, I construct the following variable measuring the share of government ownership in irriga-

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[25] In particular, it is computed by adding the following numbers: for adult males, 1.0; for adult females, 0.9; for males aged 13-18, 0.94; for females aged 13-18, 0.83; for children aged 7-12, 0.67; for children aged 4-6, 0.52; for toddlers 1-3, 0.32; and for infants 0.05.

[26] Given this data limitation, the analysis below effectively assumes that the three villages analyzed are representative in each district to which they belong. This data is available under http://micensus.gov.in

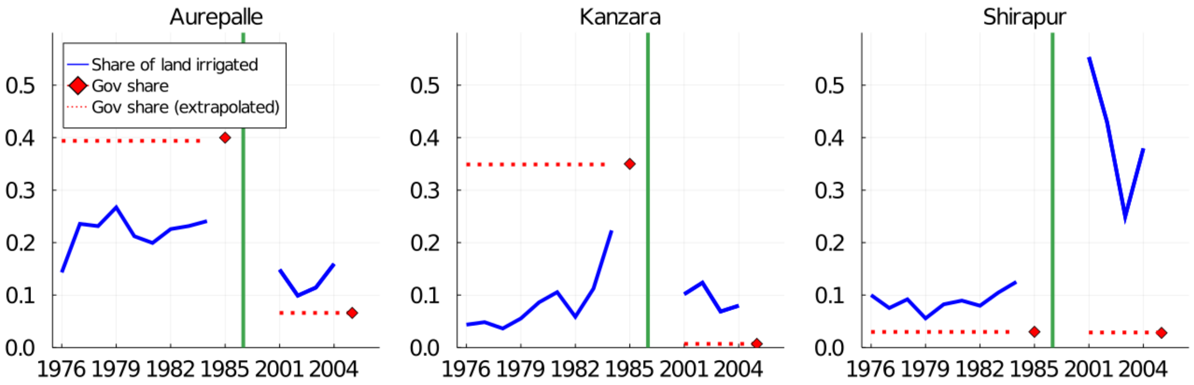

Figure 1: Irrigation use and ownership in the ICRISAT villages

Note: Irrigated land is defined as the share of total cultivated land in each village that has been actually irrigated. Government share is defined as the share of irrigation units that are not owned by co-operative societies, panchayats, groups of farmers or individuals.

tion infrastructure of each village in each wave of the panel:

$$gov = \sum_i share\ of\ gov.\ owned\ units_i \cdot \frac{irrigation\ area_i}{\sum_j irrigation\ area_j} \tag{15}$$

where (i) the summations are over indices i, j indicating the type of the infrastructure unit (such as dugwell, tank, deep or shallow tubewell, check dam or diversion channel); (ii) $share\ of\ gov.\ owned\ units$ is defined as[27] $\frac{No.\ of\ gov.-owned\ units}{No.\ of\ gov.-owned+No.\ of\ village-owned\ units}$ for a given unit type i; and (iii) $irrigation\ area$ is the irrigated area covered by irrigation units of type i. Finally, I use the high resolution rainfall data from the University of Delaware precipitation database for estimating the aggregate risk process and returns to irrigation.

Figure 1 presents the data on each village's share of total land that has actually received irrigation in a given year and the government's share in the village's irrigation infrastructure. We can observe that the districts of Aurepalle and Kanzara have experienced significant privatization (understood as increasing community participation in management of the irrigation infrastructure) of irrigation infrastructure from 35-39% of government ownership in 1980s down to 0-7% in 2000s. On the other hand, in Shirapur these rates have always been low, at levels between 2-3%. These changes reflect the general shift in Indian

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[27] Village owned units are defined as units owned by co-operative societies, panchayats, groups of farmers and individual farmers.

public policy towards increasing involvement of local communities in the management of irrigation infrastructure (Ministry of Water Resources, 2002).[28]

4.2 Estimation strategy

In order to fit the model to the setting of three ICRISAT villages, I follow a two-step estimation procedure. For a given vector of parameters, I solve an inner maximization problem of computing the optimal policy functions in the joint co-operation subject to limited commitment. See Appendix B for description of the algorithm used for solving the model.

Then, I solve an outer maximization problem of choosing the vector of parameters giving best fit of the moments generated in simulations to the variations in the first wave of the ICRISAT panel. Apart from the irrigation depreciation rate δ and subsidy rates s_k that are taken directly from the data, all remaining structural parameters are pinned down using the simulated method of moments. This task is non-trivial as the income process, risk sharing and investment decisions are all endogenous and depend on actions of every other household in the village. Similarly, since the equilibrium analyzed is complex, in some cases one parameter may affect many targeted moments.[29]

Identification is based on employing indirect inference methods in order to match the empirical evidence below on (i) consumption smoothing; (ii) the impact of bad weather shocks and irrigation on household's income; and (iii) the nature of idiosyncratic and aggregate risk processes. Since my structural model features interactions between all rel-

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[28] For instance, the "Participatory Approach to Water Resources Management" section of the National Water Policy 2002 says the following: "Management of the water resources for diverse uses should incorporate a participatory approach; by involving not only the various governmental agencies but also the users and other stakeholders, in an effective and decisive manner, in various aspects of planning, design, development and management of the water resources schemes. Necessary legal and institutional changes should be made at various levels for the purpose, duly ensuring appropr iate role for women. Water Users' Associations and the local bodies such as municipalities and gram panchayats should particularly be involved in the operation, maintenance and management of water infrastructures / facilities at appropriate levels progressively, with a view to eventually transfer the management of such facilities to the user groups / local bodies."

[29] For instance, the elasticity of consumption w.r.t. idiosyncratic income shocks is affected not only by households' patience and nature of the idiosyncratic risk process, but also by the nature of the aggregate risk process and the associated investments into irrigation by other households and government.

evant margins, indirect inference takes into account possibly complex endogeneities between the income process, self-insurance, investments into irrigation and risk sharing. Conditional on having a high enough number of periods recorded in the data, this approach allows for a consistent estimation by introducing into the model the same biases as in the regressions generating the moments below, if any. For a general treatment of the indirect inference method, see Smith (2008).

Finally, I set the periodicity of the model to one year and its population size equal to the one of the empirical samples in the first wave, i.e. to $N = 33$ in Aurepalle, and $N = 32$ in Kanzara and in Shirapur.[30] Table 5 presents the parameter values chosen and respective target moments or sources. I now move on to discussing details of the estimation strategy.

Preferences and investment technology

Utility function and time preferences. I assume that agents value consumption according to the log-utility function, i.e. $u(c) = \log(c)$. The time preference parameter β is used to target elasticity of consumption w.r.t. idiosyncratic income shocks derived from the standard test of consumption smoothing in the spirit of Townsend (1994):

$$\log\left(cons_{i,t}\right) = \alpha + \beta \log\left(inc_{i,t}\right) + \tilde{\beta}_i + \gamma_{v,t} + \epsilon_{i,t} \tag{16}$$

where $cons_{i,t}$ is per capita expenditure of households on non-durable consumption, $inc_{i,t}$ is their income, $\tilde{\beta}_i$ is a household fixed effect, $\gamma_{v,t}$ is a village-year fixed effect that captures the total resources available to the village at time t (i.e. it controls for aggregate fluctuations) and errors $\epsilon_{i,t}$ are clustered at the village-year level.

Table 2 presents the results of running regression (16) for all the three villages in the first wave of ICRISAT panel.[31] We see that although the test for all three villages rejects

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[30] This follows the practice common in the literature on rural risk-sharing applying similar approximations, see e.g. Ligon et al. (2002), Laczo (2015) and Bold and Broer (2020).

[31] Notice that the obtained elasticities may differ from results obtained in other papers using ICRISAT data due to a different specification of the econometric test ((16) is similar to the one used by Morten, 2019; see Townsend, 1994, Mazzoco and Saini, 2012 or Abraham and Laczo, 2018 for other specifications) or due to

perfect insurance, the shocks to income are relatively well insured with the best insurance against idiosyncratic shocks in Shirapur.[32]

Dep var: consumption	Aurepalle	Kanzara	Shirapur
income	0.37***	0.34***	0.32***
	(0.03)	(0.08)	(0.07)
Village-time FE	Yes	Yes	Yes
Household FE	Yes	Yes	Yes
R^2	0.83	0.78	0.76
Number of observations	279	280	269

Table 2: Consumption smoothing in ICRISAT villages

Note: Table presents the coefficient β from running regression $\log(cons_{i,t}) = \alpha + \beta\log(inc_{i,t}) + \tilde{\beta}_i + \gamma_{v,t} + \epsilon_{i,t}$ on the first wave of the ICRISAT panel. Standard errors clustered at the village-year level are reported in parentheses.

Depreciation. I pin down the depreciation parameter δ using the Indian Ministry of Statistics data on national accounts on input and output of crop sector in the country for the years 2011-2017. Based on those, I assume that the depreciation rate in all three villages equals 4.5%.

Irrigation and government. I choose ω such that the average share of irrigation infrastructure owned by government $GS = \frac{\omega}{\omega + \frac{1}{T}\frac{1}{1-s_k}\sum_{t=0}^{T}\sum_j k_{j,t}}$ in the simulated economy matches the evidence of $GS \in \{39\%, 35\%, 3\%\}$ presented in Figure 1.

Furthermore, I pin down the subsidy parameter for village-owned irrigation s_k using data from the Minor Irrigation Census (see Appendix C for details on this procedure). Based on this, I assume that the village-owned infrastructure investments in Aurepalle, Kanzara and Shirapur are co-financed at the rates of 58.12%, 10.40% and 5.44%.

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focusing the analysis on households actively engaged into agriculture.

[32] The estimated values of β in Table 5 are in the ballpark of time preference estimates in the structural literature studying the ICRISAT villages (e.g. 0.7-0.95 in Ligon et al., 2002; and 0.65-0.78 in Morten, 2019).

