Pro-Social Preferences Improve Climate Risk Management in Subsistence Farming Communities

Nicolas Choquette-Levy (nclevy@bu.edu)
Boston University https://orcid.org/0000-0002-9986-0267
Matthias Wildemeersch
International Institute for Applied Systems Analysis https://orcid.org/0000-0002-6660-2712
Fernando Santos
University of Amsterdam
Simon Levin
7. Department of Ecology & Evolutionary Biology, Princeton University, Princeton NJ
https://orcid.org/0000-0002-8216-5639
Michael Oppenheimer
Princeton University https://orcid.org/0000-0002-9708-5914
Elke Weber
Princeton University https://orcid.org/0000-0002-1678-3631

Article

Keywords:

Posted Date: June 9th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2845875/v1

Additional Declarations: There is **NO** Competing Interest.

Pro-Social Preferences Improve Climate Risk Management in Subsistence Farming Communities

Nicolas Choquette-Levy[1,2*], Matthias Wildemeersch[3*], Fernando P. Santos[4], Simon A. Levin[5], Michael Oppenheimer[2,6,7], and Elke U. Weber[2,8,9]

[1]Department of Earth and Environment, Boston University, USA
[2]School of Public and International Affairs, Princeton University, USA
[3]International Institute for Applied Systems Analysis, Austria
[4]Informatics Institute, University of Amsterdam, Netherlands
[5]Department of Ecology and Evolutionary Biology, Princeton University, USA
[6]Department of Geosciences, Princeton University, USA
[7]High Meadows Environmental Institute, Princeton University, USA
[8]Andlinger Center for Energy and the Environment, Princeton University, USA
[9]Department of Psychology, Princeton University, USA
* These authors contributed equally to the manuscript

Abstract

Several governments have tested formal index-based insurance to build climate resilience among smallholder farmers. Yet, adoption of such programs has generated concerns that insurance may crowd out long-established informal risk transfer arrangements. Understanding this phenomenon requires new analytic approaches that capture dynamics of human social behaviour when facing risky events. Here, we develop a modelling framework, based on evolutionary game theory and empirical data from Nepal and Ethiopia, to demonstrate that insurance may introduce a new social dilemma in farmer risk management strategies. We find that while socially optimal risk management is achieved when all farmers pursue a combination of formal and informal risk transfer, a community of self-interested agents is unable to maintain this coexistence at moderate to high covariate risks. We find that a combination of pro-social preferences - namely, moderate altruism and solidarity - helps farmers overcome these concerns and achieve the social optimum. Behavioural interventions that cue such preferences can render financial incentives more efficient in promoting optimal climate risk management, with potential savings worth approximately 5-15 percent of community agricultural income under a range of risk levels.

1 Introduction

Rising climate risks threaten the livelihoods of many of the world's 500 million smallholder farming households [1], the vast majority of whom lack financial protection against climate-driven agricultural losses [2]. To cope with the risks of droughts, floods, and heat waves, development agencies and several national governments have tested formal risk transfer mechanisms, such as index-based crop and livelihood insurance [3–5]. Whereas indemnity insurance generally entails high administrative costs to accurately measure specific losses suffered by individual policyholders, index insurance ties payouts to an exogenous indicator that measures seasonal weather variables and/or crop yields at a regional scale. When the index exceeds a chosen threshold, all policyholders in a given region receive a pre-specified payout, foregoing the need to assess individual damages and reducing costs. As climate-driven risks to rural livelihoods increase in coming decades [6], index insurance programs may therefore be a promising tool for climate adaptation.

Yet, initiatives to promote index insurance are often deployed in contexts in which subsistence farming communities have already developed mechanisms to manage longstanding livelihood risks [7–9]. These mechanisms include intra-household strategies, such as diversifying household income streams through migration remittances [10, 11], and community-wide informal risk transfer mechanisms, including informal lending and revenue-sharing cooperatives [12–14]. However, although informal mechanisms may effectively reduce independent risks (such as individual health shocks) and provide other societal benefits [15, 16], they generally exhibit diminished capacity to protect livelihoods in the face of rising climate-driven covariate risks [17].

Recent literature has sought to understand the potential for new index insurance programs to either serve as complements (i.e. "crowd in") or substitutes (i.e. "crowd out") to informal community risk transfer mechanisms [18]. Studies of index insurance experiments in India [19] and Ethiopia [12–14] demonstrate that formal insurance and informal lending can serve as complementary mechanisms, especially for lending among relatives or close neighbours [13], and if basis risk is high (i.e. a high potential mismatch between a climatological index and actual damages experienced by a policyholder) [19]. However, these studies were only able to exploit data over short time frames (1-2 years). Theoretical frameworks exploring these interactions suggest that while index insurance and informal revenue transfers may initially serve as complements, over the long term, insured households acting out of self-interest may be tempted to reduce or even abandon their commitments to informal revenue transfers [20], unless some form of peer monitoring is able to enforce them [21]. Such findings indicate that self-interested agents acting strategically may not be able to reach a socially optimal outcome without additional incentives or sanctions [22].

Yet, a growing body of empirical evidence suggests that observed levels of human cooperation cannot be explained by completely self-interested, *homo economicus* preferences [23–25]. In particular, Fehr and Shurtenberger identify fundamental mechanisms, including an intrinsic desire for equity, the desire to reciprocate others' behaviour, and self-image as a pro-social actor, that may compel individuals to comply with social norms, even when doing so impinges on their material self-interest [25]. In a similar vein, Alger and Weibull demonstrate that a combination of selfishness and morality (the desire to "do the right thing") is an evolutionary stable preference [26, 27]. Additionally, direct experimental and empirical evidence indicates that altruism - the consideration of others' well-being in an individual decision-maker's objectives - plays a significant role in shaping inter-household risk transfer in rural farming communities [28, 29]. Together, such frameworks and evidence call for incorporating more realistic alternatives to purely rational, self-interested preferences in explaining the emergence of cooperative behaviour [30].

Our aim in this analysis is to investigate the role that alternative decision-making preferences may play in the ability of a smallholder farming community to maintain socially optimal risk management strategies under various levels of climate risk. Specifically, we address four research questions. First, what are the implications of different risk management strategies on long-term community development outcomes, including average community income, inequality, and poverty rates? Second, do different levels of climate-driven covariate risk affect whether formal index insurance is likely to crowd out or complement informal revenue-sharing as a long-term risk management strategy? Third, how do alternative economic preferences affect the risk management choices that emerge from farming communities? Fourth, how might financial and informational policies aimed at promoting socially optimal risk management strategies affect these equilibria?

2 Risk management choices under bounded rationality and different social preferences

The core question underpinning this study is to find what risk management strategies are likely to emerge in a community of subsistence farmers, each making strategic decisions in response to those of their peers. We consider an agricultural community where farmers choose between different risk management strategies at three different scales. These are (i) intra-household risk transfer: whether to exclusively farm, or combine farming with rural-urban migration, (ii) informal risk transfer: whether to take part in a revenue-sharing pool at the community scale, and (iii) formal risk transfer: whether to purchase index insurance covering households at the regional scale (leading to $2^3 = 8$ discrete strategy options). We set up a population game based on evolutionary game theory to improve our understanding of how strategy choices change over time as a result of repeated interactions across a large population of agents that simultaneously make strategic decisions [31]. The population game allows for the integration of bounded rationality. For example, households make decisions by imitating the strategic choices of peers who receive higher utility, rather than by rationally optimizing their actions across the full strategy set. Further background on evolutionary game theory is provided in SI 1.1.

In our model, farmers evaluate strategies based on a utility function that accounts for risk aversion, loss aversion, and time discounting, based on established theories of decision-making under uncertainty [32]. Grounded in the New Economics of Labor Migration (NELM) [11, 33], agents in the model seek to improve expected profits while reducing the volatility of their income streams. In addition to penalizing income volatility, agents in our model also exhibit loss aversion; i.e. they assign a higher penalty to perceived losses than the benefits experienced from gains of a similar magnitude. This is especially relevant in the context of insurance decisions, in which one of the most salient motivations is to protect against a possible loss [34, 35]. Agents considering migration strategies exponentially discount expected future remittance income relative to immediate migration costs, and also apply loss aversion to these costs. Finally, agents in the evolutionary game seek to minimize perceived gaps between their well-being and that of their peers, which echoes findings from NELM and the importance to decision-makers of meeting basic aspiration levels from the Security-Potential/Aspiration framework [36].

We investigate how social preferences affect the share of chosen strategies in the population. Here, we examine the consequences of two different types of prosociality: (i) altruism, which includes the utility of peers in the evaluation of personal utility, and (ii) solidarity, which represents the assumption of coordinated action between like-minded households, resulting from a union of purpose. These are parameterized through α and κ, which each range from 0-1 and indicate the respective degrees of altruism and solidarity in agent utility functions (Methods). We assume that these preferences are homogeneous throughout the population and remain stable over the modelled timeframe, though we assess sensitivities of equilibrium strategy outcomes under different combinations of pro-social preferences (Section 3.3).

Existing informal risk management strategies are limited in their capacity to address covariate risks (in the case of this analysis, drought risk) affecting an entire community at once. Here, we use the base-level correlation ϱ between household farming incomes before any risk management strategies are applied, and drought probability p to create three risk scenarios of covariate risk: Low ($p = 0.2$, $\varrho = 0.1$), Medium ($p = 0.35$, $\varrho = 0.35$), and High ($p = 0.6$, $\varrho = 0.5$). Note that a higher drought probability also implies a higher farming income correlation, hence the increase in ϱ for higher risk scenarios. The Low risk parameters are a composite of the lowest observed drought risk and income correlations from the two considered regions (Nepal's Chitwan District and the Borena region in Ethiopia), and likely serve as a lower bound of covariate risk in most subsistence farming contexts, given the prospect of increased frequency of extreme events as a result of global climate change

[6]. By contrast, the Medium risk scenario is parameterized using the highest drought risks and income correlations observed from the considered regions (SI 1.5). We focus on results from this scenario in the main text, as it likely best describes the types of risks that farmers in both the Chitwan District and Borena region will face in the coming 1-2 decades. Finally, the High risk scenario is a speculative case of a context where climate-driven risks have substantially increased, and also led to higher correlation among household incomes. We establish this as a potential upper bound of covariate risk in which insurers may still wish to offer formal index insurance, and also conduct sensitivity analyses of equilibrium strategy choices to both drought risk and income correlation.

Governments may intervene in multiple ways to shape incentives for household risk management decisions. For example, several national governments are already experimenting with various levels of subsidies for insurance premiums, in order to encourage uptake of new index-based insurance products [2, 12, 14]. Alternatively, policymakers may also wish to overcome information asymmetries between households and governments or insurance agencies. This can for instance be achieved by releasing aggregate information about risk management preferences and choices in a community. If several farmers desire greater risk protection, making this type of information observable may enable households to more easily coordinate on strategies that contribute to risk reduction, but might otherwise be subject to free-riding concerns [37, 38]. We consider the effects of such policies, both in isolation and in tandem, in Section 3.4.

