Supplementary Material

1.   Theoretical Framework: Climate Shocks, Risk Sharing, and Social Network Relationships

Following Coate and Ravallion [42] and De Weerdt and Fafchamps [43] model of risk sharing based on repeated game theory, I assume an economy consisting of two individuals *i* and *j,* who are infinitely lived and receive income y_t^i and y_t^j, respectively. For any given period, income is assumed to be uncertain and varies over time. Both individuals derive utility from earnings (primarily through consumption) and are assumed to be non-satiated and risk-averse, such that for all $y > 0$, $u'(y) > 0$, and $u''(y) < 0$, with any form of savings assumed to be zero. Individuals are also assumed to mitigate risks primarily through investments in social network relationships. These network relationships bring with them tangible and intangible social benefits and costs. Tangible social benefits include reciprocal income transfers among network members[1], shared labor, machinery, and stores. Intangible benefits can include prestige gained from becoming a network member, shared information, monitoring and enforcement of contracts, and access to key leaders or decision-makers. Social costs include reciprocal transfers made to affected network members, membership fees, and time spent attending network gatherings, which can otherwise be used to earn income[2]. Based on this, individual *i* is assumed to derive utility from income y_t^i earned in period *t*, plus net benefits from participation in social networks nsb_t^{ij} such that:

$$U_i = u_i(y_t^i + nsb_t^{ij})\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.1$$

where

$$nsb_t^{ij} = sb_t^{ij} - sc_t^{ij}$$

Net benefits stem from the value of social benefits sb_t^{ij}, less costs incurred from network participation sc_t^{ij}. It is important to note that nsb_t^{ij} can be negative or positive for individual *i*. For instance, when an individual *i* makes transfers to individual *j* over the benefits received from the network participation, *nsb* can be negative. Alternatively, when an individual *i* receives tangible and intangible benefits from network participation greater than the costs incurred to stay in the network, *nsb* will be positive. Finally, by participating in the network arrangement, individuals *i* and *j* not only benefit from increasing prestige, and, technological and information gains, but also can smooth consumption in the face of unforeseen shocks. I can formalize this aspect of the relationship by stating that through network participation, individual *i* can achieve a guaranteed level of consumption given by:

$$c_t^{ij} = y_t^i + nsb_t^{ij}$$

I also assume that the guaranteed level of pooled consumption c_t^{ij} will be based on some pooled level income y_t^{ij} such that

$$c_t^{ij} = y_t^{ij}$$

For any network arrangement to be implementable and self-reinforcing, the benefits from continued participation should be greater than the cost of defecting from the network in any period s. Therefore, for individual i an *implementarity* constraint takes the form of:

$$U_i((y_s^{ij}) - U_i(c_s^{ij})) \leq E_t [\![F_i(t, nsb)]\!] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.2$$

Where,

$$F_i(t, nsb) \equiv \sum_{s=1}^{\infty} \beta^s \left(U_i(c_{t+s}^{ij}) - U_i(y_{t+s}^{iA}) \right) \ldots\ldots\ldots\ldots\ldots.3$$

The left-hand side of the inequality represents the cost of defecting from the network arrangement in time s. I assume that after defection, individual i will be penalized by the network and will be unable to participate in future network sharing arrangements. Therefore, individual i must balance the short-term net utility gain from leaving the network in period s against all possible net future benefits which can be gained from continued network participation. The benefit derived from deviating from the network arrangement becomes positive when individual i makes transfers or incurs network costs during the time s to a value greater than the benefits derived from participating in the network sharing arrangement, such that $sb_s^i < sc_s^i$, or $nsb_s^{ij} < 0$. In this case, pooled consumption will be less than pooled income such that

$$c_s^{ij} < y_s^{ij} \text{ in period } s.$$

The right-hand side (given by equation 3) represents the present value of net future benefits gained from continued network participation. This is the present value of all future guaranteed consumption generated through continued network participation, minus the future value of autarky level of earnings (y_t^{iA}). Autarky earnings represent income that can be earned if an individual i chose not to be part of the network for all future periods. This expectation is based on information available at the time s for all possible states of the world. When i is risk-averse, the expected gain from the risk-sharing is typically positive [1] such that:

$$E_t [\![F_i(t, nsb)]\!] \geq 0$$

I assume non-satiation and risk aversion such that $U'(\cdot) > 0$, and $U''(\cdot) \leq 0 \ \forall \ i$ and $U''(\cdot) < 0$ for some i. Additionally, all future gains from continued network participation are assumed to share a common discount factor β which is less than one and reflects each member's time preference and ultimately the value of future benefits gained from network

participation. Since individuals *i* and *j* are assumed to be risk-averse, the more impatient they are to receive the benefits of network arrangements, the smaller the discount factor. However, for simplicity, I assume that all households face similar time preferences such that $\beta_i^t = \beta_j^t$.