Stochastic processes

Both the idiosyncratic and the aggregate risk processes are modeled as symmetric two-state Markov processes with persistence parameters $\{\rho_\theta, \rho_\phi\}$ and a strictly positive probability for realization of all shock levels $\{\theta_H, \theta_L, \phi_H^B, \phi_H^G, \phi_L^B, \phi_L^G\}$.

Aggregate risk. First, for the impact of investments on the probability of the "good" distribution realization, I make a parametric assumption of

$$P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}, \omega\right) = 1 - \frac{1}{N}\sum_{j=1}^{N} \exp\left(-\nu\left[\frac{1}{1-s_k}k_{j,t+1} + \frac{1}{N}\omega\right]\right)$$

with ν standing for the scaling or investment efficiency parameter.

Then, I normalize the average level of good aggregate productivity to 1, i.e. I assume that $\phi_H^G + \phi_L^G = 2$. Furthermore, I assume that irrigation reduces only the downside risk without affecting the upside, i.e. that $\phi_L^G > \phi_L^B$ and $\phi_H^G = \phi_H^B$. I pin down the low value of the good aggregate productivity level ϕ_L^G by matching each village's model-implied aggregate income's coefficient of variation with their empirical counterparts of 0.27, 0.28 and 0.24 in Aurepalle, Kanzara and Shirapur.

The low level of the bad aggregate productivity shock ϕ_L^B and the irrigation investment efficiency parameter ν are pinned down using the following regression relating household's income with bad weather shocks and irrigation use:

$$\log\left(inc_{i,t}\right) = \alpha + \beta_1 1_{v,t}^B + \beta_2 irr_{i,t} + \beta_3 1_{v,t}^B \cdot irr_{i,t} + \beta_4 \cdot X_i^D + \gamma_t + \epsilon_{i,t} \tag{17}$$

where $1_{v,t}^B$ is an indicator function taking value of 1 if in a given village and in a given year there was a bad weather shock,[33] $irr_{i,t}$ is the share of a household's land that received irrigation in a given year, and X_i^D is a vector of household demographic characteristics (household's caste, landholding class and household size).

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[33] The bad weather shock is defined as a year with the level of rainfall falling below the 20th percentile of the long-run (1900-2017) rainfall distribution (using the data from University of Delaware).

Dep var: log-income	(1)	(2)	(3)	(4)
β_1 bad weather shock	-0.57*	-0.60**	-0.57	-0.54
	(0.28)	(0.27)	(0.38)	(0.38)
β_2 share of land irrigated	0.49**	0.36	0.50*	0.65**
	(0.21)	(0.23)	(0.26)	(0.25)
β_3 share of land irrigated*bad shock	0.60**	0.80**	0.61*	0.44
	(0.27)	(0.27)	(0.31)	(0.31)
Demographic controls	Yes	No	No	Yes
Village FE	No	No	Yes	Yes
R^2	0.14	0.05	0.09	0.17
Number of observations	709	709	709	709

Table 3: Mitigating role of irrigation on negative weather shocks

Note: Table presents the coefficients from running regression $\log(inc_{i,t}) = \alpha + \beta_1 1^B_{v,t} + \beta_2 irr_{i,t} + \beta_3 1^B_{v,t} \cdot irr_{i,t} + \beta_4 \cdot X^D_i + \gamma_t + \gamma_v + \epsilon_{i,t}$ on the first wave of the ICRISAT panel. Demographic controls include household's caste, landholding class and age-weighted household size. Standard errors clustered at the village-year level are reported in parentheses. The sample size is smaller than the full sample of the first wave due to the fact that not all households cultivate land in all periods.

The results of regression (17) are in Table 4. Using regression (1) as a baseline, I find that in Aurepalle, Kanzara and Shirapur (i) the bad weather shock lowers the level of household's income by 38%, 42% and 39%, relative to the mean income in years without bad shocks; and (ii) a one standard deviation increase in the share of household's land that is irrigated in years with good (bad) weather increases the level of household's income by 11% (26%), 6% (15%) and 12% (29%), relative to the mean income with average share of irrigated land. These significant returns to irrigation are roughly in line with empirical literature on irrigation in India (Duflo and Pande, 2007; Sekhri, 2014).

I choose the values of ϕ^B_L and ν so that results from the corresponding regressions ran on the model-generated data reproduce these findings on average.[34] Notice that although

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[34] In particular, I use the following regression: $\log(\phi_t \cdot \theta_{i,t}) = \alpha + \beta_1 1^B_{v,t} + \beta_2 \frac{1}{1-s_k} k_{i,t} + \beta_3 \frac{1}{1-s_k} k_{i,t} 1^B_{v,t} + \epsilon_{i,t}$ in order to match (i) the impact of bad weather shocks on household's income (equal to 38%, 42% and 39% in Aurepalle, Kanzara and Shirapur); and (ii) the average impact of a one standard deviation increase in the

the share of land irrigated and income are clearly endogenous to each other, I model this channel and so the indirect inference approach accounts for this.[35]

Finally, assuming that the persistence of the weather process and of the implied aggregate risk process in the village is the same, I estimate persistence of the aggregate risk ρ_ϕ in each village using the following AR(1) process for the rainfall:

$$rainfall_{v,t} = \alpha_v + \beta_v \cdot rainfall_{v,t-1} + \epsilon_{v,t} \tag{18}$$

The estimated persistence of the AR(1) rainfall process β_v is essentially the same in all three villages and equals 0.13. Thus, I choose the value of ρ_ϕ such that the persistence of the simulated AR(1) process for the aggregate productivity ϕ equals 0.13 in all the three villages.

Idiosyncratic risk. I estimate parameters of the idiosyncratic risk process following the methodology in Storesletten, Telmer and Yaron (2004). In particular, I use the following decomposition of household i's real per-capita income:

$$\log\left(inc_{i,t}\right) = \alpha + \tilde{\beta}_i + \gamma_{v,t} + \tilde{\epsilon}_{i,t} \tag{19}$$

where $\tilde{\beta}_i$ is a household fixed effect and $\gamma_{v,t}$ stands for village-time fixed effects capturing the aggregate risk. Consequently, $\tilde{\epsilon}_{i,t}$ is an indirect measure of households' idiosyncratic risk. In order to allow for some persistence of shocks, I model the idiosyncratic risk component as an AR(1) process:

$$\tilde{\epsilon}_{i,t} = \Pi_\theta \tilde{\epsilon}_{i,t-1} + \theta_{i,t} \tag{20}$$

I compute volatility of idiosyncratic risk $\bar{sd}\left(\theta_{i,t}\right)$ as a mean of its standard deviation

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household's irrigation capital stock on household's income (equal to $18.5(=\frac{11+26}{2})\%$, $10.5(=\frac{6+15}{2})\%$ and $20.5(=\frac{12+29}{2})\%$ in the respective villages).

[35] For instance, wealthier households may be also able to irrigate more, or they may be able to adopt modern high-yielding varieties that are complementary with irrigation. See Foster and Rosenzweig (1996) for analysis of these issues while estimating effects of Green Revolution on the returns to schooling.

taken over all the village households. Table 4 shows results of this estimation. Recall that the empirical measure of income in regression (19) does not include the stock of self-insurance assets and so the estimated persistence of idiosyncratic shocks is not biased by adjustments in savings for consumption smoothing purposes.

	Aurepalle	Kanzara	Shirapur
Π_θ	0.71*** (0.08)	0.11* (0.06)	0.57*** (0.06)
$\bar{sd}\left(\theta_{i,t}\right)$	0.39	0.33	0.49

Table 4: Persistence and volatility of idiosyncratic risk in ICRISAT villages

Note: Table presents results of running regression $\tilde{\epsilon}_{i,t} = \Pi_\theta \tilde{\epsilon}_{i,t-1} + \theta_{i,t}$, where $\tilde{\epsilon}_{i,t}$ is an error term from regression $\log\left(inc_{i,t}\right) = \alpha + \tilde{\beta}_i + \gamma_{v,t} + \tilde{\epsilon}_{i,t}$. Statistic $\bar{sd}\left(\theta_{i,t}\right)$ stands for mean standard deviation of idiosyncratic risk $\theta_{i,t}$ taken over all the village households.

In the model, I assume that (i) the idiosyncratic shock levels add up to 1 (i.e. $\theta_H + \theta_L = 1$); and (ii) that they are independently distributed among the village's population. Given the above, I impose the moment restrictions for regressions from the simulated model to replicate their empirical counterparts in Table 4. In particular, I choose parameters ρ_θ and θ_L such that (i) the standard deviation of $\theta_{i,t}$; and (ii) the persistence of idiosyncratic shocks Π_θ match the empirical evidence provided.

Table 5 summarizes estimated parameter values and the corresponding targets for all the three villages.

4.3 Estimation fit

Table 6 presents the targeted moments in the baseline model of joint co-operation with limited commitment and their empirical counterparts.[36] The quantitative model performs reasonably well in overall, with a somewhat larger deviation in the impact of irrigation on income in Kanzara.

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[36] To generate the respective moments, I simulate the model for 50,000 periods, with the first 100 being discarded.