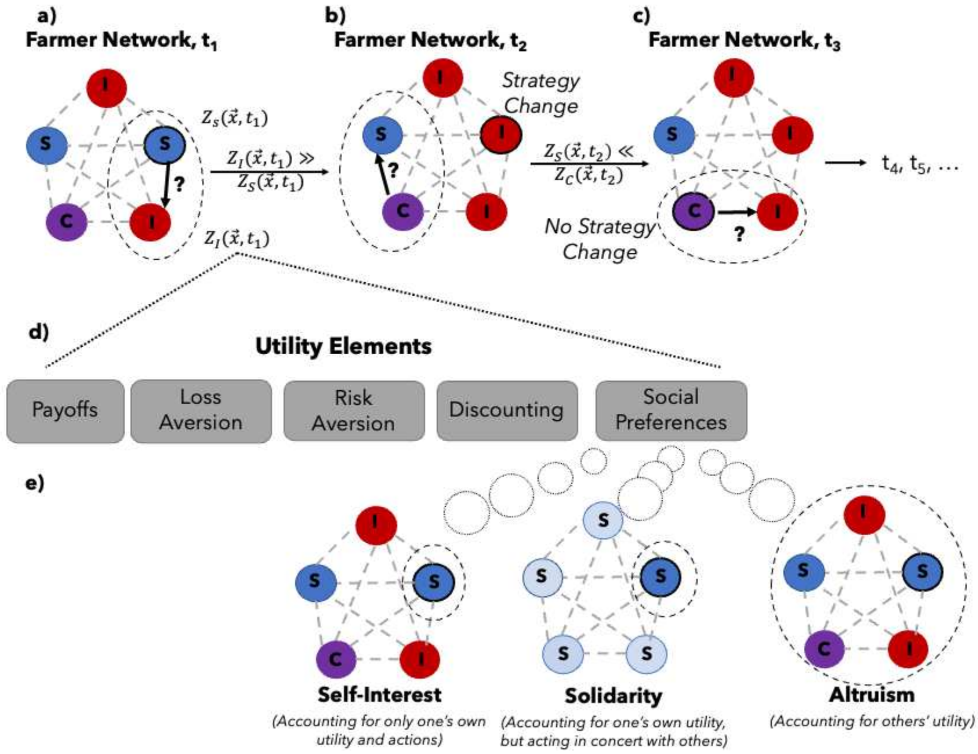


Figure 1: **Overview of the Evolutionary Game Theory Model.** We develop a novel evolutionary game theory model to evaluate the effect of pro-social preferences on risk management strategies that emerge from interactions among smallholder farming households. **a)** Households (represented here by circles) are connected via a social network, and their risk management strategies are indicated by colour (blue = informal revenue-sharing, S; red = formal insurance, I; purple = combination of revenue-sharing and insurance, C). In any given time step, one household is selected as the focal agent (in time t_1, this agent deploys strategy S) and another household is selected as the comparison agent (in this case, this agent deploys strategy I). The focal agent compares the utility of its strategy, $Z_s(\vec{x}, t_1)$, given the distribution of strategies deployed across the community, $\vec{x}$, at time t_1, to that of the comparison agent. **b)** In this case, the utility of adopting I is substantially higher than that of S, so the focal agent adopts insurance in t_2 with high probability. Two more households - one deploying strategy C and one adopting S - are randomly selected as the focal and comparison agent, respectively. **c)** In this case, the utility of S is substantially less than that of C, so the focal agent does not change strategies. Another focal and comparison agent are selected at random, and this sequence repeats for T time steps, corresponding to approximately 50 years. **d)** The elements that constitute utility evaluation include payoffs (parameterized as $\pi_i(\mathbf{x}, t)$), loss aversion (λ), risk aversion (b), discounting (r), and the social preferences (α and κ). **e)** Social preferences consist of self-interest, in which the focal agent considers only their own utility and actions; altruism, in which the focal agent considers the utilities of every other agent playing their current strategies; and solidarity, in which the focal agent considers its own utility if other households (represented by light blue nodes) also adopt the same strategy of the focal agent. The degree to which altruism and solidarity are incorporated in utility evaluation is determined by the values of α and κ, respectively.

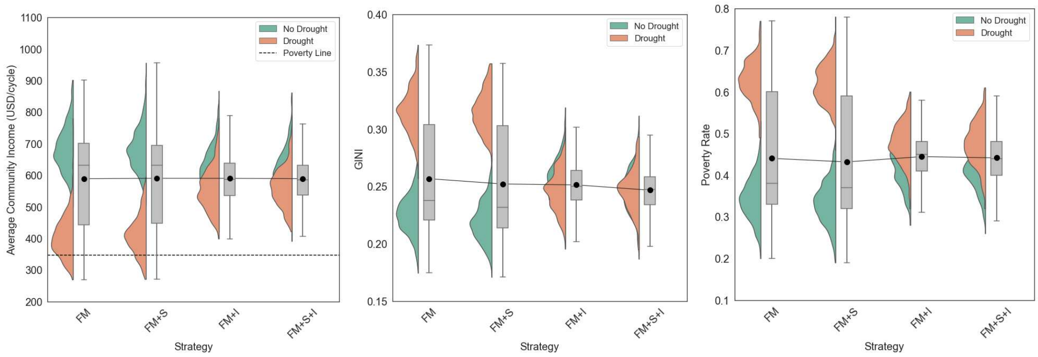
3 Results

3.1 Combining Formal and Informal Risk Transfer Provides More Robust Protection to Drought Risks

Identifying an optimal risk management strategy for subsistence farming communities is complex and involves tradeoffs between multiple objectives. As a first-order approximation, here we simulate collective-scale outcomes of farming communities pursuing monomorphic strategies, i.e. boundary cases in which all households in a community opt for the same strategy, over 1000 cropping cycles with stochastic drought events and income draws. As collective-scale metrics, we consider average community income, inequality (measured by the GINI coefficient), and poverty rate (measured by the World Bank threshold of an income of less than 1.90 USD/household/day). As shown below, most equilibrium outcomes that arise from strategic interactions between farming households fall into one of these four risk management strategies: (i) farming and migration (FM); (ii) farming, migration, and community revenue-sharing (FM+S); (iii) farming, migration, and formal insurance (FM+I); and (iv) farming, migration, revenue-sharing, and insurance (FM+S+I). We include a comparison of strategies without migration and the performance of all strategies under Low and High Risk scenarios in SI 2.2, and consider mixed equilibria between the three most common strategies to emerge in subsequent sections.

Under the Medium risk scenario, layering formal and informal risk transfer effectively shields farming communities against extreme outcomes in drought cropping cycles (Fig. 2). While risk management options do not change the expected income across cropping cycles, formal insurance in particular reduces downside risks to income during drought years (orange), including cycles in which the mean community income falls below the poverty line (Fig. 2a, dashed line). Combining formal insurance with informal revenue-sharing further reduces this collective-scale volatility. However, the reduction of downside risk comes at the cost of foregoing the potential for high community incomes in non-drought years (green) due to costly premiums. The combination of informal and formal risk transfer also limits inequality over long time horizons (Fig. 2b). Droughts drastically reduce all households' farming incomes, which leaves them mostly dependent on highly-variable migration remittances, leading to high income inequality. However, the combination of formal crop insurance and informal revenue-sharing attenuates this inequality by providing households with more stable and equal farming revenues. The tradeoffs inherent in deploying risk transfer mechanisms are most apparent in evaluating poverty rates (Fig. 2c). Without formal insurance, an average of 63 percent of households fall under the poverty threshold in drought years. Deploying formal insurance attenuates these rates in drought years, but costly insurance premiums increase the proportion of households falling into poverty during non-drought years, relative to the absence of such mechanisms. Still, such mechanisms may be preferable if a community wishes to avoid extremely high poverty levels in any given cropping cycle, and pairing insurance with informal revenue-sharing can help mitigate this effect by allowing for some inter-household income transfers.

While formal and informal risk transfer leads to complex tradeoffs at the collective scale, the benefits of layering these mechanisms are evident at the individual household scale (Fig. 3). By construction, all four risk management strategies involving migration lead to the same expected income (Fig. 3, left column), but pairing formal insurance with informal revenue-sharing slightly lowers income volatility across cropping cycles (Fig. 2, middle column). Most importantly, household income losses in communities that deploy both formal insurance and informal revenue-sharing are on average 60 percent those of losses in communities without either risk transfer mechanism, and significantly better than either mechanism on its own (Fig. 3, right column, $p < 0.01$). Based on its ability to reduce inequality and attenuate extreme poverty at the collective scale, and to minimize income volatility and expected losses at the household scale, we designate the combination of migration, informal revenue-sharing, and formal insurance as the socially optimal strategy for risk- and loss-averse decision-makers.



(a) **Med Risk; Income** (b) **Med Risk; GINI** (c) **Med Risk; Poverty Rate**

Figure 2: **Community Outcomes for Monomorphic Risk Management Strategies.** We assess how a community of 100 households would fare when all households adopt one of the eight possible risk management strategies, with random income draws and drought events under the Medium risk scenario ($p = 0.35$, $\varrho = 0.35$). Here, we compare the distributions of average community income (left), GINI coefficient (centre), and poverty rate (right) when the community adopts each of four strategies involving migration: farming and migration (FM); farming, migration, and informal revenue-sharing (FM+S); farming migration, and formal insurance (FM+I); and a combination of all strategies (FM+S+I). Each data point in the distribution represents the results from one simulation, averaged over the 100 households. Distributions are shown separately for outcomes in drought years (orange) and non-drought years (green), with boxplots summarizing the total distribution over both drought and non-drought years. Black dots connected by the line plot indicate mean values for each strategy. Results for other risk levels and non-migration strategies are shown in SI 2.2.