To guarantee continued network participation and for income sharing arrangements to be self-reinforcing, inequality 2 needs to be satisfied in all cases for all individuals and states of the world over time.

Including the Impact of Negative Climate Shocks

De Weerdt and Dercon [44] and De Weerdt and Fafchamps [43] modify the voluntary participation constraint (2) to include short-term and persistent health shocks. I again adapt this model by assuming all unexpected shocks to be derived from negative climate events. In this case, climate shocks can vary in intensity and be persistent in some regions, thereby having varied impacts on social network arrangements among individuals and across locations. The impact of negative climate shocks can also vary among individuals depending on the nature of income-earning activities households are involved in (farm or non-farm income) and the degree of preparedness each household may be. I adapt Model 2 to suggest that individuals *i* and *j* are now both assumed to be vulnerable to negative climate shocks, such that the utility of individual *i*, is now given by $U_i = u_i(y_t^i + nsb_t^{ij} - w_t^i)$, where $w_t^i \geq 0$ denotes the value of losses due to negative climate events. Therefore, if there are no climate shocks in period *t*, $w_t^i = 0$.

Climate shocks can be considered transitory if the experience of climate shocks today, contains no information or indication regarding the experience of shocks in the future[3]. On the other hand, if past climate shocks are persistent, they can provide information and influence expectations for future occurrence of negative climate events such that $\partial E_{t|w_t^i}[w_{t+s}^i]/\partial w_t^i > 0$ for some period s > 0. In the face of negative climate shocks, the implementability constraint, which determines voluntary participation in a network, now takes the form:

$$u_i(y_s^{ij} - w_s^i) - u_i(c_s^{ij} - w_s^i) \leq E_{t|w_t^i,w_t^j}[\![F_i(t,nsb)]\!]\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.4$$

where,

$$F_i(t,nsb) \equiv \sum_{s=1}^{\infty} \beta^s\left(u_i(c_{t+s}^{ij} - w_{t+s}^i) - u_i(y_{t+s}^{iA} - w_{t+s}^i)\right)\ldots\ldots\ldots\ldots.5$$

And c_s^{ij} continues to be defined by:

$$c_s^{ij} = y_s^i + nsb_s^{ij}$$

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Any cooperation scheme must now satisfy:

$$E_{t|w_t^i, w_t^j}[\![F_i(t, nsb)]\!] \geq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .4$$

Equation 3 states that future payoffs are influenced by the expectation of future losses due to climate shocks. Indeed, if climate shocks are persistent, the expectation of future losses due to negative climate events will be higher. A basic assumption can be that, for any cooperation scheme to be implementable, the present value of expected net future benefits from continued network participation must be positive, even after discounting for expected losses due to future climate shocks (Equation 4).

Conditions for Voluntary Participation

Conditions for voluntary network participation or the "implementability constraint" also directly set an upper limit on the amount individual i is willing to invest in social networks, either through reciprocal income transfers, memberships fees, or the total value of any other network obligations (sc_t^{Max}). Specifically, for a given level of expected future benefit from participating in a social network ($\overline{sb}_t$), there exists a maximum net social benefit value (nsb_t^{Max}) which can be derived from participating in the network risk-sharing arrangement. By extension, this implies that there is a potential maximum social cost individual i is willing to incur to stay within the network given by sc_t^{Max} such that:

$$nsb_t^{Max} = \overline{sb}_t^i - sc_t^{iMax} \geq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .5$$

In this case, continued voluntary participation can be re-written as

$$u_i(y_s^{ij} - w_s^i) - u_i(c_s^{ij} - w_s^i) \leq E_{t|w_t^i, w_t^j}[\![F_i(t, nsb^{Max})]\!] \ldots\ldots\ldots .6$$

Where,

$$E_{t|w_t^i, w_t^j}[\![F_i(t, nsb^{Max})]\!] \equiv \sum_{s=1}^{\infty} \beta^s \left(u_i\left((y_{t+s}^i + nsb_{t+s}^{Max}) - w_{t+s}^i\right) - u_i\left(y_{t+s}^{iA} - w_{t+s}^i\right) \right) \geq 0$$

This relationship can now be used to examine the impact of short term and repeated negative climate shocks on participation in social network relationships.