Parameter	Aurepalle	Kanzara	Shirapur	Source/target
Preferences and investment technology				
Time preference β	0.88	0.76	0.78	Consumption elasticity, Table 2
Depreciation rate δ	4.5%			Indian Ministry of Statistics
Gov.-owned irrig. ω	1.83	0.48	0.12	Minor Irrigation Census, Figure 1
Irrigation efficiency ν	1.80	7.90	5.60	Regression (17), Table 3
Subsidy rate s_k on k	58.12%	10.40%	5.44%	Minor Irrigation Census, Table 9
Stochastic processes				
Idiosyn. shock θ_H	0.76	0.66	0.77	Std. dev. in Table 4
Idiosyn. shock persist. ρ_θ	0.86	0.56	0.79	Persistence in Table 4
Low $B-$Aggr. shock ϕ_L^B	0.59	0.57	0.58	Regression (17), Table 3
Low $G-$Aggr. shock: ϕ_L^G	0.94	0.91	0.95	Variance of average village income
High Aggr. shock $\phi_H^B = \phi_H^G$	1.06	1.09	1.05	Normalization $\frac{1}{2}\left(\phi_H^G + \phi_L^G\right) = 1$
Aggr. shock persistence ρ_ϕ	0.55	0.54	0.51	Persistence of rainfall, reg. (18)

Table 5: Parameter values in the quantitative model

Furthermore, because self-insurance is an important element and determinant of economic activities (and especially risk sharing), it is important to verify that the implied amount of savings is realistic. The average ratio of depreciated irrigation capital stock to income in the estimated model amounts to 9% in Aurepalle, 5% in Kanzara and 17% in Shirapur, giving an average saving rate of 10% across the three villages. These results are very close to empirical evidence in Rosenzweig and Wolpin (1993) who find that bullocks were a predominant asset used for self-insurance in the first wave of the ICRISAT panel and that in 1983 an average household owned 0.94 bullocks, with one bullock being worth on average 992 rupees. Given that the average household income in the first wave of ICRISAT panel amounted to 8,323 rupees (= $\exp(7.18) \cdot 6.34$, see Table 1), the average value of self-insurance assets reported in Rosenzweig and Wolpin (1993) implies a saving rate of 11% - a number very close to the one generated by the quantitative model.

Finally, the implied degree of risk sharing is further validated by the model-generated "transfers to consumption" ratio of 25%, 18% and 27% in Aurepalle, Kanzara and Shira-

Moment	**Aurepalle**		**Kanzara**		**Shirapur**	
	Data	**Model**	**Data**	**Model**	**Data**	**Model**
Cons. elasticity	0.37	0.36	0.34	0.31	0.32	0.32
Gov. share in irrigation	39%	36%	35%	35%	3%	4%
Std. dev. of θ process	0.40	0.40	0.33	0.33	0.49	0.49
Persistence of θ process	0.71	0.72	0.11	0.11	0.57	0.58
Coef. of var. of avg village income	0.27	0.25	0.28	0.28	0.24	0.26
Persistence of ϕ process	0.13	0.14	0.13	0.12	0.13	0.13
Impact of ϕ_L^B on income	-38%	-36%	-42%	-45%	-39%	-40%
Impact of irrigation on income	+19%	+19%	+10%	+2%	+21%	+25%

Table 6: Moments in the data and generated by the quantitative model

pur. Their average of 23% is very close to the average ratio of 19% reported in Mazzocco and Saini (2012).[37] Since neither of the self-insurance nor the transfer moments have been targeted in my estimation, they pass as a validation of the strategy employed, with a further test of it in Section 5.1 below.

5 Quantitative results

This section presents quantitative results from the estimated model. I begin by showing empirically that increases in the size of village-owned irrigation are associated with improvements in consumption smoothing and that increases in government-ownership of irrigation are associated with its worsening. Importantly, I also show that although not targeted, the model-generated dynamics are in line with this empirical evidence.

Then, I conduct two counterfactual experiments. First, I quantify the mutual reinforcement between the two institutions of co-operation over risk sharing and irrigation. Sec-

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[37] Mazzocco and Saini (2012) document that the real per-capita transfers given and received by households in the first wave of ICRISAT panel amount on average to 28.3% and 21.1% of non-durable expenditures in Aurepalle; 8.9% and 15.9% in Kanzara; and 16% and 21% in Shirapur.

ond, I investigate the impact of replacing the government-owned irrigation on villagers' welfare. In order to quantify the welfare impact of those counterfactuals, I use a standard measure of consumption-equivalent changes in well-being. This metric shows by how much should households' consumption change in every period such that their expected utility in the pre-reform scenario is equal to their expected utility associated with a given policy reform. With the assumption of log-utility, this measure is equivalent to:

$$W = \exp\left((1-\beta)\left(V^1 - V^0\right)\right) \tag{21}$$

where V^0 and V^1 stand for the value functions pre- and post-reform. Thus, W greater (lower) than 1 indicates that post-reform households' consumption needs to be decreased (increased) in every period by $|W-1| \cdot 100\%$ in order to keep the household indifferent w.r.t. the pre-reform status quo, indicating a welfare improvement (deterioration).

See Appendix D for example simulation paths from the limited commitment and first best allocations.

5.1 Validation of the model and estimation strategy

In what follows, I investigate the dynamics implied by the model and verify that they are in line with empirical evidence. To do so, I run an extended consumption smoothing test both on the actual and simulated data. The actual data is made of the two waves of ICRISAT panel with government shares in irrigation from the two waves of Minor Irrigation Census, as described in Section 4.1. On the other hand, the simulated data comes from the model with parameters as in Table 5 and is divided into two parts: with high and low average values of the parameter ω, such that the government shares in each quantitative village economy vary as in Figure 1. In particular, the analyzed regression reads:

$$\begin{aligned}\log\left(cons_{i,t}\right) = \alpha + \beta_1 \log\left(inc_{i,t}\right) + \beta_2 \log\left(inc_{i,t}\right) \cdot irr_{v,t} + \beta_3 \log\left(inc_{i,t}\right) \cdot irr_{v,t} \cdot gov_{v,t} \\ + \beta_4 \log\left(inc_{i,t}\right) \cdot gov_{v,t} + \tilde{\beta}_i + \gamma_{v,t} + \epsilon_{i,t}\end{aligned} \tag{22}$$

where $gov_{v,t}$ is the measure of government ownership share (15) in village v in period t, $\tilde{\beta}_i$ is the household i fixed effect, $\gamma_{v,t}$ is the village-time fixed affect, $irr_{v,t}$ stands for the share of irrigated land and errors $\epsilon_{i,t}$ are clustered at the village-year level.

My findings indicate that irrigation and risk sharing complement each other, if irrigation is under management of the local community. In particular, results in Table 7 show that (i) an increase in the amount of irrigation is associated with a significant improvement in risk sharing ($\beta_2 < 0$); and that (ii) conditional on the amount of irrigation, an increase in the government ownership of the irrigation units is associated with a significant reduction in risk sharing ($\beta_3 > 0$). While this holds qualitatively both in the model and in the data, the estimated coefficients are somewhat different.[38] Nonetheless, the implied economic effects are close to each other: a one standard deviation increase in irrigation reduces the elasticity of consumption by 9% in the data and by 12% in the model, and a one standard deviation increase in the government share increases the elasticity of consumption by 26% in the data and by 18% in the model.

Since the key assumption underlying the quantitative results is the difference in available punishment technologies associated with irrigation provided by the villagers and government, results in Table 7 validate the model employed. Similarly, since I have not targeted the coefficients of regression (22), these results constitute another validation of the estimation strategy pursued.

Existing evidence in the literature provides further support for the modeling assumption of local irrigation ownership and management allowing for stronger punishments

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[38] One explanation of these differences may lie in that the measure of irrigation in the data is the share of irrigated land in the village, while in the model it is the mean value of the irrigation stock.

Estimates		
Dep var: consumption	Data	Model
(β_1) income	0.31*** (0.07)	0.30*** (0.003)
(β_2) income·irrigation	-0.57*** (0.17)	-0.29*** (0.02)
(β_3) income·irrigation·government share	6.70*** (1.94)	1.32*** (0.12)
(β_4) income·government share	-0.71 (0.42)	0.12*** (0.01)
Implied effects		
Government share 1 st.dev. increase	26%	18%
Irrigation 1 st.dev. increase	-9%	-12%

Table 7: Empirical interaction of risk sharing with irrigation and its ownership structure

Note: Table presents the coefficients $\beta_1, \beta_2, \beta_3$ and β_4 of running regression (22) on both actual and simulated data. Actual data comes from two waves of ICRISAT panel (1976-1984 and 2001-2004) with government shares from the first (1986-1987) and fourth (2006-2007) Minor Irrigation Censuses. Simulated data has been generated by the baseline calibration in two parts, with values of ω s.t. the implied government shares in Aurepalle, Kanzara and Shirapur vary as in Figure 1. Standard errors clustered at the village-year level are reported in parentheses.

and so for eliciting better co-operation, as opposed to its centralized counterpart. In particular, Wade (1988) conducts a study of 31 irrigated villages in Andhra Pradesh (the state of Aurepalle) between the 1970s and 80s. Among other findings, he points out that in many villages access to irrigation water has been regulated partly by the local community and partly by the state Irrigation Department (Wade, 1988, pp. 7, 72). More importantly however, Wade (1988, pp. 14-18, 73, 146, 193) finds that the latter has been largely unable to efficiently regulate this access vis a vis the local community (which succeeded in eliciting much better co-operation through social ostracism or imposing local norms).[39]

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[39] For instance, Wade (1988, p. 193) writes: "The available sanctions include fines of non-trivial amounts [...] [which are] reinforced by considerations of reputation. Whether because the desire for social acceptance by a group is a fundamental principle of social behavior or because reputation loss has material consequences for an individual in terms of contracts foregone, reputation in a small agricultural community is

Similar conclusions are found by Bardhan (2000, pp. 849, 852) in an independent set of South Indian villages. He studied 48 irrigated villages where in 1990s on average half of irrigation units were funded and administered by the central government's Public Works Department, and the other half by the local community. Furthermore, he documents higher degrees of social co-operation in cases where communities have more autonomy in self-regulating the distribution of water as opposed to the ones where this is mostly handled by the Public Works Department.[40]

5.2 Interaction between irrigation and risk sharing

I now proceed to quantifying the interaction between the two institutions of co-operation over irrigation and risk sharing. Table 8 presents the key welfare statistics from the benchmark of joint co-operation over irrigation and risk sharing ("IRS"), and the relative differences to it in the irrigation only ("I") and risk sharing only ("RS") allocations (with the same parameter values across them). Appendix A contains formal outlines of these two allocations.