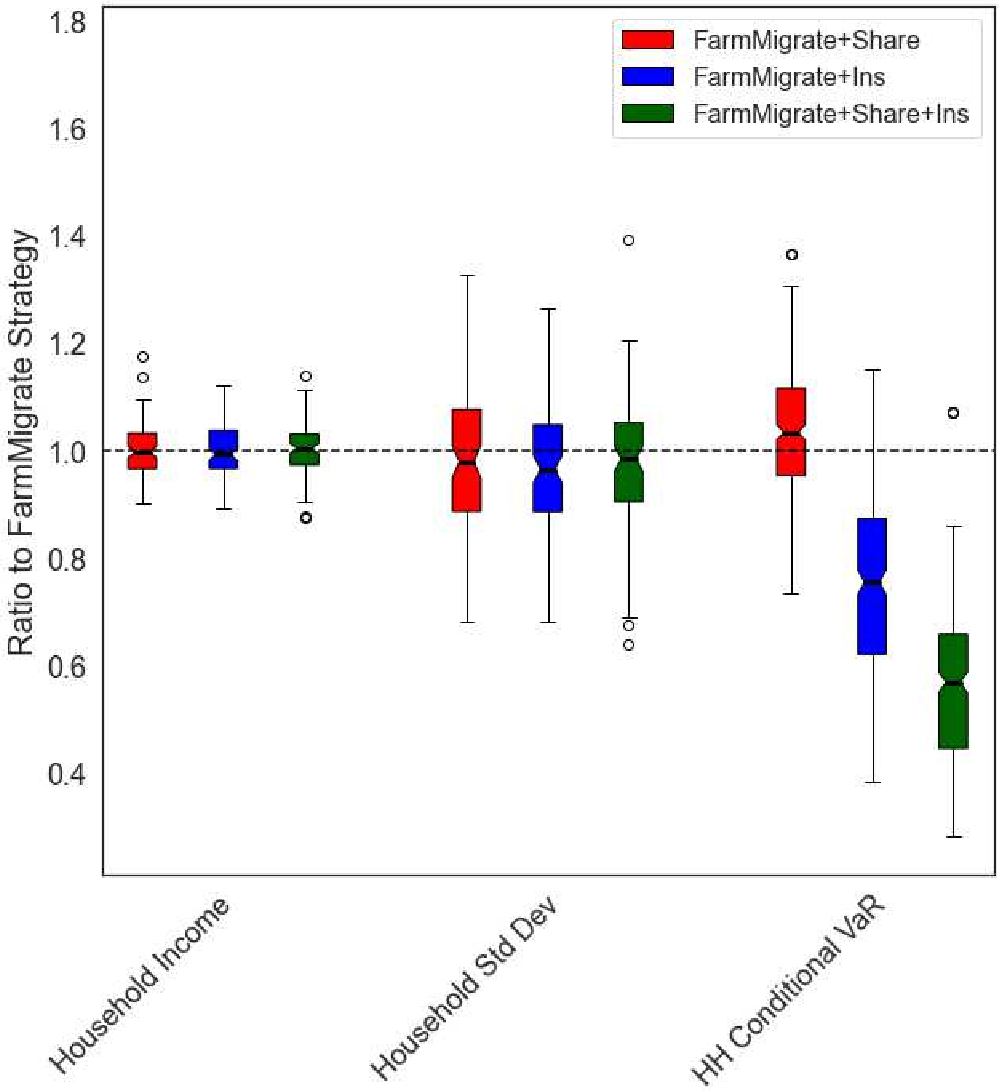


Figure 3: **Decomposition of Household Utility Components.** Individual household strategy decisions are governed by a utility function that incorporates expected income, volatility (measured as standard deviation), and potential losses. The latter metric is expressed as the conditional value at risk, or the weighted probabilistic average of losses below a farming household's break-even point. Here, we decompose household utilities into these three components for four monomorphic strategy distributions (i.e. every household adopting the same strategy). The average household income, standard deviation, and loss for each of three risk management strategies involving risk transfer (FarmMigrate+Share, FarmMigrate+Ins, FarmMigrate+Share+Ins) are displayed relative to the FarmMigrate strategy. Results are generated by simulating random income draws for 100 households adopting the specified strategy over 1000 crop cycles. Each point in the boxplot represents a value for one household, averaged over the 1000 cycles. While average incomes are almost identical across the four monomorphic strategies, median volatility is slightly lower for all strategies that incorporate some form of risk transfer, and losses are significantly lower for strategies incorporating insurance. In particular, the combination of informal revenue-sharing and insurance significantly reduces expected losses compared to the other strategies $p < 0.01$.

3.2 Bottom-up decision-making leads to sub-optimal risk management

In the absence of a legal framework to impose socially optimal strategies, we assess which strategies are likely to emerge as a result of strategic interactions between self-interested farming households. As index insurance programs are still relatively unknown in most subsistence farming communities [2, 3], we first examine which strategies emerge in the absence of formal insurance, and then assess how the introduction of formal insurance may affect this distribution of strategies.

For all covariate risk scenarios, households consistently choose migration as an intra-household risk transfer strategy. Migration serves as an effective means of buffering household incomes against both covariate and independent shocks. However, migration remittance incomes are themselves subject to uncertainty, and may indirectly affect which risk transfer strategies emerge (SI 2.3).

The level of covariate risk affects whether formal insurance and/or informal revenue-sharing are part of the risk portfolios that emerge from bottom-up decision-making. The coexistence of formal index insurance and informal revenue-sharing can emerge under low levels of covariate risk (Fig. 4, $0.0 < p < 0.23$, $0.0 < \varrho < 0.8$). Despite the low degree of covariate risk, farmers' loss aversion motivates the purchase of insurance to avoid losses in drought years, and risk aversion motivates farmers' participation in income-sharing cooperatives to reduce volatility in both drought and non-drought years. While we are unaware of farming contexts in which such widespread adoption of both crop insurance and informal revenue-sharing has been attained over the long term, early data from Ethiopia's index-based livestock insurance suggest that the introduction of insurance may indeed induce increased inter-household income transfers [13, 14].

While self-interested agents are able to achieve optimal risk management under low covariate risk, free-riding concerns and high insurance premiums inhibit their ability to manage coexistence of formal and informal risk management under higher covariate risk (Fig. 4). As covariate risk increases to moderate levels, self-interested participants in the cooperative will benefit even more from the stable income that insured members contribute, and will have less of an incentive to purchase insurance themselves. At the same time, purchasing insurance at actuarially-fair premiums is also more expensive in scenarios with higher drought risk. This social dilemma drives a collapse in the coexistence of formal and informal risk management at a threshold drought risk of approximately $p = 0.23$ (SI 2.4), with formal insurance emerging as the dominant form of risk management.

For the region of high covariate risk, households stay in the revenue-sharing pool but do not purchase formal insurance (Fig. 4a). Under drought risks $p > 0.4$, insurance premiums are now sufficiently costly (> 97 USD/cycle) that households would perceive a greater average loss in utility from purchasing insurance compared to remaining uninsured. Thus, households are left with participating in informal revenue-sharing cooperatives as the equilibrium risk management strategy (Fig. 4d). However, such mechanisms are especially ineffective under conditions of high covariate risk.

A scan of sensitivities to other key decision-making parameters - including farmer risk aversion, loss aversion, discount rates, and the proportion of income contributed to the revenue-sharing pool - indicates that other risk management outcomes are also possible (SI 2.5). Overall, the strategy selection over different levels of drought risk and income correlation indicates the limits to adaptation. Indeed, subsistence farming communities will find it difficult to organize effective risk management strategies in the absence of policy intervention.

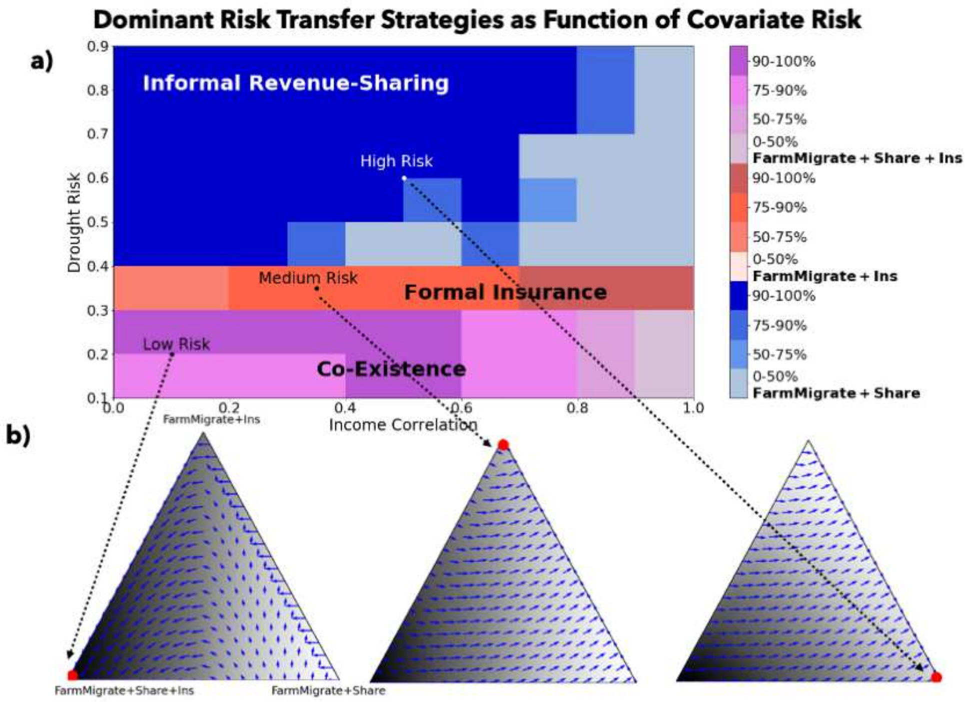


Figure 4: **Equilibrium Risk Transfer Strategies for Self-Interested Farmers.** In communities of purely self-interested farmers, coexistence of formal and informal risk management can emerge at low covariate risk, but collapses at higher levels of risk due to free-riding concerns. **(a)** We assess which risk management strategies are most likely to emerge as a function of farm income correlation (x-axis) and drought risk (y-axis). Colours indicate the the most common strategy at terminal time (averaged over 100 simulations), with gradations indicating the percent of the population adopting this strategy. Generally, as drought risks increase (i.e. higher y-axis values), equilibrium outcomes transition from a majority of farmers adopting both formal and informal mechanisms ($p < 0.3$), to most farmers only adopting formal insurance ($0.3 < p < 0.4$), to a majority of farmers only adopting informal revenue-sharing ($p > 0.4$). As the base-level correlation among farming incomes increases (i.e. higher x-axis values), the effectiveness of the informal revenue-sharing pool decreases (SI 2.1), and a lower proportion of farmers adopts this strategy. **(b)** For three risk scenarios, utility gradient plots identify the equilibrium points (red dots) between the three risk transfer strategies. Each point in the triangle represents the distribution of households according to the proportion of farmers adopting FarmMigrate+Share, FarmMigrate+Insurance, and FarmMigrate+Share+Insurance. Blue arrows indicate the incremental direction of highest utility, given the distribution of strategies in the population at that coordinate. Grey shading indicates the aggregate utility of the population (darker grey = higher utility) for the given distribution of strategies. Under the Low Risk scenario, the equilibrium point corresponds with the point of highest aggregate utility at [0,0] (representing 100 percent of households adopting FarmMigrate+Share+Insurance). Under the Medium and High Risk scenarios, the equilbrium point shifts to all farmers pursuing FarmMigrate+Ins and FarmMigrate+Share, respectively, while the highest aggregate utility remains at the origin. In this analysis, we assume that migration remittances are unaffected by drought risk, either because destinations are remote from the drought-stricken area or because migration incomes are typically earned in non-agricultural sectors.