Scenario 1 – Short-term and Repeated Negative Weather Shocks Affecting Either Individuals *i* or *j*

In the face of short-term climate shocks, individual *i* is willing to pay an income transfer to network member *j*, to the value $sc_t^i \leq sc_t^{Max}$ once the implementability constraint 6 is satisfied[4]. However, if negative climate shocks are expected to persist, impacting individual *j*, individual *i* will now be expected to make continuous transfers to *j*. Additionally, since individual *j* is consistently impacted by negative weather shocks, this can undermine *j*'s future income and as such, their ability to reciprocate income transfers. This will have the effect of lowering future expected social benefits to individual *i* (i.e. $E'_{t|w_t^i,w_t^j}[\![F_i(t,nsb')]\!] < E_{t|w_t^i,w_t^j}[\![F_i(t,nsb^{Max})]\!]$, such that $sb_t'^i \leq \overline{sb}_t^i$ and $nsb_t' < nsb_t^{Max}$).

As social benefits decline, the maximum value individual *i* be willing to pay to stay in a network sharing arrangement will also decline such that $sc_t' \leq sc_t^{Max}$. The latter inequality implies that individual *i* will be contributing smaller and smaller amounts to the network sharing arrangement. Furthermore, the more persistent and deleterious climate shocks are expected to be, individual *i* will have a greater incentive to deviate and discontinue participating in the network relationship. Specifically, individual *i* will depart from the network sharing arrangement if the gains from deviating in period *s* are greater than the discounted expected net future benefits from participating in the network.

$$u_i(y_s^{ij} - w_s^i) - u_i(c_s^{ij} - w_s^i) \geq E'_{t|w_t^i,w_t^j}[\![F_i(t,nsb)]\!]$$

Scenario 2 – Negative Weather Shocks (Repeated) Affecting Individuals *j* or *i* and Individual *i* Continues Income Transfers

A second scenario predicts instances where individual *i* is willing to continue paying transfer costs to individual *j* in the face of repeated climate shocks. This can occur if net social benefits, however small, remain positive and tends to some minimum value $(\overline{sb}_t^{ij})$, which individual *i* is willing to accept to stay in the network arrangement such that $sb_t'^{ij} \to \overline{sb}_t^{ij}$. I assume that the implementability constraint 6 continues to be satisfied, since $nsb_t' > 0$ and $sc_t^{Max} \leq \overline{sb}_t^{ij}$. The key policy implication from this scenario will be to find ways to extend social benefits from network participation in the face of repeated shocks. Benefits can take many forms, both tangible and intangible. Examples include government transfers or technological assistance, which are delivered only through associations or formalized network arrangements rather than on an individual basis, adaptive technologies developed by network members who have experienced repeated climate shocks in the past, or utility and prestige gained from supporting other kin or family members (altruistic motives).

In general, the model predicts that network members will continue to invest in network relationships, once expected future benefits from network participation, exceed the short-term benefits or opportunity costs of deviating from the network arrangement. The model also predicts continued network participation in the face of short term (idiosyncratic)

climate shocks, once the implementability constraint continues to be met, i.e. once network members are assured that net future benefits can be gained from network participation, either through contributions from other network members or as a result of other tangible and intangible benefits derived from being a network member. Once climate shocks become persistent or are expected to be more widespread (systematic), the model predicts network members have a greater incentive to deviate from a network sharing arrangement.

It should be noted that continued network participation in the face of repeated climate shocks depends on the ability to extend net future benefits among network members. These include instances where social networks continue to provide high social benefits in the form of adaptive information, income transfers, or prestige to the network members, or where "pooled" income levels are sufficiently high to insulate against repeated negative climate events. I, therefore, also utilize the data to test the extent that "pooled" and "altruistic" motives can influence network participation in the face of negative climate shocks.

References

42. Coate, S. and M. Ravallion, *Reciprocity without commitment: Characterization and performance of informal insurance arrangements.* Journal of development Economics, 1993. **40**(1): p. 1-24.
43. De Weerdt, J. and M. Fafchamps, *Social identity and the formation of health insurance networks.* Journal of Development Studies, 2011. **47**(8): p. 1152-1177.
44. De Weerdt, J. and S. Dercon, *Risk-sharing networks and insurance against illness.* Journal of development Economics, 2006. **81**(2): p. 337-356.

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1 Reciprocal income transfers are assumed to be particularly important to households during times of crisis. Such transfers are used to supplement income shortfalls and sustain consumption along a permanent consumption level. However, households are expected to reciprocate transfers when other households are negatively impacted by idiosyncratic shocks.

2 Other authors have researched the "dark-side" of social network relationships which can include discrimination, or negative sanctions against network members.

3 An example of more transitory climate shocks includes sporadic climate events such as spikes in temperature levels or sudden heavy rainfall patterns, which may not fit past climate patterns for a given location.

4 In this case climate shocks are assumed not be affecting individuals i or j equally, such that individual i can still support transfers to individual j even in the face of negative climate events.