Similarly as with results from the extended consumption smoothing test above, I find here further support for strong complementarities between the two institutions. On one hand, we see that households co-operating over irrigation are ready to give up between 2% (in Kanzara) and 10% (in Aurepalle) of their consumption in order to maintain the co-operation over risk sharing. The value of this institution comes mostly through a significantly improved insurance against idiosyncratic shocks. In particular, if villagers had no access to risk sharing, their elasticity of consumption would increase by 156-185%.[41]

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not lightly exposed to attack. We have seen the council deliberately seeking to activate reputation sanctions [...]. The effects of fines and reputation loss are reinforced by stratification. Many who might be tempted to free ride are socially subordinate to others in the user group, and are checked from doing so by sanctions which derive from the wider order of caste and property without the council having to use its own authority."

[40] See also Bardhan (1993) for an overview of literature arguing for mechanisms along these lines.

[41] The role of risk sharing becomes more important with increases in either the variance or persistence of idiosyncratic shocks (compare Kanzara with the least volatile and persistent θ-process to the other two villages in Table 4).

Statistic	Aurepalle			Kanzara			Shirapur		
	IRS	**I**	**RS**	**IRS**	**I**	**RS**	**IRS**	**I**	**RS (=NC)**
Welfare									
Cons.-eq. welfare	1	0.90	0.97	1	0.98	0.96	1	0.93	0.84
Irrigational Investments and Production									
Mean investment	0.05	+87%	-3%	0.02	+34%	-10%	0.08	+42%	-12%
Var. of investments	0.01	+227%	+12%	0.01	+103%	-20%	0.01	+147%	+46%
Mean productivity	0.87	+1%	-2%	0.87	+1%	-3%	0.88	+1%	-7%
Var. of productivity	0.05	-6%	+8%	0.06	-3%	+11%	0.05	-7%	+23%
Consumption and Risk Sharing									
Mean consumption	0.44	+1%	-2%	0.44	+1%	-3%	0.43	+1%	-7%
Var. consumption	0.02	+181%	+4%	0.02	+57%	+15%	0.02	+184%	+175%
Cons. elasticity	0.36	+156%	+5%	0.31	+185%	+16%	0.32	+159%	+178%
Transfers	0.25	-100%	-3%	0.18	-100%	-10%	0.27	-100%	-100%

Table 8: Comparison of key statistics across models of various degrees of co-operation.

Note: IRS stands for the allocation with co-operation over both margins, I - over irrigation only, RS - over risk sharing only, NC - non-cooperative allocation. "Cons. elasticity" refers to the coefficient β in regression (16). "Investment" refers to the before-subsidy investment decisions k_{t+1}. "Productivity" refers to values taken by the random variable ϕ. "Transfers" are computed as a ratio of mean positive out-transfers to consumption.

This finding shows that well-functioning informal credit markets are critical for welfare of rural communities living in developing countries, where self-insurance remains very limited.[42]

Moreover, since lack of risk sharing gives rise to stronger precautionary saving motives, the mean irrigational investment increases by 34%-87%, depending on the village. Nonetheless, this does not bring similarly sized improvements in neither the level nor variance of consumption and aggregate productivity. These results show that, by providing better insurance against income shocks, informal insurance is also critical for enhancing the efficiency of investments in rural areas.

On the other hand, households in Aurepalle and Kanzara are willing to give up 3-4% of

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[42] See Dercon (2002) for a literature review of these issues.

consumption, and as much as 16% in Shirapur, in order to maintain the co-operation over irrigation. The latter number is strikingly high as it reflects the significance of mutual stabilization between informal institutions. In particular, I find that if the villagers of Shirapur had not co-operated over irrigation, they would not be able to sustain any co-operation over risk sharing either. In other words, the efficiency gains and possibility of additional punishments coming from the co-operation over irrigation allow Shirapur farmers to maintain well-functioning informal credit markets and so to avoid relying only on self-insurance.

In any case, without the co-operation over irrigation, households invest between 3-12% less as they cease to internalize effects of their actions on others. As a result, their aggregate productivity declines by 2%-7% and its variance goes up by 8%-23%. Furthermore, we observe that the lack of co-operation over irrigation significantly deteriorates informal insurance against idiosyncratic shocks, as evinced by a 5% increase in the elasticity of consumption in Aurepalle, 16% in Kanzara, and - for the reasons described above - whole 178% in Shirapur. Similarly, the amount of risk sharing transfers declines by 3%-10% in Aurepalle and Kanzara, and they vanish entirely in Shirapur due to unraveling of the risk sharing co-operation.

5.3 Replacing the government-owned irrigation

As a final experiment, I evaluate the key welfare statistics upon changing the value of government irrigation parameter ω in the three villages from 100% down to 0% of its calibrated value, holding other parameters fixed. Figure 2 presents results of this exercise.

The reform comes with sizable welfare gains. In Kanzara, where the initial share of government-owned irrigation and the marginal efficiency of investments ν are largest on average, villagers are willing to give up 9% of consumption in order to have the reform implemented. These welfare gains stem from significant improvements in risk sharing (as evinced by an up to 80% reduction in elasticity of consumption and a 35% increase in the amount of risk sharing transfers), a 7% increase in the mean value of aggregate productivity and a 33% reduction in its variance. Due to the particularly large share of government in irrigation ownership, the welfare gains in Aurepalle are of a comparable magnitude, with insurance transfers increasing by whole 52%.

Interestingly, although the baseline size of government-owned irrigation in Shirapur amounts to only 4%, the reform delivers significant welfare gains equivalent to 4% of consumption. This is mostly due to the high efficiency of irrigation ν and a particularly large variance of idiosyncratic shocks, implying a high shadow value of additional risk sharing.

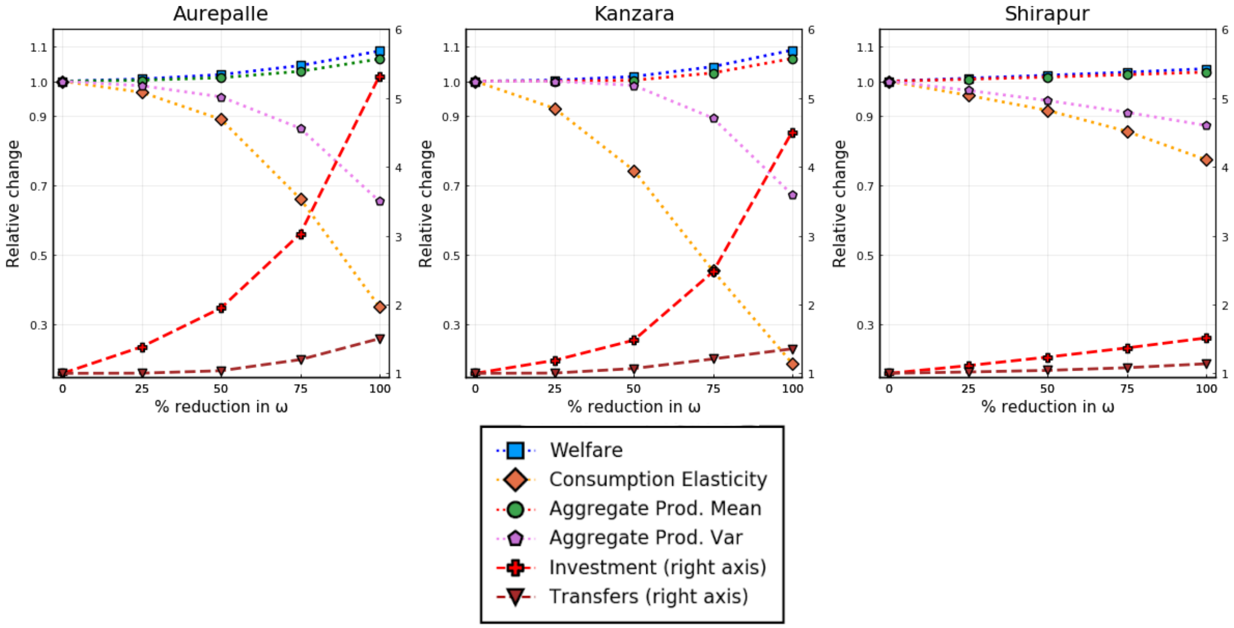

Figure 2: Change in welfare statistics upon reducing government irrigation

In general, these large welfare gains arise as the reform unleashes powerful complementarities between the irrigation and risk sharing. When villagers compensate for reduced government investments by increasing their own inputs, they also relax the limited commitment constraints allowing for even better insurance against idiosyncratic shocks. Improved insurance reduces consumption fluctuations, allowing for higher and more efficient investment of resources, and so on. These complementarities imply that removing the government-managed irrigation can surprisingly lead to a net increase in the total size of irrigation. In case of Aurepalle and Kanzara, setting $\omega = 0$ leads to an approximately four-fold increase in the mean level of village-owned irrigation capital. In the case of Shirapur, investments increase by approximately 50%. Thus, since the subsidy rate s_k is held constant, this experiment should not be viewed as a simple removal of government-owned irrigation from the villages, but rather as an endogenous replacement of it by the community-owned infrastructure.

6 Conclusion

The economic literature has well-documented the prevalent use of informal insurance contracts in rural areas of developing countries. Since functioning of such contracts often relies on the idiosyncratic nature of shocks affecting the income of population, their ability to provide insurance against aggregate shocks is very limited. However, rural communities engaged in agriculture can significantly mitigate the effects of aggregate shocks due to erratic rainfall through co-ordinated irrigation investments. This paper studies how these two margins of co-operation interact with each other.