3.3 Moderate Pro-Sociality Can Promote Socially Optimal Risk Management

Can strategy selection be modulated by pro-social preferences? In our model, we represent altruistic preferences via the index α ($0 \leq \alpha \leq 1$), and set the altruism factor $\alpha = 0.6$ as an example of high altruism. This level of altruism is at the highest end of the ranges estimated in laboratory experiments [29] and statistical inference [28]. Similarly, we capture solidarity-based worldviews with the index κ ($0 \leq \kappa \leq 1$) and set the solidarity factor $\kappa = 0.6$ as an example of high solidarity. One interpretation of this value is that a decision-maker trusts that 60 percent of other households in their community will make the same strategic decision. While we know of no empirical work specifically measuring solidarity, studies demonstrating the prevalence of "false consensus" (i.e. a bias that most other community members act and think in a similar fashion as oneself) in several settings [37, 39] lend credence to this value as a feasible, if not common, condition. Further, cross-national surveys demonstrate that moderate amounts of community trust are common across several cultures [40, 41], and experimental evidence demonstrates that universal cooperation is more prevalent than what can be explained through mechanisms such as direct reciprocity [42].

Neither altruism nor solidarity by themselves are sufficient to promote high adoption of both formal insurance and informal revenue-sharing (Fig. 5a) under the Medium risk scenario. Perhaps counterintuitively, farmers acting out of high altruism select the same strategy as self-interested households, and the community reaches a monomorphic equilibrium where all farmers only pursue formal insurance (Fig. 5b, left). Although altruistic farmers consider how their choices affect the utilities of their peers, their own individual strategy choices do not have sufficient impact on the collective utility to move from this equilibrium. Even a community composed entirely of perfect altruists ($\alpha = 1.0$) is not likely to sustain high levels of both formal and informal risk transfer, as individuals assess their own actions as insufficient to overcome a coordination threshold.

By contrast, communities in which farmers act out of solidarity do reach a different type of equilibrium, known as a limit cycle. In this case, the community continually cycles between mixes of informal revenue-sharing, formal insurance, and a combination of both strategies, periodically approaching, then leaving, states where collective utility is maximized (Fig. 5b, centre). Limit cycles reveal how communities organize their risk management over time, and indicate that the increased adoption of an optimal strategy can be transient. In principle, periodical cycling may help subsistence communities learn about the relative ability of different strategy mixes to contend with drought risks. In practice, over time communities may anticipate this cyclic behaviour and proactively adjust their decisions, leading to more stable strategies. More generally, this behaviour arises when the level of solidarity is enough to partially, bot not completely, overcome the free-riding problem common to self-interested farmers. Only around $\kappa = 0.8$ would solidarity be sufficiently high to overcome this social dilemma on its own and push the equilibrium strategy toward the social optimum.

In communities with high amounts of both altruism and solidarity ($\alpha = \kappa = 0.6$), which we term "high pro-sociality", all households purchase formal insurance and participate in the revenue-sharing cooperative in steady state (Fig. 5b, right). Neither high altruism nor high solidarity on their own are sufficient to reach this state, but they have a synergistic effect in promoting optimal risk management. Altruism leads to the desire to contribute to others' utility, and solidarity provides farmers with the confidence that combining formal and informal risk transfer will have a material impact on collective utility. While it may not be realistic to expect all members of a farming community to act with high altruism and high solidarity, even moderate amounts of both preferences (e.g., $\alpha = \kappa = 0.3$) promote equilibria that include some households deploying a combination of insurance and revenue-sharing (Fig. 5a). As with the high solidarity case, communities with this type of pro-sociality cycle through different states. While not as socially beneficial as the equilibrium that emerges under high pro-sociality, it is notable that moderate pro-sociality comprises a value of altruism that is in line with observed values in many subsistence societies, at least in experimental settings [28]. Similarly, it is plausible that in a typical community, an average decision-maker would trust at least 30 percent of his or her neighbours to also act in a similar fashion.

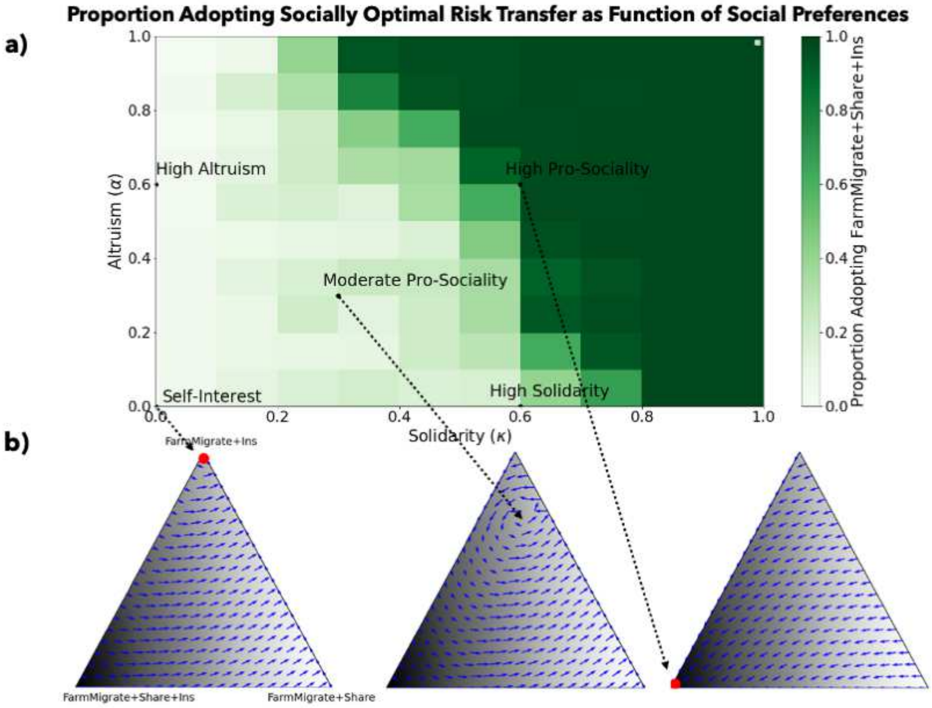


Figure 5: **Effect of Alternative Social Preferences on Risk Management Equilibria.** Alternatives to purely self-interested preferences may shift the risk management equilibria that emerge in a subsistence farming community. We focus here on the Medium risk scenario ($p = 0.35$; $\varrho = 0.35$), while results for other scenarios are included in SI 2.6. **a)**Various combinations of altruism- and solidarity-based preferences can support a socially optimal combination of index insurance and informal revenue-sharing. Here, for different degrees of solidarity (κ, x-axis) and altruism (α, y-axis), the proportion of the community adopting the socially optimal strategy (FarmMigrate+Share+Insurance) is indicated by the green colourbar, with darker shadings indicating higher adoption of this strategy. Generally, adoption increases with increasing levels of altruism and/or solidarity. Downward-sloping diagonal gradients indicate that pro-social preferences exhibit a synergistic effect: the presence of some altruism reduces the threshold level of solidarity needed to achieve high adoption of the socially optimal strategy, and vice versa. **b)** Different ideal types of social preferences can lead to substantially different equilibrium points among the three main risk management strategies. Here, equilibria are shown under the Medium Risk scenario for Self-Interest ($\alpha = 0$, $\kappa = 0$), Moderate Pro-Sociality ($\alpha = 0.3$, $\kappa = 0.3$), and High Pro-Sociality ($\alpha = 0.6$, $\kappa = 0.6$) (also indicated by the points in **a)**. Under Self-Interest and High Pro-Sociality, a single equilibrium point emerges in which 100 percent of farmers adopt insurance only and a combination of insurance and revenue-sharing, respectively.Under Moderate Pro-Sociality, a limit cycle emerges in which the equilibrium distribution of strategies shifts between different proportions of all three strategies, all with at least 60 percent of farmers adopting insurance only. Similar plots for other social preference types and risk scenarios can be found in SI 2.6.

3.4 Pairing Financial and Behavioural Interventions Yields a Pro-Social Dividend

One way in which governments can promote socially optimal risk management is through financial incentives. Here, we consider the effects of insurance premium subsidies, a tool already widely used to promote adoption of index insurance with mixed results on observed patterns of insurance uptake [18, 43, 44], in which the population is homogeneous in its economic preferences.

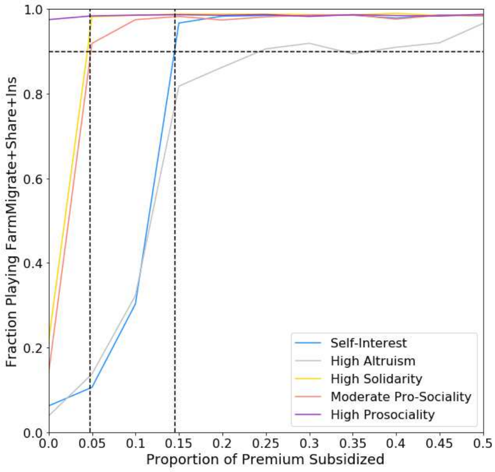
Under the Medium risk scenario, different economic preferences of a community can lead to significantly different subsidies (Fig. 6a). For example, in communities of Self-Interested agents, a subsidy of approximately 15 percent of premiums (equivalent to 13.40 USD/household/crop cycle) would be required to achieve widespread adoption ($\geq$ 90 percent of households) of the socially optimal strategy. This is slightly lower than the threshold of a 23 percent subsidy that was found to promote high index insurance uptake in Bangladesh [44], though it is unclear if farmers in that case study also participated in an informal risk-sharing arrangement. By contrast, for communities in which High Pro-Sociality ($\alpha = \kappa = 0.6$) predominates, no premium subsidy is needed; pro-social preferences are already sufficient in promoting near-universal uptake of insurance and informal revenue-sharing. Even in communities espousing Moderate Pro-Sociality ($\alpha = \kappa = 0.3$) or High Solidarity ($\alpha = 0.0$, $\kappa = 0.6$), a subsidy of only 5 percent of premiums (4.50 USD/household/crop cycle) is needed to achieve the same objective.

This reflects the complementary nature of pro-social preferences and financial incentives in advancing robust risk management. Premium subsidies provide an incentive for individual households to purchase insurance, and pro-social preferences partially overcome the temptation to free-ride on others' insurance purchases. Together, financial incentives and pro-sociality can assist farmers in overcoming the social dilemma that arises when formal insurance is introduced in communities with informal risk-sharing arrangements. Interestingly, communities with High Altruism ($\alpha = 0.6$, $\kappa = 0.0$) would require even higher subsidies (24 percent of premiums, or 21.40 USD/household/crop cycle) than communities of Self-Interested agents. This is another example of how altruism by itself may not be sufficient in overcoming social dilemmas. As altruistic agents assign less weight than self-interested agents to their own well-being, a higher personal gain (i.e. higher subsidy) is needed for pecuniary policies to have the same effect.