I perform this analysis through the lenses of a dynamic village economy where risk sharing against idiosyncratic shocks and co-operation over irrigation investments mitigating aggregate shocks are jointly determined and are subject to limited commitment constraints. The model suggests that the two institutions can be complementary to each other, if the community can regulate access to the irrigation and as such punish deviators by excluding them from it. In such a case, increased value of co-operation due to improvements in irrigation increases the extent of efficient risk sharing. On the other hand, by reducing the degree of uninsured idiosyncratic risks affecting community, the risk sharing institution improves the allocation of investments. However, if exclusion from irrigation is not feasible, as I argue is the case when irrigation is owned and managed by central authorities, improvements in its provision may render the possibility of being excluded from the intra-village co-operation less painful, ultimately leading to crowding out of local co-operation.

In order to shed light on this intertwined relationship, I structurally estimate the model on the first wave of ICRISAT panel to the empirical setting of three rural Indian villages. I do so by employing methods of simulated moments and indirect inference for matching the empirical evidence on the degree of consumption smoothing, characteristics of the aggregate and idiosyncratic income shocks, and the impact of bad weather and irrigation on income. I show that the estimated village economies fit both the targeted and non-targeted moments in the data well. Most importantly, I show that an extended consumption smoothing test ran both on the data generated by the quantitative model and on an extended long-run panel has the same implications: while increases in the amount of irrigation improve risk sharing, increases in irrigation's government-ownership share crowd it out.

I use the estimated model to conduct two counterfactual experiments. First, comparing models with various degrees of co-operation confirms significant reinforcing effects between the two institutions. Importantly, I show that in presence of limited commitment constraints, mutual reinforcement of endogenous institutions also implies their mutual stabilization: sustaining co-operation over one margin may be sometimes impossible without co-operation over the other. Second, replacing the government-owned infrastructure by the village-owned one significantly strengthens the within-village co-operation by improving both the informal insurance and the efficiency of irrigational investments.

Given the experimental results shown, policy recommendations may seem obvious. In a way, National Water Policy (Ministry of Water Resources, 2002) and the presented here evidence from the Minor Irrigation Census suggest that attempts of increasing local participation in management over irrigation systems in India have already been followed to some extent. However, policy makers need to bear in mind that traditional functioning of Indian rural communities built around castes may generate unwanted redistribution of welfare gains towards the more privileged castes.[43] Thus, it may be necessary to establish appropriate institutions aimed at facilitating fair access to irrigation that, at the same time, also respect superior local management practices. To this end, it could be worthwhile to consider different types of interventions supporting inter-caste co-operation within villages. At the same time, however, the documented in this paper link between increases in community involvement in irrigation management and improvements in risk sharing (which often takes place at the caste level) suggest that co-operation over local public goods may encourage more inter-caste co-operation. Examining this relationship may be particularly important from the development and government policy points of view.

Furthermore, analytical and computational complexities of the general equilibrium framework employed forced me to effectively treat the villages analyzed here as island economies without any interdependencies. In reality, governments play important role in ensuring fair distribution of water in macro scale, e.g. by preventing water theft from canals running through multiple villages (Fatima, Jacoby and Mansuri, 2016) or regulating groundwater extraction (Jacoby, 2017). Similarly, governmental interventions may be particularly needed for financing large water facilities affecting multiple villages or even regions (e.g. canals or dams).[44] Although outside the scope of this paper, these concerns would certainly increase the optimal scope of centralized irrigation ownership. Nonetheless, any solutions to irrigation investment problems should be informed by the analysis spelt out in this paper.

Finally, analysis in this paper assumed away any type of private information frictions, shown by Ligon (1998) to be potentially relevant in the Indian villages analyzed here.[45]

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[43] See work of Anderson (2011), Munshi and Rosenzweig (2016, 2018) and Munshi (2019).

[44] While not so much on grounds of fixed costs associated with large irrigation projects per se, government interventions may be particularly needed in cases where property rights over projects cannot be clearly defined for one particular community (Coase, 1960), as is for example the case with irrigation dams.

[45] Similarly, a more recent paper by Ligon and Schechter (2018) shows in the context of Paraguayan villages that considering both frictions at the same time might be important. See also Pietrobon (2020) for analysis of interaction between unobservable production effort, fertilizer use and risk sharing.

Thus, it could be fruitful to extend the model studied in this paper in order to analyze implications of moral hazard for local co-operation and agricultural production in these traditional communities. Equally, one could study the core mechanism of this paper in the context of different traditional communities that are similarly characterized by high reliance on social norms, informal institutions and common goods. To this end, in Manalis and Mazur (2020), we investigate the impact of land titles on agricultural productivity and local co-operation in rural Ghana, where communal land ownership is particularly prevalent.

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Appendix A: Risk sharing only and irrigation only allocations

Co-operation over irrigation with limited commitment

For this allocation, I assume that villagers co-operate over irrigational investments, but not over risk sharing. In this case, the centralized version of the agreement is a solution to maximizing SWF:

$$V_t^I\left(x^t\right) = \max_{\left\{c_{i,t}^I, k_{i,t+1}^I\right\}_i} \sum_{i=1}^{N} \lambda_{i,t-1}^I \cdot u\left(c_{i,t}^I\right) + \beta \mathrm{E}_{\phi,\theta} V_{i,t}^I\left(x_{t+1}|x^t\right) \tag{23}$$

subject to (i) the set of budget constraints as in (4); and (ii) the set of limited commitment constraints as in (12) with an inside value adjusted accordingly.

Interestingly, although she cannot do so directly, the planner with a utilitarian SWF still wants to insure households against idiosyncratic shocks. Thus, she will do so through adjusting investment assignments. In particular, a household that is subject to a low idiosyncratic shock will be indirectly insured by reducing their irrigation investments, which will be partly balanced by increased investments on the side of households enjoying high productivity. This will lead to: (i) an increase in the consumption of low productivity households; and (ii) maintenance of their continuation value at a relatively high level due to higher investments made by others who are currently better-off. This inefficient insurance mechanism suggests that in the presence of limited commitment constraints, risk sharing facilitates voluntary co-operation over irrigation: it provides resources to "critical" households with low productivity that would otherwise find themselves on the verge of defaulting, allowing them to increase their consumption by undercutting their investments.

This can be seen by comparing the FOCs 13-(14) with the ones characterizing this allocation:

$$c:\ \zeta^I_{i,t} = u_{i,c_t} \cdot \left(\lambda^I_{i,t-1} + \mu^I_{i,t}\right)\ \forall i \ \Rightarrow\ \frac{u_{i,c_t}}{u_{j,c_t}} = \frac{\zeta^I_{i,t}}{\zeta^I_{j,t}} \cdot \frac{\lambda^I_{j,t-1} + \mu^I_{j,t}}{\lambda^I_{i,t-1} + \mu^I_{i,t}}\ \forall i \neq j \tag{24}$$

$$\begin{aligned} k:\ u_{i,c_t} = \beta \Bigg[& \frac{\mathrm{d}P\left(\frac{1}{1-s_k}\mathbf{k}^I_{t+1}, \omega\right)}{\mathrm{d}k^I_{i,t+1}} \sum_{j=1}^{N} \left(\mathrm{E}^G_\theta \frac{\lambda^I_{j,t} + \mu^I_{j,t+1}}{\lambda^I_{j,t}} V^I_{j,t+1} - \mathrm{E}^B_\theta \frac{\lambda^I_{j,t} + \mu^I_{j,t+1}}{\lambda^I_{j,t}} V^I_{j,t+1} \right) \\ & - \frac{\mu^I_{i,t+1}}{\lambda^I_{i,t}} \frac{\mathrm{d}P\left(\frac{1}{1-s_k}k^I_{i,t+1}, \omega\right)}{\mathrm{d}k^I_{i,t+1}} \left\{ \mathrm{E}^G_\theta V^{nc}_{i,t+1} - \mathrm{E}^B_\theta V^{nc}_{i,t+1} \right\} \\ & + P\left(\frac{1}{1-s_k}\mathbf{k}^I_{t+1}, \omega\right) \mathrm{E}^G_\theta \left[u_{i,c_t} \frac{\lambda^I_{j,t} + \mu^I_{j,t+1}}{\lambda^I_{j,t}} (1-\delta) - \frac{\mu^I_{i,t+1}}{\lambda^I_{i,t}} \frac{\partial V^{nc}_{i,t+1}}{\partial k^I_{i,t+1}} \right] \\ & + \left(1 - P\left(\frac{1}{1-s_k}\mathbf{k}^I_{t+1}, \omega\right)\right) \mathrm{E}^B_\theta \left[u_{i,c_t} \frac{\lambda^I_{j,t} + \mu^I_{j,t+1}}{\lambda^I_{j,t}} (1-\delta) - \frac{\mu^I_{i,t+1}}{\lambda^I_{i,t}} \frac{\partial V^{nc}_{i,t+1}}{\partial k^I_{i,t+1}} \right] \Bigg] \end{aligned} \tag{25}$$

This comparison shows that while the joint co-operation over risk sharing and irrigation equalizes the value of Lagrange multiplier on budget constraints for each household, this is not the case with the co-operation over irrigation only (compare $\zeta^I_{i,t}$ vs ζ^{IRS}_t). As a result, we have that:

Proposition 2. *Introducing risk sharing reduces excessive consumption fluctuations due to self-insurance by setting* $\frac{\zeta^I_{i,t}}{\zeta^I_{j,t}} = \frac{\zeta^{IRS}_t}{\zeta^{IRS}_t} = 1$.