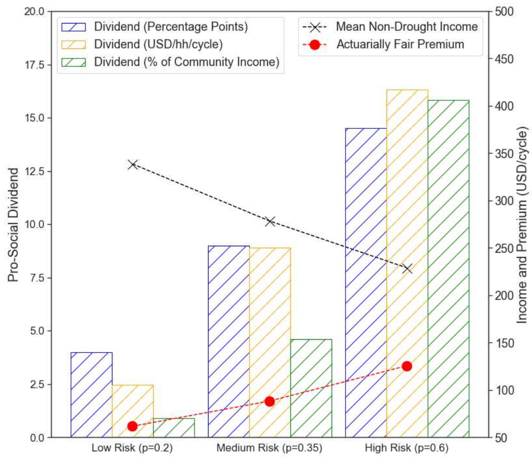
Pairing financial incentives for climate risk management with behavioural interventions promoting pro-sociality is a strategy that merits strong consideration as climate-driven risks increase in the coming decades. Interventions could include strategies that have been used to address collective action problems in climate mitigation. Examples are mass informational campaigns that promote a shared identity and injunctive norms, more targeted campaigns that frame specific actions (e.g. purchasing index insurance and contributing to revenue-sharing pools) as contributions to a public good, and communication outlets through which farmers can gain awareness of their peers' risk management intentions [45, 46]. Such policies can contribute to cultivating altruism and solidarity as general values that predominate in farming communities, and/or activating such values in specific decision environments, e.g., community meetings in which farmers have the opportunity to purchase insurance and contribute to revenue-sharing pools.

To help governments evaluate the value of such interventions, we define a metric called the pro-social dividend, which reflects the monetary benefit of cultivating pro-social preferences with respect to improved efficiency of financial policies relative to a community without such preferences. The pro-social dividend represents the difference in subsidy levels required to achieve optimal risk management in a community espousing moderate pro-sociality vs. a community of self-interested farmers. Under Medium risk, this pro-social dividend is equal to 8.90 USD/household/cycle, or 1790 USD per year for a community of 100 households.

For subsistence farming communities, this is a non-negligible sum, equal to approximately 4.6 percent of the community's total annual farming income. Further, this pro-social dividend is likely to increase with increasing climate risk (Fig. 6b). Under High risk, the pro-social dividend would be equal to 16.30 USD/household/cycle, or 3260 USD/year for the community - roughly double the dividend under Medium risk conditions. Under such conditions, higher climate risks drive higher premiums while also reducing farmers' disposable incomes. Under High risk, an actuarially-fair premium would represent 54.9 percent of the mean income in a non-drought cycle - compared to 18.2 and 31.7 percent under Low and Medium risk, respectively - increasing the temptation to free-ride on other community members' insurance purchases. Further, as high climate risks depress crop yields, this dividend would be equivalent to 15.8 percent of average annual farming income. While the benefits of cultivating pro-social preferences under rising climate risk appear substantial, we note two caveats. First, the pro-social dividend may accrue to insurance companies and/or different levels of governments, and may not be fully re-invested in the community itself. Second, as rising climate risks increase the temptation to free-ride, behavioural interventions that were successful in promoting pro-social preferences under lower climate risks may lose effectiveness.



(a) **Medium Risk, All Preferences**



(b) **Pro-Social Dividend, All Risks**

Figure 6: **Effect of Financial Policy Incentives and Pro-Social Preferences on Risk Management Strategy Choices. a)** Under the Medium Risk scenario ($p = 0.35$, $\varrho = 0.35$), the proportion of households pursuing the socially optimal strategy (FarmMigrate+Share+Insurance) is displayed as a function of the insurance subsidy (x-axis), expressed as a proportion of the total premium, for communities exhibiting five types of economic preferences: Self-Interested (blue, $\alpha = 0.0$, $\kappa = 0.0$); High Altruism (grey, $\alpha = 0.6$, $\kappa = 0.0$); High Solidarity (yellow, $\alpha = 0.0$, $\kappa = 0.6$); Moderate Pro-Sociality (red, $\alpha = 0.3$, $\kappa = 0.3$), and High Pro-Sociality (purple, $\alpha = 0.6$, $\kappa = 0.6$). The horizontal line indicates an objective of attaining 90 percent adoption of this strategy, and vertical lines indicate the subsidy levels at which the Moderate Pro-Sociality and Self-Interested preferences reach this threshold, enabling a comparison of the ”prosocial dividend” - i.e. how much is saved in subsidies required to achieve a socially optimal goal as a result of the presence of prosocial preferences. In this scenario, the dividend is equal to approximately 10 percent of the actuarially-fair premium, or 8.90 USD/hh/crop cycle. Results are expressed as the average terminal time frequency of households pursuing this strategy over 100 simulations. **b)** The value of the pro-social dividend depends substantially on the risk level, and is displayed here under the Low ($p = 0.2$, $\varrho = 0.1$), Medium, and High Risk ($p = 0.6$, $\varrho = 0.5$) scenarios. We compare the dividend by three related metrics: the percentage point difference in subsidy levels required to attain 90 percent adoption of the socially optimal strategy between Self-Interested and Moderate Pro-Social communities (blue), the monetary difference between these subsidy levels per household and per cropping cycle (orange), and the aggregate community-wide monetary difference between these subsidy levels per cropping cycle, expressed as a percentage of total community farming income (green). The ratio of the dividends under High vs. Low Risk is higher when they are expressed as a monetary difference and as a percentage of total community income, as higher covariate risks increase the actuarially-fair premium (red line, circle markers) and reduce mean farming income (black line, ’x’ markers).

4 Discussion

Rising climate risks are likely to impose increased losses on subsistence farming communities over the remainder of the 21st century, threatening the viability of rural livelihoods. Such a future calls for risk transfer instruments that offer farmers protection against climate-driven losses, thereby enabling households and communities to deploy livelihood strategies with more stable economic outcomes. A combination of the three levels of risk management offers farming communities more complete protection against climate-driven losses than any other combination of strategies. This is because migration and informal revenue-sharing helps households cope with independent shocks to their farming incomes, while insurance helps communities manage covariate shocks that could otherwise limit the effectiveness of informal revenue-sharing mechanisms. However, the coexistence of formal and informal mechanisms would collapse in a community of purely self-interested agents, with farming households pursuing either index insurance or informal revenue-sharing depending on climate risks and income correlation. Interestingly, a combination of moderate altruism and solidarity, in line with empirically measured values, can be sufficient to promote at least some uptake of optimal risk management layering. These pro-social preferences can render pecuniary incentives, e.g. premium subsidies, more efficient in their ability to promote optimal risk management.

This analysis contributes to two emerging strands of literature: one examining the ability of index insurance to help smallholder farmers manage livelihood risk, and one examining the role of pro-sociality in the provision of public goods. Consistent with previous empirical [12–14, 34, 44, 47] and theoretical [20, 21, 48] studies, we confirm that widespread adoption of index insurance is constrained by several challenges. In addition, we demonstrate that formal insurance may crowd out informal risk-sharing arrangements, and vice versa, as climate risks rise and if farmers primarily act out of self-interest. This finding supports previous work demonstrating the potential for new insurance programs to be maladaptive by crowding out existing informal lending arrangements [15]. Regarding the role of pro-sociality, we contribute to growing literature that demonstrates its importance in providing public goods. However, whereas pro-sociality is typically conceptualized as the incorporation of others' well-being in one's decision-making objectives [49], the adherence to social norms [25], or reciprocity [24, 50], here we highlight the importance of pairing two fundamental preferences, altruism and solidarity, that underlie pro-sociality. Crucially, we demonstrate that altruism alone is not sufficient to solve the dilemma of sub-optimal risk transfer. By contrast, a combination of both altruism and solidarity, in moderate amounts, may help overcome this social dilemma. Experimental evidence suggests that altruism levels in subsistence communities approximate such moderate values [28, 29]. Further, previous studies have also found that behavioural interventions can increase community trust, a necessary component of solidarity, leading low-income individuals to be less myopic in making inter-temporal decisions [51].

While our conclusions are generally robust to sensitivities in risk levels, household risk and loss aversion preferences, and community size, there are several additional considerations that add nuance to our findings. High basis risk, which has been explored in other work [19–21], may inhibit widespread adoption of index-based insurance, but increase the complementarity of formal and informal mechanisms. We also assume that the insurer is pooling sufficient independent risks to remain solvent, but increasing climate risks might require to enlarge the geographical scale of risk pooling [52]. Another substantial barrier to adoption of index insurance, even when premiums are heavily subsidized, appears to be a lack of trust in receiving timely payouts [43]. Furthermore, the importance of preference heterogeneity in communities and the impact of network effects can alter the selection of risk management strategies [25]. From a financial perspective, our model generally assumes that any farming household wishing to engage in migration or purchase insurance either has enough savings or access to credit to do so. In reality, subsistence farming communities typically have imperfect access to credit and limited ability to save [8], making it difficult to deploy strategies that provide long-term benefits for an upfront cost. These conditions may leave households exposed to other substantial risks, including human smuggling and indentured labour arrangements, which were salient risks for both Nepali and Ethiopian migrants working in Qatar on World Cup infrastructure [53, 54]. In an extension of the model, we impose restrictions on the strategies households can deploy if they do not accumulate sufficient savings; our analysis demonstrates that such restrictions may delay the dynamics with which risk management strategies are adopted in a community and lead to qualitatively different long-term equilibria (SI 2.7). Note that we assume in this analysis that insurance programs cover a sufficiently diversified population such that they can remain solvent when all households in a focal community experience a climate shock and require a payout.

Risk management strategies that may be optimal for households and small communities may not scale to larger regions or entire countries. For example, while it may be feasible and perhaps even desirable for certain communities in Nepal and Ethiopia to withstand high outmigration rates in order to receive remittance income and alleviate population pressures, high national outmigration rates could lead to large-scale demographic, economic, and food security shocks. As well, behavioural interventions that promote altruism and/or solidarity are likely to be more effective in smaller community settings, where repeated interactions and a shared identity among households contribute to pro-sociality. At larger governance scales, anonymity and even rivalry between farmers from different regions are likely to challenge the ability to draw out such preferences. Another fruitful avenue for further research is therefore to assess the potential tradeoffs in risk management objectives at different governance scales, and the ability of polycentric governance structures (i.e., overlapping institutions at multiple scales) to coordinate these tradeoffs.

Finally, classical (non-cooperative) game theory has been unable to replicate the outcomes of experimental games in which a cooperative outcome emerged. Although pro-sociality is widely studied in the social sciences [55], worldviews that incorporate pro-sociality are still mostly absent in mechanistic models that enable to study the downstream effects of these preferences. In this work, we integrated insights from social psychology into a mechanistic agent-based framework [56], notably an evolutionary game, and found that pro-sociality plays an important role in overcoming a coordination problem in risk management. However, the insights gained from this research are not unique to the context of risk management, and therefore we hope that similar modeling approaches can be applied to the study of human behavior in other social dilemmas.