Moreover, notice that the constraint set of the irrigation only problem is a strict subset of the constraint set in the joint co-operation, i.e. everything achievable in the risk sharing co-operation is achievable in the joint one, and more. Thus, the planner in the joint co-operation can replicate, and improve upon, the risk sharing only economy:

Proposition 3. *Extending the co-operation over irrigational investments by risk sharing allows for a Pareto improvement.*

Co-operation over risk sharing with limited commitment

In this allocation, I assume that villagers co-operate only over mutual insurance against idiosyncratic shocks and (for whatever reason) fail to establish co-operation over irrigation. This failure means that households do not share their irrigational infrastructure with each other (and so also ignore all the externalities on others).

Since assuming that risk sharing agents do not share irrigation with each other would effectively idiosyncratize the aggregate risk of each household, such an analysis could lead to ambiguous results as it would become difficult to disentangle how much risk sharing against idiosyncratic shocks is due to θ-shocks and how much due to ϕ-shocks. Thus, in order to preserve the model's key mechanism and its tractability, I assume that each household benefits from only one unit of village-owned irrigation equal to the average investment across the households (and all of the government-owned units). Mathematically, I assume that the aggregate risk process takes the functional form of:

$$\begin{aligned} P\left(\pi^{\phi}=\pi^{G}\right)=P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1},\omega\right) =& 1-\frac{1}{N}\exp\left(-\nu\left[\frac{1}{1-s_k}\frac{1}{N}\sum_i k_{i,t+1}+\frac{1}{N}\omega\right]\right)\\ &-\frac{N-1}{N}\exp\left(-\nu\frac{1}{N}\omega\right)\end{aligned}$$

The centralized version of such an agreement is a solution to maximizing the following SWF:

$$V_t^{RS}\left(x^t\right)=\max_{\left\{c_{i,t}^{RS},k_{i,t+1}^{RS}\right\}_i}\sum_{i=1}^{N}\lambda_{i,t-1}^{RS}\cdot u\left(c_{i,t}^{RS}\right)+\beta\mathrm{E}_{\phi,\theta}V_{i,t}^{RS}\left(x_{t+1}|x^t\right) \tag{26}$$

subject to (i) the aggregate resource constraint as in (8); (ii) the set of limited commitment constraints as in (12) with an inside value accordingly adjusted; and (iii) a constraint that households do not share irrigation with each other (in the sense described above), i.e. that they make investment decisions according to:

$$
\begin{aligned}
k:\; u_{i,c_t} =\beta \Bigg[& \frac{\partial P\left(\frac{1}{1-s_k}\mathbf{k}^{RS}_{t+1},\omega\right)}{\partial k^{RS}_{i,t+1}} \left(\mathrm{E}^G_\theta V^{RS}_{i,t+1} - \mathrm{E}^B_\theta V^{RS}_{i,t+1}\right) \\
& - \frac{\mu^{RS}_{i,t+1}}{\lambda^{RS}_{i,t}} \frac{\mathrm{d}P\left(\frac{1}{1-s_k}k^{RS}_{i,t+1},\omega\right)}{\mathrm{d}k^{RS}_{i,t+1}} \left\{\mathrm{E}^G_\theta V^{nc}_{i,t+1} - \mathrm{E}^B_\theta V^{nc}_{i,t+1}\right\} \\
& + P\left(\frac{1}{1-s_k}\mathbf{k}^{RS}_{t+1},\omega\right) \mathrm{E}^G_\theta \left[u_{i,c_t} \frac{\lambda^{RS}_{j,t} + \mu^{RS}_{j,t+1}}{\lambda^{RS}_{j,t}} (1-\delta) - \frac{\mu^{RS}_{i,t+1}}{\lambda^{RS}_{i,t}} \frac{\partial V^{nc}_{i,t+1}}{\partial k^{RS}_{i,t+1}} \right] \\
& + \left(1 - P\left(\frac{1}{1-s_k}\mathbf{k}^{RS}_{t+1},\omega\right)\right) \mathrm{E}^B_\theta \left[u_{i,c_t} \frac{\lambda^{RS}_{j,t} + \mu^{RS}_{j,t+1}}{\lambda^{RS}_{j,t}} (1-\delta) - \frac{\mu^{RS}_{i,t+1}}{\lambda^{RS}_{i,t}} \frac{\partial V^{nc}_{i,t+1}}{\partial k^{RS}_{i,t+1}} \right] \Bigg]
\end{aligned}
\tag{27}
$$

Similar logic as in the co-operation over irrigation only shows that:

Proposition 4. *Extending the risk sharing co-operation by co-operation over irrigational investments allows for a Pareto improvement.*

Intuitively, although extending co-operation over risk sharing by the irrigational margin implies higher investments and as such may increase the value of the outside option (due to better self-insurance), the planner manages to account for it. In particular, she chooses investments in such a way that the net effect of reducing aggregate risk at possible costs associated with improved self-insurance is positive, i.e. that it leads to a Pareto improvement.

When solving numerically for the allocation with risk sharing only, I use the FOC (27) and the consumption sharing rule of $\frac{u_{i,c_t}}{u_{j,c_t}} = \frac{\lambda^{RS}_{j,t-1}+\mu^{IRS}_{j,t}}{\lambda^{RS}_{i,t-1}+\mu^{IRS}_{i,t}}$. Notice that this approach constitutes an approximation of the full problem with moral hazard, i.e. with the presence of incentive compatibility constraints for households' investments. Solving such a problem with public investments lies beyond the scope of this paper (see Mele, 2014 on how to solve such problems).

Appendix B: Recursive formulation and solution algorithm

In order to save on complexity of solving for the N-agent co-operation equilibrium, I follow the commonly used approximation of solving for co-operation between one household and a pivotal household representing the rest of the village (used e.g. in Ligon et al., 2002; Laczo, 2015; Morten, 2019; Bold and Broer, 2020) extended for public irrigational investments.

In particular, I consider a problem of individual i that (i) chooses capital investment $k_{i,t}$ affecting the aggregate risk of all N households; and (ii) co-operates with agent $-i$ representing the rest of the $N-1$ households living in the village. The use of this representative agent, assumed to have the same preferences as all village members and to receive a productivity shock equal to the average across $N-1$ villagers, implicitly assumes that the rest of the village can (i) share the idiosyncratic risk; and (ii) internalize investment externalities as in the first-best allocation. Consequently, the vector of outside options' values is pinned down by consumption of individual and village-average net endowments in every period (given by $\phi_t\left(k_{i,t},\omega_t\right)\cdot\theta_{i,t}-k_{i,t+1}$ and $\phi_t\left(\mathbf{k}_t,\omega_t\right)\cdot\left(\frac{\theta_L+\theta_H}{2}\right)-k_{-i,t+1}$, respectively).

Following steps similar to the ones in Kehoe and Perri (2002), i.e. defining (i) the ratio of Pareto weights between household i and household $-i$ representing the rest of the village as $z'\left(x^t\right)=\frac{\lambda_{-i}\left(x^t\right)+\mu_{-i,t}\left(x^t\right)}{\lambda_i\left(x^t\right)+\mu_{i,t}\left(x^t\right)}$; and (ii) $v_i\left(x^t\right)=\frac{\mu_i\left(x^t\right)}{\lambda_i\left(x^t\right)}\geq 0$, the FOCs (13) and (14) for household i in the allocation of co-operation over irrigation and risk sharing can be rewritten as follows:

$$\begin{aligned}
\frac{U_{i,c_t}}{U_{-i,c_t}} =& z' \\
U_{i,c_t} =& \beta \Bigg[\frac{\mathrm{d}P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1},\omega\right)}{\mathrm{d}k_{i,t+1}} \left\{ \sum \pi^G\left(\theta',\phi'|\theta,\phi\right) \left[\frac{V_{i,t+1}}{1-v_{i,t+1}} + \frac{z'_t \cdot V_{-i,t+1}}{1-v_{-i,t+1}}\right] \right. \\
& \left. - \sum \pi^B\left(\theta',\phi'|\theta,\phi\right) \left[\frac{V_{i,t+1}}{1-v_{i,t+1}} + \frac{z'_t \cdot V_{-i,t+1}}{1-v_{-i,t+1}}\right] \right\} \\
& - \frac{\mathrm{d}P\left(\frac{1}{1-s_k}k_{i,t+1},\omega\right)}{\mathrm{d}k_{i,t+1}} \left\{ \sum \pi^G\left(\theta',\phi'|\theta,\phi\right) v_{i,t} V^{nc}_{i,t+1} - \sum \pi^B\left(\theta',\phi'|\theta,\phi\right) v_{i,t} V^{nc}_{i,t+1} \right\} \\
& + P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1},\omega\right) \sum \pi^G\left(\theta',\phi'|\theta,\phi\right) \left[U_{i,c_{t+1}} \frac{1-\delta}{1-v_{i,t+1}} - \frac{v_{i,t+1}}{1-v_{i,t+1}} \frac{\partial V^{nc}_{i,t+1}}{\partial k_{i,t+1}}\right] \\
& + \left(1 - P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1},\omega\right)\right) \sum \pi^B\left(\theta',\phi'|\theta,\phi\right) \left[U_{i,c_{t+1}} \frac{1-\delta}{1-v_{i,t+1}} - \frac{v_{i,t+1}}{1-v_{i,t+1}} \frac{\partial V^{nc}_{i,t+1}}{\partial k_{i,t+1}}\right] \Bigg]
\end{aligned}$$

Secondly, the approximation method implies that (i) a transfer of $c_{i,t}$ resources for consumption of household i leaves $c_{-i,t} = (y_{i,t} + y_{-i,t} - c_{i,t} - k_{-i,t} - k_{i,t})$ for consumption by the household representing the rest of the village; and that (ii) investments $(k_{i,t+1}, k_{-i,t+1})$ of agents $(i, -i)$ have the following impact on the probability of drawing from the good Markov process:

$$\begin{aligned}
P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1},\omega\right) = 1 &- \frac{1}{2}\exp\left(-\nu\left[\frac{1}{1-s_k}k_{i,t+1} + \frac{1}{2}\omega\right]\right) \\
&- \frac{1}{2}\exp\left(-\nu\left[\frac{1}{1-s_k}k_{-i,t+1} + \frac{1}{2}\omega\right]\right)
\end{aligned}$$

Given the recursive formulation, the model is solved using a policy function iteration method. Let $x_t = (z_t, k_{i,t}, k_{-i,t}, \phi_t, \{\theta_{i,t}\})$ be the state variable with the understanding that z_t, $k_{i,t}$ and $k_{-i,t}$ are inherited from the previous period. Given this, I define a discrete grid G on the state space. Define also value functions for each agent i:

$$
\begin{aligned}
V_{i,t}\left(x_t\right) =& u\left(c_{i,t}\left(x_t\right)\right) + \beta \left[P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}, \omega\right) \sum_{s_{t+1}} \pi^G\left(x_{t+1}|x_t\right) V_{i,t}\left(x_{t+1}\right) \right. \\
& \left. + \left(1 - P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}, \omega\right)\right) \sum_{s_{t+1}} \pi^B\left(x_{t+1}|x_t\right) V_{i,t}\left(x_{t+1}\right) \right]
\end{aligned}
$$

I proceed by guessing policy functions $\left\{c_i^0(g), k_i^0(g), z'^0(g), v_i^0(g), V_i^0(g)\right\}$ $\forall g \in G$. Given these, I update the guess in the following way. Suppose we are on the n-th iteration of updating the vector of unknown functions, and suppose we are at point q in the grid. First assume neither enforcement constraint binds. Thus, immediately $v_i(q) = 0$ and $z'^0(q) = z$. (At the same time, this assumption corresponds to solving for the first best allocation.) Given the guesses, we iterate over the Euler equations of both agents over all the grid points with consumption shared according to z.[46] This gives an update of the consumption policy function for both agents. We compute consumption policy of the rest of the village as a residual from the resource constraint. Given these updated policy functions, I update the value functions and repeat the algorithm until the optimal consumption policy function converges.[47]

Now, we check whether any of the limited commitment constraints binds. If not, we proceed to the next grid point. Otherwise, I will proceed by assuming that only one of the enforcement constraints binds, i.e. either that of the household or of the rest of the village.

If e.g. the limited commitment constraint of household i binds, we are solving for $\left\{c_i(g), k_i(g), z'(g), v_1^0(g)\right\}$ $\forall g \in G$. First, we use the old guesses of c and k' in order to compute total wealth and total consumption. Then, we use the binding enforcement constraint (still with old guesses) to solve for new relative Pareto weight z' (and so also v) at

---

[46] In particular, when solving for optimal decisions of agent i, I use his Euler equation with old guess of agent $-i$'s decisions in order to solve for optimal investment (and, by resource constraint and given the z, consumption) of agent i. Then, I proceed accordingly using the Euler equation of agent $-i$.

[47] Notice also, that in order to solve for the value of autarky it is enough to solve the model using above described algorithm and (i) imposing separate budget constraints; and (ii) assuming that agents ignore their externalities on others.

the given grid point. Given the new relative Pareto weight, we can solve for c_i and c_{-i} using the consumption sharing rule.

Then, we use the Euler equations of both agents to solve for investment decisions at the given grid point. However, since now $v_i(g) > 0$ (binding enforcement constraint), we need to take care of the derivatives of autarky value functions in period $t+1$ w.r.t. current capital. To arrive at the latter, differentiate the value function of each agent in autarky in period t w.r.t. k, use the envelope condition (guaranteeing that $\frac{\partial k_{i,t+1}}{\partial k_{i,t}} = 0$) and iterate one period forward. E.g. in case of agent i, we arrive at:

$$\frac{\partial V^{nc}_{i,t+1}\left(\tilde{x}_{t+1}\right)}{\partial k_{i,t+1}} = \left(c^{nc}_{i,t+1}\right)^{-\sigma}(1-\delta)$$

With these derivatives and old guesses in hand, we use agents' Euler equations to solve for new optimal investment decisions (similar to above). We check the sup-norm of the change in the consumption policy rule, and keep updating until the latter is very small.

I finalize the solution by constructing the panel of approximated village consumption and investment data. In order to do so, I simulate the model N times for long enough where in each period t, with state given by $x_{i,t} = \left(\phi_t, \theta_{i,t}, \frac{1}{2}\left(\theta_L + \theta_H\right), k^{approx}_{i,t}, k^{approx}_{-i,t}, z^{approx}_{i,t}\right)$ $\forall i \in \{1, ..., N\}$, I proceed according to the following steps:

1. I assign the optimal new multiplier $z'^{,approx}_{i,t} = z'_t\left(x_{i,t}\right)\ \forall i \in \{1, ..., N\}$.
2. I then compute approximate consumption rules $c^{approx}_{i,t}\left(x_{i,t}\right)\ \forall i \in \{1, ..., N\}$ according to:[48]

$$c^{approx}_{i,t}\left(x_{i,t}\right) = c_{tot,t} \cdot \frac{\left[\frac{\frac{1}{z_{i,t}}\left(1+\tilde{\mu}_{i,t}\right)}{\sum_{j\neq i}\frac{1}{z_{j,t}}\left(1+\tilde{\mu}_{j,t}\right)}\right]^{\frac{1}{\sigma}}}{1+\left[\frac{\frac{1}{z_{i,t}}\left(1+\tilde{\mu}_{i,t}\right)}{\sum_{j\neq i}\frac{1}{z_{j,t}}\left(1+\tilde{\mu}_{j,t}\right)}\right]^{\frac{1}{\sigma}}} \tag{28}$$

where:

---

[48] See equation (20) in Ligon et al. (2002) and Bold and Broer (2020) for details on deriving (28).

(a) I use the duality between the Promised Utility and Marcet and Marimon's multiplier approach implying that $z' = z \cdot \frac{1+\tilde{\mu}_{-i}}{1+\tilde{\mu}_i}$ (with $\tilde{\mu}$ being the Lagrange multiplier on the promise keeping constraint in the dual problem),

(b) the probability function of drawing from the good aggregate Markov process is $P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}, \omega\right) = 1 - \frac{1}{N}\sum_{i=1}^{N} \exp\left(-\nu\left[\frac{1}{1-s_k}k_{i,t+1} - \frac{1}{N}\omega\right]\right)$,

(c) the total consumption is derived from the resource constraint and is given by

$$\begin{aligned} c_{tot,t} =& \phi_t \left(\theta_{i,t} + \frac{N-1}{2}\left[\theta_H + \theta_L\right]\right) + (1-\delta)\left(k_{i,t}^{approx} + (N-1)\,k_{-i,t}^{approx}\right) \\ & - \left(k_{i,t+1}^{approx} + (N-1)\,k_{-i,t+1}^{approx}\right) \end{aligned}$$

3. I assign investment rules $k_{i,t+1}^{approx}(x_{i,t})$ $\forall i \in \{1, ..., N\}$ using the investment rules from the *exact* solution for a given state $x_{i,t}$ and multiplier $z'_{i,t}(x_{i,t})$. Given these, I impute the approximate investments by the rest of the village as $k_{-i,t+1}^{approx}(x_{-i,t}) = \frac{1}{N-1}\sum_{j\neq i} k_{j,t+1}^{approx}\left(x_{j,t}\right)$ $\forall i \in \{1, ..., N\}$.

4. Having computed all the objects of interest, I proceed to the next period $t+1$ with the state given by $x_{i,t+1} = \left(\phi_{t+1}, \theta_{i,t+1}, \frac{1}{2}(\theta_L + \theta_H), k_{i,t+1}^{approx}, k_{-i,t+1}^{approx}, z_{i,t+1}^{approx}\right)$ $\forall i \in \{1, ..., N\}$, where:

   (a) $k_{-i,t+1}^{approx} = \frac{1}{N-1}\sum_{j\neq i} k_{j,t+1}^{approx}$,

   (b) $z_{i,t+1}^{approx} = z_{i,t}^{\prime,approx}$,

   (c) ϕ_{t+1} is drawn from the good distribution with probability $P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{approx}, \omega\right)$ and with $1 - P\left(\frac{1}{1-s_k}\mathbf{k}_{t+1}^{approx}, \omega\right)$ from the bad one.

Importantly, since the exact solution is from the model with two households (and so are the associated value functions), I evaluate different counterfactual experiments approximating value functions as an average of discounted sums of utilities along shorter subpaths of simulations. In particular, I simulate the model for 50,000 periods and compute this average using discounted sums for 500 short paths of 100 periods length each.

In the numerical implementation, I use a k-grid made of 10 equidistant points between 0.01 and 0.6 for each household (translating into 100 capital grid points in total) and a z'-grid made of 9 equidistant points taking values between 0.25 and 0.4. These grid are sufficient for numerical precision as results do not change significantly upon increasing the grid size.

Appendix C: Estimation of irrigation subsidies

Table 9 presents the data on irrigation subsidy (or co-financing) rates estimated from the 3rd Minor Irrigation Census conducted in the years 2000-2001. The data on sources of financing is unfortunately not available in earlier censuses and thus I assume that the subsidy rates estimated using the 2000-2001 census hold in the first wave of the ICRISAT panel.