5 Methods

In the proposed modeling framework, the evolutionary dynamics of strategy choices are governed by imitation, and households within the population interact with each other through their utility functions. The state of the population is represented by the vector $\mathbf{x} \in \mathbb{N}^S$, with S the number of strategies, and where the ith element of the vector, x_i, represents the number of households that selects pure strategy i. At any given time, households can select one of the eight strategy options representing different combinations of intra-household livelihood strategies (farming with or without migration), informal risk transfer (revenue-sharing), and formal risk transfer (index insurance). Households selecting strategy i receive an expected profit $\pi_i(\mathbf{x}, t)$, but are risk- and loss-averse as they are sensitive to the variance $\sigma_i^2(\mathbf{x}, t)$ of strategy i and negative net income, respectively. To incorporate different decision-making preferences, we first consider the payoff function $u_i(\mathbf{x}, t)$ of the risk- and loss-averse *homo economicus*, and add an altruism index in $v_i(\mathbf{x}, t)$ and a solidarity index in $w_i(\mathbf{x}, t)$. These preferences may be combined into one generalized utility function, $z_i(\mathbf{x}, t)$ incorporating both altruism and solidarity.

5.1 Material payoff functions

Each agent following strategy i has an expected payoff $\pi_i(\mathbf{x}, t)$, which can be written as

$$\pi_i(\mathbf{x}, t) = I_i(t) + R_i(t) + S_i(\mathbf{x}, t) - C_i(t)\,. \tag{1}$$

We assume that agents consider one pair of strategies at a time (Section 5.6), and have perfect information about the expected income and variance of these strategy options, which may change based on the strategy choices played by other households in the community. The expected income from farming $I_i(t)$ at time t for strategy i accounts for the number of farming household members in case of migration through the migration adjustment factor η. The variance of the farming income is represented by $\sigma^2_{I,i}$. A drought occurs in any cropping cycle with probability p, and the expected income in a non-drought (drought) year is represented by I^{nd} (I^{d}), with corresponding variance $\sigma^2_{I^{\mathrm{nd}}}$ ($\sigma^2_{I^{\mathrm{d}}}$). We assume all agents farm mostly cereal crops based on a weighted average of crop production data from Nepal's Chitwan Valley (SI), though previous work has demonstrated that risk transfer policies may lead farmers to shift cropping strategies over the long term [57]. $R_i(t)$ are the expected remittances of strategy i with corresponding variance σ^2_R. $S_i(t)$ represents the income originating from informal and formal risk transfer in strategy i. In case of informal revenue-sharing, β represents the proportion of household farming income that is shared in an informal risk-sharing pool. $C_i(t)$ are the costs corresponding to strategy profile i, and can consist of the farming cost C^{F}, upfront migration cost C^{M}, revenue-sharing cost $\beta \cdot (I_i(t) - C^{\mathrm{F}})$, and formal insurance premium C^{FI}. An overview of the mean and variance of all strategy options can be found in the SI, Section 1.2.

5.2 Utility including risk- and loss-aversion

Grounded in the theory of the new economics of labour migration (NELM), we assume that households diversify their strategies to reduce the risk to their livelihood. To this purpose, the utility can be defined as the difference of the expected profit and the weighted profit volatility, given by $\pi_i(\mathbf{x}, t) - b \cdot \sigma_i(\mathbf{x}, t)$ where b represents the risk-aversion parameter. However, as decision-makers tend to be more sensitive to experiencing losses versus gains of a similar magnitude [58], any potential loss is penalized with factor λ, with $\lambda > 1$ for most decision-makers. According to the loss aversion framework, decision-makers interpret payoffs in terms of gains and losses relative to a reference point. In the particular decision-making context of subsistence farming, the salient reference point is average farming cost, C^{F}. That is, households will perceive farming investments as a loss if the net farming revenues they accrue (including costs and payouts from insurance and/or the revenue-sharing pool) do not cover their initial expenses for a cropping season. Conversely, net farming revenues above those expenses are considered gains. This is equivalent to the status quo reference point evaluated by Lampe and Wurtenberger in their study of loss aversion and demand for index insurance [34], and allows us to evaluate the gains and losses of all farming risk management options on an equivalent basis. Households account for migration decisions separately from farm management decisions. Here, the relevant reference point for evaluating gains or losses from migration is 0. That is, if a household has not yet engaged in migration, then it will perceive an initial loss of C^{M}, representing the upfront cost of migration. On the other hand, if a household has already engaged in migration, we assume there are no additional upfront costs borne by the household, and the expected remittance income $R_i(t)$ is seen as a gain.

Loss aversion is typically measured empirically using a cumulative prospect theory (CPT) utility function. Since the utility function in this work is derived from mean-variance theory (MVT), rather than CPT, the loss-aversion parameter is re-scaled such that it retains the same meaning in the MVT framework. We do this by comparing the ratio of farming utilities in a drought vs. non-drought year under both CPT and MVT (see SI, Section 1.3 for more details). Accounting for loss aversion related to farming and migration losses, the utility at time t from farming and migration of a self-interested, risk- and loss-averse household following strategy i can be written as

$$u_i^{\mathrm{F}}(\mathbf{x},t) = \begin{cases} I_i(t) + S_i(\mathbf{x},t) - C^{\mathrm{F}} - b \cdot \sigma_{I,i}(\mathbf{x},t) & \text{if } I_i(t) + S_i(\mathbf{x},t) \geq C^{\mathrm{F}} \\ \lambda \cdot \left[I_i(t) + S_i(\mathbf{x},t) - C^{\mathrm{F}} - b \cdot \sigma_{I,i}(\mathbf{x},t)\right] & \text{if } I_i(t) + S_i(\mathbf{x},t) < C^{\mathrm{F}} \end{cases} \tag{2}$$

and

$$u_i^{\mathrm{M}}(t) = \begin{cases} R_i(t) - b \cdot \sigma_{\mathrm{R}}(t) & \text{if } C^{\mathrm{M}}(t) = 0 \\ -\lambda \cdot C^{\mathrm{M}}(t) & \text{if } C^{\mathrm{M}}(t) > 0 \end{cases} \tag{3}$$

Similar to the CPT framework, the loss-aversion factor is applied to the loss corrected for the risk penalty. We further explain the re-scaling of these parameters in Section 1.3 of the SI.

Using (2) and (3), the total utility of a self-interested household at time t is given by

$$u_i(\mathbf{x},t) = u_i^{\mathrm{F}}(\mathbf{x},t) + u_i^{\mathrm{M}}(t)\,, \tag{4}$$

and the expected utility over drought and non-drought periods for each farming strategy i can be calculated as

$$\mathbb{E}[u_i^{\mathrm{F}}(\mathbf{x},t)] = p \cdot u_i^{\mathrm{d}}(\mathbf{x},t) + (1-p) \cdot u_i^{\mathrm{nd}}(\mathbf{x},t)\,, \tag{5}$$

with $u_i^{\mathrm{d}}(\mathbf{x},t)$ and $u_i^{\mathrm{nd}}(\mathbf{x},t)$ the utility in a drought and non-drought period, respectively.

5.3 Utility under pro-social preferences

Building on frameworks from Foster and Rosenzweig [28], Lin et al. [29], and Tilman et al. [59], we introduce an altruism index, α, which governs the degree to which individual households prioritize the collective well-being of the community over their individual utility. Different levels of altruism can be captured as follows in the utility function

$$\begin{aligned} v_i(\mathbf{x},t) &= (1-\alpha) \cdot u_i(\mathbf{x},t) + \alpha \cdot \frac{1}{N} \cdot \sum_j x_j \cdot u_j(\mathbf{x},t) \\ &= (1-\alpha) \cdot u_i(\mathbf{x},t) + \alpha \cdot \frac{W(\mathbf{x},t)}{N}\,, \end{aligned} \tag{6}$$

where α takes values in the interval $[0,1]$, and $W(\mathbf{x},t) = \sum_j u_j(\mathbf{x},t)$ represents the social welfare function. For $\alpha = 0$, the decision-maker coincides with the self-interested household (*homo economicus*) defined in (4), while for $\alpha = 1$, the decision-maker is a complete altruist, attaching equal weight to the utility of each individual in the population, including him- or herself. In this case, $v_i(\mathbf{x}, t)$ reflects the average per capita utility of the community; that is, the sum of all individual utilities normalized by the population size, N.

We next introduce a solidarity parameter, κ, which specifies the degree to which a decision-maker takes actions that he or she wishes to be universalized. Different levels of solidarity are captured as follows in the utility function

$$w_i(\mathbf{x}, t) = \mathbb{E}_{\tilde{\mathbf{x}}}\left[u_i(\tilde{\mathbf{x}}, t)\right] . \tag{7}$$

In this utility function, the expectation is taken over the random vector $\tilde{\mathbf{x}}$ where the strategy of each household is changed to strategy i with probability κ. Higher values of $\kappa \in [0, 1]$ indicate a greater propensity to adopt the strategy that household i wishes were universalized. An alternative interpretation of κ is a trust parameter, in which higher values of κ indicate greater trust that other households will also act in solidarity with the focal household. For $\kappa = 0$, this decision-maker coincides with a *homo economicus* household, while for $\kappa = 1$ the decision-maker acts as if all households select the same strategy. A high value of κ therefore corresponds with the concept of *homo moralis*, i.e. a decision-maker that defines what is 'the right thing to do' from a self-regarding perspective and overcomes a priori the coordination problem [26]. This utility function may resemble the strategy of conditional cooperation [25], in which agents are predisposed to cooperate towards a pro-social goal, provided they have some confidence that other agents are also likely to cooperate. To calculate the utility function including solidarity, we present an approximation in Section 1.6 of the SI.

The self-interested, altruist, and solidarity preferences can be captured by a single generalizing utility function as follows

$$z_i(\mathbf{x}, t) = \mathbb{E}_{\tilde{\mathbf{x}}}\Big[(1 - \alpha) \cdot u_i(\tilde{\mathbf{x}}, t) + \alpha \cdot \frac{1}{N} \cdot \sum_j x_j \cdot u_j(\tilde{\mathbf{x}}, t)\Big] , \tag{8}$$

which allows us to model combinations of different levels of altruism and solidarity. An interpretation of households evaluating strategy options using $z_i(\mathbf{x}, t)$ with non-zero α and κ, is that households in a community consider their peers' well-being while trusting that a share κ of the community will follow the strategy choice of the focal household. Note that if $\alpha = 0$, (8) reduces to the *homo moralis* preference in (7). Similarly, if $\kappa = 0$, $z_i(\mathbf{x}, t)$ reduces to the altruist preference in (6), and if both $\alpha = \kappa = 0$, the same equation reduces to the risk-averse *homo economicus* household of (4).