The subsidy rate s_k in village $v$is computed using the following formula:

$$s_{k,v} = \sum_i share\ total_{i,v} \cdot share\ subsidized_{i,v} \cdot \frac{irrigated\ area_{i,v}}{\sum_j irrigated\ area_{j,v}} \tag{29}$$

where (i) i is the index for types of irrigation units (as in the construction of the data in (15)), (ii) $share\ total_{i,v}$ is the share of village-owned units in the total number of irrigation units in village v; (iii) $share\ subsidized_{i,v} \equiv \frac{No.of\ subsidy\ financed\ units}{No.of\ subsidy\ financed\ units + No.of\ private/loan\ financed\ units}$; and (iv) the "irrigated area" metric is the same as the one for "irrigated land" (as in construction of the data in Figure 2).

There are two important caveats to the construction of this variable. First, some of the irrigation units recorded in the Minor Irrigation Census are financed by "some loan and some subsidy". In such a case, I assume that half of such units have been financed by loan (private sources) and the other half by subsidy. Second, the census does not contain information on sources of finance for village-owned units *separately* (i.e. it only contains information on sources of finance for the aggregate number of units). Thus, I impute the

Village (district)	metric	Subsidy rate
Aurepalle (Mahbubnagar)	CCA	54.21%
	IPU	62.04%
Kanzara (Akola)	CCA	9.04%
	IPU	11.70%
Shirapur (Solapur)	CCA	5.56%
	IPU	5.32%

Table 9: Subsidy rates on village-owned irrigation in ICRISAT villages

Note: Table presents the subsidy rates of irrigation structures in districts of Mahbubnagar, Akola and Solapur in the third (2000-2001) Minor Irrigation Census. "CCA" stands for Culturable Command Area ("The area which can be irrigated from a scheme and is fit for cultivation."); and "IPU" - for Irrigation Potential Utilised ("The gross area actually irrigated during reference year out of the gross proposed area to be irrigated by the scheme during the year.") - see http://micensus.gov.in for more details.

latter as $share\ total_{i,v} \cdot share\ subsidized_{i,v}$.

For the purpose of calibrating the model, I use subsidy rates equal to the mean of CCA and IPU metrics.

Appendix D: Additional results

Model simulation paths

Figure 3 presents results of simulating household i's decisions in the first best (with constant and symmetric Pareto weight) and limited commitment allocations approximated to the N-household case in Aurepalle (see Appendix B for description of the algorithm).[49] Firstly, notice how the Pareto weights are adjusted along the simulations: due to high assumed persistence of θ, as household i spends more and more time with high idiosyncratic productivity, the planner attaches a higher weight on household i (relative Pareto weight decreases) and so its consumption share in the total village consumption increases. For instance, consumption of household i exceeds the first best assignment in periods of

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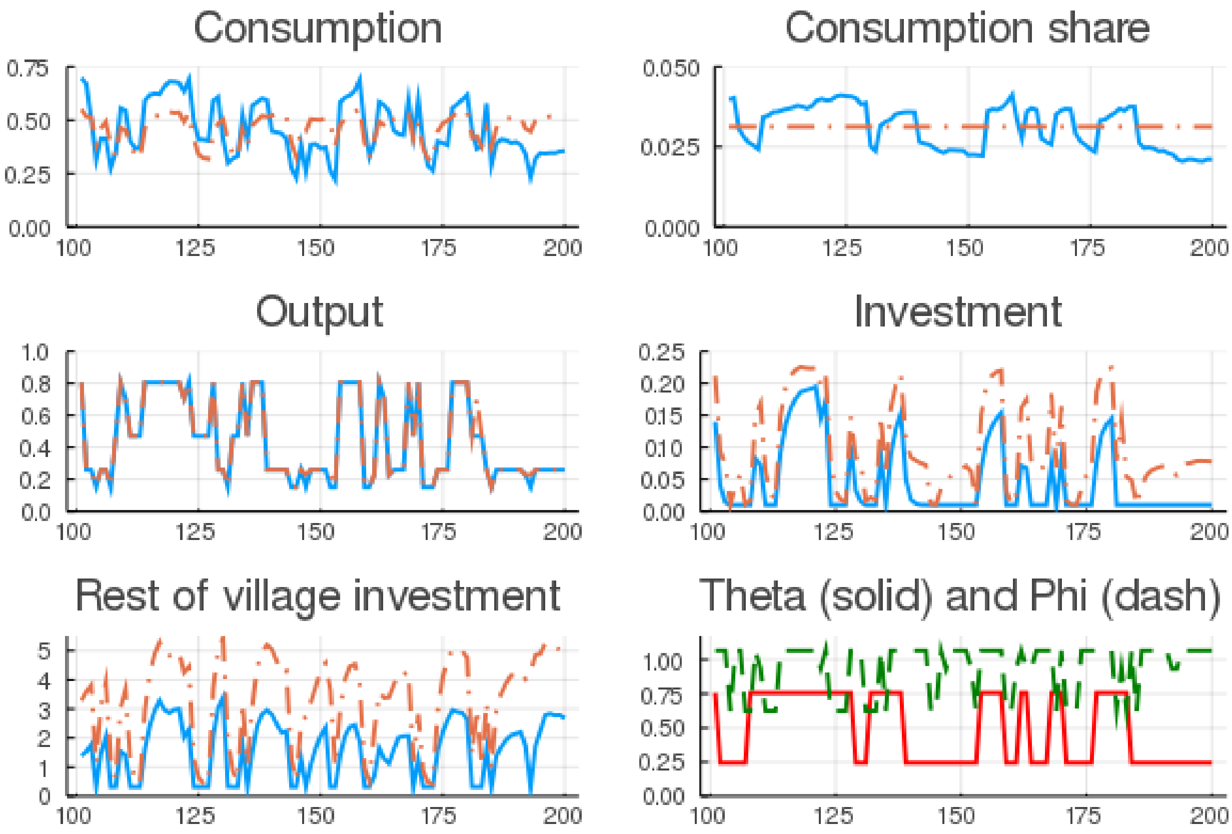
[49] In order to ensure comparability, I feed in the same stochastic process into the two allocations.

high idiosyncratic productivity, when their relative Pareto weight increases.

Furthermore, we observe lower consumption fluctuations in the first best allocation as compared to the model with limited commitment.[50] In particular, since the enforcement issues are not present in the latter, in first best each household receives the constant share of $\frac{1}{N}$ in every period.



Note: Output stands for $y_{i,t} = \phi_t \cdot \theta_{i,t}$ and consumption share is defined as $\frac{c_{i,t}^{approx}(x_{i,t})}{c_{tot,t}(x_{i,t})}$. See Appendix B for details on computing these simulation paths.

Figure 3: Model simulations for Aurepalle: first best (dashed) and limited commitment (solid)

In terms of optimal investment decisions, we observe two interesting patterns. First, conditional on idiosyncratic productivity θ, households invest more in periods of low aggregate productivity $\phi \in \{\phi_L^B, \phi_L^G\}$ (as compared to $\phi = \phi_H^B = \phi_H^G$). This dynamic

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[50] In particular, for the case of Aurepalle, the elasticity of consumption w.r.t. idiosyncratic shocks amounts to 0.38 and to 0.08 in the limited commitment and first best cases (respectively).

is due to the fact that (i) both the Good and Bad aggregate risk Markov processes are persistent and symmetric; and that (ii) the high value of productivity is equal across the two distributions. These imply that the marginal benefit of investing is higher in low ϕ states, as these are the states when it makes a large difference whether the productivity is drawn from the Bad or Good distribution.

Second, notice that investments in the limited commitment model are usually made at a level strictly below the one in the first best allocation. This is due to the fact that the planner shades these decisions in order to account for improvements in the value of outside option that negatively affect the degree of equilibrium co-operation (see the FOC (14)).

Irrigation use in ICRISAT villages

Based on data from the three villages in first wave of the ICRISAT panel, Figure 4 presents patterns of irrigation use according to households' landholdings.

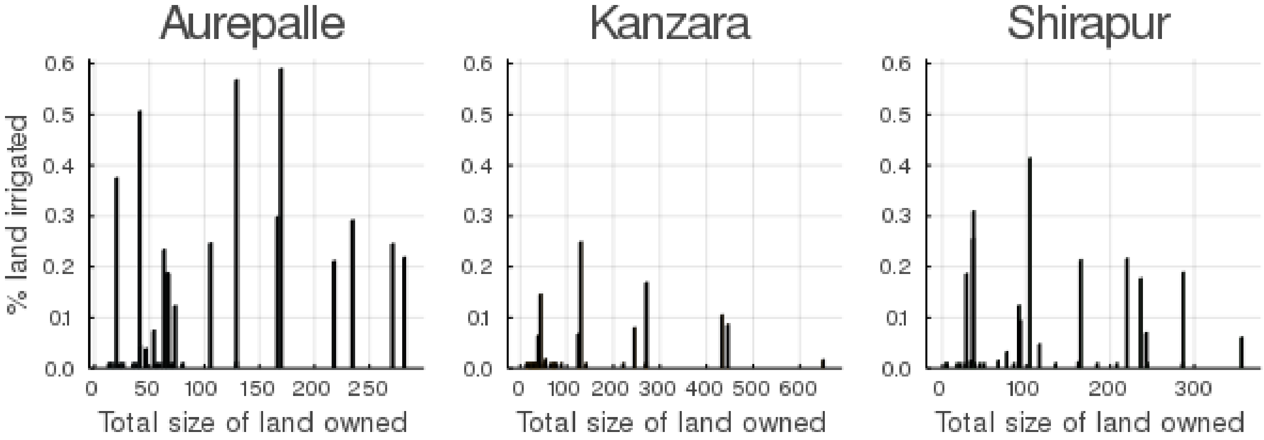

Figure 4: Use to irrigation in the ICRISAT villages

Note: Total size of land owned is a sum of owned land between 1976-1984. Datapoints-households with no irrigated land are marked as 1% irrigated share datapoints; so the 0% points imply that there is no household in the data with a given landholding size.