In their decision-making, households consider the aggregated utility over time, which in case of a self-interested household is defined as

$$z_i(\mathbf{x}, t) = \sum_{s=t}^{s=t+h} \frac{u_i(\mathbf{x}, s)}{(1 + r)^{s-t}} . \tag{9}$$

The parameter h represents the time horizon over which farming households evaluate their strategy options, and r is the discount factor. This is particularly relevant for evaluating strategy options that include migration. Here, we assume that households engaging in migration pay an upfront cost C^{M} in the first time step, and begin receiving remittances in subsequent time steps.

5.4 Accounting for independent and covariate risk

An important element of the model is to determine how different levels of independent and covariate risk affect the risk management strategies that emerge from farmer decision-making. The risk is determined through the standard deviations σ_i, covering the independent risk of livelihood strategy i; ϱ, capturing the base level correlation between household farming incomes before any risk management strategies are applied; and p, capturing the probability of a shock event, e.g. drought, represented by a threshold frequency in the income cumulative distribution function below which income is assumed to be the result of an extreme event. Note that p also affects the expected income by re-shaping the income distribution as described in the SI, Section 1.4.2). Generally, independent risk increases with σ_i, whereas covariate risk increases with p and ϱ. The precise level of risk faced by each household depends on its risk management strategy and those of its fellow community members.

Income correlation is relevant in case of revenue-sharing, which is only applied to the portion of the income originating from farming. The revenue of household k pursuing revenue-sharing from the combination of farming and revenue-sharing is given by

$$I_{i,k}^{\mathrm{RS}}(\mathbf{x},t) = (1-\beta)I_{i,k} + \beta \cdot \frac{1}{|\mathcal{P}(t)|} \sum_{l \in \mathcal{P}_i(t),\, i \in \mathcal{S}^{\mathrm{RS}}} I_{i,l}\,, \tag{10}$$

where $I_{i,k}$ is the income from farming for household k following strategy i. The income of household k pursuing revenue-sharing can be found by adding the proportional share of the total contributions by the revenue-sharing pool $\mathcal{P}(t) = \bigcup_{i \in \mathcal{S}^{\mathrm{RS}}} \mathcal{P}_i(t)$, where $\mathcal{S}^{\mathrm{RS}}$ stands for the subset of strategies that include revenue-sharing. The mean farming income under revenue-sharing can be written as

$$I_i(t) + S_i(\mathbf{x},t) = \mu_{I_i^{\mathrm{RS}}}(\mathbf{x},t) = (1-\beta)\mu_{I_i} + \frac{\beta}{|\mathcal{P}(t)|} \cdot |\mathcal{P}(t)| \cdot \mu_{I_i} = \mu_{I_i}\,, \tag{11}$$

and income variance under revenue-sharing can be written as

$$\sigma^2_{I_i^{\mathrm{RS}}}(\mathbf{x},t) = \Big((1-\beta)^2 + 2(1-\beta)\frac{\beta}{|\mathcal{P}(t)|}(1+\varrho(|\mathcal{P}(t)|-1)) + \frac{\beta^2}{|\mathcal{P}(t)|}(1+\varrho(|\mathcal{P}(t)|-1))\Big)\sigma_I^2\,, \tag{12}$$

with ϱ the Pearson correlation coefficient assumed constant over time and equal between all pairs of households.

5.5 Policy interventions

We model the effect of a government providing a monetary subsidy, I^{s}, to purchasers of formal insurance, and analyze its relative effectiveness in encouraging household adoption of socially-optimal risk management strategies. We assume that such subsidies are provided immediately upon purchase of the insurance product in each cropping cycle, and take the form of a fixed cash amount. The premium for insurance in each cycle can be written as

$$C^{\mathrm{FI}} = p \cdot (I^{\mathrm{nd}} - I^{\mathrm{d}}) - I^{\mathrm{s}}\,. \tag{13}$$

This type of intervention raises the expected profit of risk management strategies that include formal insurance, which increases their utility relative to strategies without formal insurance, *ceteris paribus*. However, the subsidies do not change the variance of strategies that include formal insurance: each intervention simply shifts the expected income higher for the strategies including formal insurance, while conserving the shape of their income distributions.

5.6 Evolutionary selection mechanism

Considering a population of N households, each of which is following a strategy $i \in \{1, \cdots, S\}$, we simulate how the fraction $x_i(t)$ of the population adopting strategy i evolves over time. In each time step, a household is matched with another household randomly, and over one generation of N time steps the entire population has, on average, the opportunity to change strategy. We also allow for a small mutation probability $\mu = 1/N$ representing the random exploration of the strategy space. Mutations ensure that monomorphic states can be left. The matching process does not correspond to a physical meeting between households, but could also stand for information that arrives at a given household. When a household of strategy i is matched with a household following strategy j, then we get the following transition probabilities $T_{i\to j}$ between strategies i and j

$$T_{i\to j} = (1-\mu)\cdot \frac{1}{1+\exp\left(-\beta\cdot \frac{z_j(\mathbf{x},t)-z_i(\mathbf{x},t)}{z_i(\mathbf{x},t)}\right)} \tag{14a}$$

$$T_{i\to k} = \mu\cdot \frac{1}{S-1}, \qquad k \neq i \tag{14b}$$

$$T_{i\to i} = 1-(1-\mu)\cdot \frac{1}{1+\exp\left(-\beta\cdot \frac{z_j(\mathbf{x},t)-z_i(\mathbf{x},t)}{z_i(\mathbf{x},t)}\right)} - \mu\cdot\frac{1}{S-1}\,, \tag{14c}$$

where $1/(1+\exp(-\beta\cdot x))$ is the logistic function with steepness β. The transition probability in equation (14a) is based on utility differentials between household i and household j. Equation (14b) represents the probability of a random mutation, and (14c) is the probability that the focal household does not change strategy.

5.7 Model setup

We construct a Base Case to compare how different levels of risk and pro-social preferences shape risk management strategies most likely to emerge, given a consistent set of assumptions. In this analysis, we assume a community of $N = 100$ households, and simulate results for 200 generations of N decisions. Such a timeframe allows us to explore the long-term dynamics as households update their risk management strategies, in relation to those espoused by others in their community. To mimic real-world conditions such as those in Nepal and Ethiopia, in which formal climate insurance is not yet common, we further assume that the initial distribution of strategies in the community excludes formal insurance.

We parameterize our model with economic and risk preference data from Nepali farming communities (SI Section 1.4, Table 3). Data on expected incomes and standard deviations of farming and migration livelihoods are taken from the Chitwan Valley Family Study [60], a longitudinal survey of farming households in one of Nepal's most prominent agricultural regions. The correlation between farming incomes is also estimated from this source (SI 1.4.2) and data from the Index-Based Livestock Insurance program in Ethiopia's Borena region [61], two regions of subsistence farming communities whose governments are experimenting with index insurance programs. We derived risk parameters from a composite of these correlation data and drought data for these two regions from the Standardized Precipitation and Evapotranspiration Index (SPEI) [62]. Data on farming costs are taken from Katovich and Sharma [63], and migration costs come from Shrestha [64]. Farmer risk preferences are derived using data from Mohan [65].

Code Availability

The code for the game theory model developed in this study is available via a GitHub repository (to be made public upon publication) at: `https://github.com/nchoquettelevy/FarmerGameTheorySimulation`.

Data Availability

The game theory model from which results are generated is available via a GitHub repository (to be made public upon publication) at: `https://github.com/nchoquettelevy/FarmerGameTheorySimulation`.

Acknowledgments

NCL gratefully acknowledges financial and organizational support from the Center for Policy Research on Energy and the Environment at Princeton University and the International Institute of Applied Systems Analysis, as well as financial support from the Social Sciences and Humanities Research Council of Canada (752-2020-077).

Author Contribution

NCL and MW conceived of and developed an initial design for the study, and drafted the initial manuscript. FPS, SAL, MO, and EUW proposed modifications incorporated in the final design. NCL wrote the model code. NCL and MW analysed model results. All authors contributed to drafting the final manuscript. Correspondence and requests for materials should be addressed to NCL (nclevy@bu.edu) and MW (wildemee@iiasa.ac.at).

Competing Interests Statement

The authors declare no competing interests.

References

[1] S. Mark Howden, Jean-Francois Soussana, Francesco N. Tubiello, Netra Chhetri, Michael Dunlop, and Holger Meinke. Adapting agriculture to climate change. *PNAS*, 104:19691–19696, 2007.

[2] Peter Hazell, Rachel Sberro-Kessler, and Panos Varangis. When and how should agricultural insurance be subsidized? issues and good practices. Technical report, International Labour Organization and International Finance Corporation, 2017.

[3] Helen Greatrex, James Hansen, Samantha Garvin, Rahel Diro, Margot Le Guen, Sari Blakeley, Kolli Rao, and Dan Osgood. Scaling up index insurance for smallholder farmers: Recent evidence and insights. Technical Report CCFAS Report No. 14, CGIAR Research Programme on Climate Change, 2015.

[4] Laura Schaefer and Eleanor Waters. Climate risk insurance for the poor & vulnerable: How to effectively implement the pro-poor focus of InsuResilience. Technical report, Munich Climate Insurance Initiative, 2016.

[5] Lena Weingärtner, Alice Caravani, and Pablo Suarez. The role of multilateral climate funds in supporting resilience and adaptation through insurance initiatives. Technical report, Overseas Development Institute, 2018.

[6] Intergovernmental Panel on Climate Change. Climate change 2022: Impacts, adaptation, and vulnerability - summary for policymakers. Technical report, Cambridge University Press, 2022.

[7] Frank Ellis. Household strategies and rural livelihood diversification. *The Journal of Development Studies*, 35(1):1–38, 1998.

[8] Stefan Dercon. Income risks, coping strategies, and safety nets. *The World Bank Research Observer*, 17(2):141–166, 2002.

[9] Marcel Fafchamps and Flore Gubert. The formation of risk-sharing networks. *The Journal of Development Economics*, 83:326–350, 2007.

[10] Robert E.B. Lucas and Oded Stark. Motivations to remit: Evidence from Botswana. *Journal of Political Economy*, 93, 1985.

[11] Oded Stark and David E. Bloom. The New Economics of Labor Migration. *The American Economic Review*, 75, 1985.

[12] Stefan Dercon, Ruth Vargas Hill, Daniel Clarke, Ingo Outes-Leon, and Alemayehu Seyoum Taffesse. Offering rainfall insurance to informal insurance groups: Evidence from a field experiment in Ethiopia. *Journal of Development Economics*, 106:132–143, 2014.

[13] Kazushi Takahashi, Christopher B. Barrett, and Munenobu Ikegami. Does index insurance crowd in or crowd out informal risk sharing? evidence from rural Ethiopia. *American Journal of Agricultural Economics*, 101:672–691, 2018.

[14] Erlend Berg, Michael Blake, and Karlijn Morsink. Risk sharing and the demand for insurance: Theory and experimental evidence from Ethiopia. *Journal of Economic Behavior and Organization*, 195:236–256, 2022.

[15] Birgit Muller, Leigh Johnson, and David Kreuer. Maladaptive outcomes of climate insurance in agriculture. *Global Environmental Change*, 46:23–33, 2017.

[16] Shree Maharjan and Keshav Maharjan. Roles and contributions of community seed banks in climate adaptation in Nepal. *Development in Practice*, 28(2):292–302, 2018.

[17] Sara LM Trærup. Informal networks and resilience to climate change impacts: A collective approach to index insurance. *Global Environmental Change*, 22(1):255–267, 2012.

[18] Williams Ali, Awudu Abdulai, and Ashok K. Mishra. Recent advances in the analyses of demand for agricultural insurance in developing and emerging countries. *Annual Review of Resource Economics*, 12:411–430, 2020.

[19] Ahmed Mushfiq Mobarak and Mark R. Rosenzweig. Informal risk sharing, index insurance and risk-taking in developing countries. *American Economic Review*, 103:375–380, 2013.

[20] Meike Will, Jurgen Groeneveld, Karin Frank, and Birgit Muller. Informal risk-sharing between smallholders may be threatened by formal insurance: Lessons from a stylized agent-based model. *PL0S ONE*, 16(3), 2021.

[21] Fernando P. Santos, Jorge M. Pacheco, Francisco C. Santos, and Simon A. Levin. Dynamics of informal risk sharing in collective index insurance. *Nature Sustainability*, 4:426–432, 2021.

[22] Alessandro Tavoni, Maja Schlüter, and Simon Levin. The survival of the conformist: Social pressure and renewable resource management. *Journal of Theoretical Biology*, 299:152–161, 2012.

[23] Robert Axelrod and William D. Hamilton. The evolution of cooperation. *Science*, 211(4489):1390–1396, 1981.

[24] Simon A. Levin. Public goods in relation to competition, cooperation, and spite. *PNAS*, 111:10838–10845, 2014.

[25] Ernst Fehr and Ivo Schurtenberger. Normative foundations of human cooperation. *Nature Human Behaviour*, 2:458–468, 2018.

[26] Ingela Alger and Jörgen W Weibull. Homo moralis—preference evolution under incomplete information and assortative matching. *Econometrica*, 81(6):2269–2302, 2013.

[27] Ingela Alger and Jörgen W Weibull. Evolution and kantian morality. *Games and Economic Behavior*, 98:56–67, 2016.

[28] Andrew D. Foster and Mark R. Rosenzweig. Imperfect commitment, altruism, and the family: Evidence from transfer behavior in low-income rural areas. *The Review of Economics and Statistics*, 83(3):389–407, 2001.

[29] Wanchuan Lin, Yiming Liu, and Juanjuan Meng. The crowding-out effect of formal insurance on informal risk sharing: An experimental study. *Games and Economic Behavior*, 86:184–211, 2014.

[30] Kurt B. Waldman, Peter M. Todd, Shahera Omar, Jordan P. Blekking, Stacey A. Giroux, Shahzeen Z. Attari, Kathy Baylis, and Tom P. Evans. Agricultural decision making and climate uncertainty in developing countries. *Environmental Research Letters*, 15, 2020.

[31] J. Maynard Smith. The theory of games and the evolution of animal conflicts. *Journal of Theoretical Biology*, 47:209–221, 1974.

[32] Elke U. Weber and Eric J. Johnson. Sdecisions under uncertainty: Psychological, economic, and neuroeconomic explanations of risk preference. In Paul W. Glimcher, Colin F. Camerer, Ernst Fehr, and Russell A. Poldrack, editors, *Neuroeconomics: Decision Making and The Brain*. Academic Press, 2009.

[33] Douglas S. Massey, Joaquin Arango, Graeme Hugo, Ali Kouaouci, Adela Pellegrino, and J. Edward Taylor. Theories of international migration: A review and appraisal. *Population and Development Review*, 19(3):431–466, 1993.

[34] Immanuel Lampe and Daniel Wurtenberger. Loss aversion and the demand for index insurance. *Journal of Economic Behavior and Organization*, 180:678–693, 2020.

[35] Frederik Sagemuller and Oliver Musshoff. Effects of household shocks on risk preferences and loss aversion: Evidence from upland smallholders of South East Asia. *The Journal of Development Studies*, 56(11):2061–2078, 2020.

[36] Lola L. Lopes and Gregg C. Olden. The role of aspiration level in risky choice: A comparison of Cumulative Prospect Theory and SP/A Theory. *Journal of Mathematical Psychology*, 43:286–313, 1999.

[37] Dale T. Miller and Deborah A. Prentice. Changing norms to change behavior. *Annual Review of Psychology*, 67:339–361, 2016.

[38] John Beshears, James J. Choi, David Laibson, Brigitte C. Madrian, and Katherine L. Milkman. The effect of providing peer information on retirement savings decisions. *The Journal of Finance*, 70(3):1161–1201, 2015.

[39] Fernando P. Santos, Simon A. Levin, and Vitor V. Vasconcelos. Biased perceptions explain collective action deadlocks and suggest new mechanisms to prompt cooperation. *iScience*, 24, 2021.

[40] Joseph Henrich, Robert Boyd, Samule Bowles, Colin Camerer, Ernst Fehr, Herbert Gintis, Richard McElreaath, Michael Alvard, Abigail Barr, Jean Ensminger, Natalie Smith Hnerich, Kim Hill, Francisco Gil-White, Michael Gurvey, Frank W. Marlowe, John Q. Patton, and David Tracer. "Economic man" in cross-cultural perspective: Behavioral experiments in 15 small-scale societies. *Behavioral and Brain Sciences*, 28(6):795–815, 2005.

[41] World Values Survey, Wave 7, 2017-2021, 2021.

[42] Jörg Gross, Zsombor Z. Méder, Carsten K.W. De Dreu, Angelo Romano, Welmer E. Molenmaker, and Laura C. Hoenig. The evolution of universal cooperation. *Science Advances*, 9, 2023.

[43] Rajalakshmi Nirmal and Suresh Chandra Babu. When implementation goes wrong: Lessons from crop insurance in India. Technical Report IFPRI Discussion Paper 02012, International Food Policy Research Institute, 2021.

[44] Ruth Vargas Hill, Neha Kumar, Nicholas Magnan, Simrin Makhija, Francesca de Nicola, David J. Spielman, and Patrick S. Ward. Ex ante and ex post effects of hybrid index insurance in Bangladesh. *Journal of Development Economics*, 136:1–17, 2019.

[45] Sönke Ehret, Sara M. Constantino, Elke U. Weber, Charles Efferson, and Sonja Vogt. Group identities can undermine social tipping after intervention. *Nature Human Behaviour*, 2022.

[46] Sara M. Constantino, Gregg Sparkman, Gordon T. Kraft-Todd, Cristina Bicchieri, Damon Centola, Bettina Shell-Duncan, Sonja Vogt, and Elke U. Weber. Scaling up change: A critical review and practical guide to harnessing social norms for climate action. *Psychological Science in the Public Interest*, 23(2):50–97, 2022.

[47] Nanda Kaji Budhathoki, Jonatan A. Lassa, Sirish Pun, and Kerstin K. Zander. Farmers' interest and willingness-to-pay for index-based crop insurance in the lowlands of Nepal. *Land Use Policy*, 85, 2019.

[48] Jorge M. Pacheco, Francisco C. Santos, and Simon A. Levin. Evolutionary dynamics of collective index insurance. *Journal of Mathematical Biology*, 72:997–1010, 2016.

[49] Avinash Dixit and Simon Levin. Social creation of pro-social preferences for public action. In W. Buccholz and D. Rubbelke, editors, *The Theory of Externalities and Public Goods*. Springer, 2017.

[50] Shaheen Z. Attari, David H. Krantz, and Elke U. Weber. Reasons for cooperation and defection in social dilemmas. *Judgment and Decision Making*, 9(4):316–334, 2014.

[51] Jon M. Jachimowicz, Salah Chafik, Sabeth Munrat, Jaideep C. Prabhu, and Elke U. Weber. Community trust reduces myopic decisions of low-income individuals. *PNAS*, 114(21):5401–5406, 2017.

[52] Franziska Gaupp, Georg Pflug, Stefan Hochrainer-Stigler, Jim Hall, and Simon Dadson. Dependency of crop production between global breadbaskets: a copula approach for the assessment of global and regional risk pools. *Risk Analysis*, 37(11):2212–2228, 2017.

[53] Ministry of Labour, Employment, and Social Security. Nepal Labour Migration Report. Technical report, Government of Nepal, 2020.

[54] Natasha Iskander. *Does Skill Make Us Human? Migrant Workers in 21st-Century Qatar and Beyond*. Princeton University Press, 2021.

[55] Detlev Fetchenhauer, Bram Buunk, Andreas Flache, Abraham P Buunk, and Sigwaart Lindenberg. *Solidarity and prosocial behavior: An integration of sociological and psychological perspectives*. Springer Science & Business Media, 2006.

[56] Christoph Adami, Jory Schossau, and Arend Hintze. Evolutionary game theory using agent-based methods. *Physics of life reviews*, 19:1–26, 2016.

[57] Nicolas Choquette-Levy, Matthias Wildemeersch, Michael Oppenheimer, and Simon A. Levin. Risk transfer policies and climate-induced immobility among smallholder farmers. *Nature Climate Change*, 11:1046–1054, 2021.

[58] Amos Tversky and Daniel Kahneman. Loss aversion in riskless choice: A reference-dependent model. *The Quarterly Journal of Economics*, 106(4):1039–1061, 1991.

[59] Andrew R. Tilman, Avinash K. Dixit, and Simon A. Levin. Localized prosocial preferences, public goods, and common-pool resources. *PNAS*, 116:5305–5310, 2018.

[60] Dirgha J. Ghimire, William G. Axinn, Prem B. Bhandari, Humnath Bhandari, and Rebecca Thornton. Chitwan Valley Family Study: Labour Outmigration, Agricultural Productivity and Food Security, Nepal, 2015-2017, 2019.

[61] Munenobu Ikegami and Megan Sheahan. Index Based Livestock Insurance (IBLI) Borena Household Survey, 2014.

[62] Sergio M. Vicente-Serrano, Santiago Begueria, Jorge Lorenzo-Lacruz, Jesus Julio Camarero, Juan I. Lopez-Moreno, Cesar Azorin-Molina, Jesus Revuelto, Enrique Moran-Tejeda, and Arturo Sanchez-Loreno. Performance of drought indices for ecological, agricultural, and hydrological applications. *Earth Interactions*, 16, 2012.

[63] Erik Katovich and Asin Sharma. Costs and returns of grain and vegetable crop production in Nepal's Mid-Western Development Region. Technical report, US Agency for International Development, 2014.

[64] Maheshwor Shrestha. Push and pull: A study of international migration from Nepal. Technical report, World Bank, 2017.

[65] Sarah Mohan. Risk aversion and certification: Evidence from the Nepali tea fields. *World Development*, 129, 2020.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- ProSocialPreferencesandFarmerRiskTransferStrategiesSI.pdf