How Do Low-Income Rural Households Smooth Consumption?

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Abstract

How do low-income, rural households with imperfect access to formal financial services smooth consumption in the face of seasonal and stochastic income variation? How does this vary with goods' storability, and as transport infrastructure improves? We explore these questions using high-frequency household panel data from rural India. Comparison of perishable milk and storable staple cereals, production of which is far more seasonal than for milk, highlights the prominence of household storage and market transactions, and the comparatively modest consumption smoothing role of inter-household transfers. The introduction of new roads reduces the costs of spatial arbitrage, further reducing the role of informal transfers while boosting that of storage. These patterns underscore the central importance of product market participation and own storage for risk management in low-income rural communities.

Keywords: India, insurance, market participation, risk sharing, transaction costs

JEL codes: O12, D12, Q12

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1 Introduction

A large body of economic theory and empirical evidence supports the hypothesis that people try to smooth consumption in the face of income that varies over time due to life cycle, seasonal, and/or stochastic processes (Carroll, 1997; Friedman, 1956; Gourinchas and Parker, 2002; Hall, 1978; Modigliani and Brumberg, 1954; Paxson, 1992, 1993). Financial services – i.e., credit, insurance, and savings – are typically the preferred means by which people smooth consumption (Besley, 1995; Deaton, 1997). People with reasonable financial services access commonly borrow or dissave using credit or debit cards or mobile money transactions to cover consumption expenditures between pay periods. Low-income agricultural households, however, routinely have limited access to formal financial services, face binding liquidity constraints, and are unable to fully smooth consumption (Deaton, 1991, 1992; Zeldes, 1989; Zimmerman and Carter, 2003). An extensive literature therefore explores alternative methods by which low-income rural households use alternative mechanisms, such as savings in kind – especially in the form of livestock – adjustments to labor supply, storage of nonperishables like cereals, or informal credit or insurance, to smooth consumption.[1]

But what is the relative importance of different consumption smoothing mechanisms? And how do households smooth consumption when we disaggregate household consumption and begin to examine individual essential commodities with distinct production features and storability? In particular, the literature has largely overlooked the relative roles of informal transfers or storage relative to, for example, product market sales and purchases in commodity markets.[2] The straightforward intuition behind households using product market transactions to smooth consumption, by selling surpluses and buying to fill deficits, is perhaps easily overlooked.

[1] A sample of such work includes Ábrahám and Laczó (2018); Alderman and Paxson (1994); Attanasio et al. (2005); De Weerdt and Dercon (2006); Dercon (2004); Fafchamps (1992, 2011); Fafchamps and Gubert (2007a,b); Fafchamps and Lund (2003); Fafchamps et al. (1998); Fink et al. (2020); Ito and Kurosaki (2009); Kazianga and Udry (2006); Kochar (1995, 1999); Morduch (1995); Morten (2019); Rose (2001); Rosenzweig and Wolpin (1993); Townsend (1994); Udry (1994); Zimmerman and Carter (2003)

[2] Barrett (2007) discusses how the 'displaced distortions' of financial market failures often manifest in product market transactions, for example, the buy-low-sell-high phenomenon often observed in staple grains commodity markets (Burke et al., 2019; Stephens and Barrett, 2011).

But product markets are essential to consumption smoothing. Under perfect autarky, people only consume what they produce; thus, consumption varies intertemporally with seasonal or stochastic variation in production and the household's capacity to store unconsumed production. Deviations between consumption and production (plus storage) for purely autarkic households arise mainly due to informal inter-household transfers – gifts, loans, state-contingent insurance payments, etc. But few people live in autarky. The vast majority engage in market-based exchange, selling surpluses and purchasing to cover shortfalls relative to their optimal consumption levels in any given period, smoothing out intertemporal variation in own production.

The literature on agricultural household models and product market participation formalizes this intuition, explaining how market frictions destabilize consumption (Barrett, 2008; De Janvry et al., 1991; Rosenzweig, 1988; Singh et al., 1986; Zimmerman and Carter, 2003). The agricultural household modeling and market participation literatures, however, are largely silent about the possibility of informal mutual insurance among households and largely abstract away from intertemporal issues like storage and consumption smoothing. Likewise, the literature on informal insurance largely assumes away consumption smoothing through commodity market transactions. Our framework bridges these gaps by integrating market, storage, and transfer mechanisms across two essential commodities, thereby offering a richer, more realistic account of how rural households smooth consumption under production risk. The framework enables us to decompose consumption smoothing across different mechanisms (market exchange, storage, informal transfers) in a way not possible with single-good models. Our theoretical framework is essential for the empirical decomposition that follows, and forms an important methodological contribution of this paper.

We use monthly household panel data from rural India to study milk and staple cereals consumption smoothing in the face of seasonal and stochastic production. In 2022, staple cereals and milk together accounted for 62 percent of both calorie and protein intake nationwide (and surely far more in low-income rural areas).[3] Food consumption for energy and protein intake is essentially a daily necessity; studying how rural Indian households smooth consumption of these two commodities affords a compact view into the relative roles of different consumption

[3]Per FAO Food Balance Sheet data, downloaded 17 May 2025 from https://www.fao.org/faostat/en/data/FBS.

smoothing mechanisms among poor rural households.

We first describe the data and establish the considerable seasonality and stochasticity of milk and staple cereals production in rural India. We then develop a conceptual framework that accommodates multiple consumption smoothing mechanisms, including informal transfers, commodity market transactions, and storage. Our empirical strategy builds on and extends the canonical social planner-based risk-sharing model (Townsend, 1994), modifying it to incorporate multiple essential commodities, storage, and market-based trade. This allows us to test for within-community household risk-sharing while explicitly accounting for commodity-specific frictions such as perishability, storability, and transaction costs. As is standard in the literature, consumption smoothing in this context is relative to the community mean, i.e., aggregate business cycle fluctuations may remain. We then decompose observed consumption smoothing into the contributions of different channels: market sales and purchases, as well as non-market government or inter-household transfers, supplemented by storage for non-perishables.

There are three advantages to studying consumption smoothing within the risk-sharing framework. First, we can decompose consumption smoothing among different mechanisms, opening a window into how households manage risk. Second, the risk-sharing formulation essentially tests for complete markets. By comparing what we observe in the data with the social planner's optimum, we establish how far or close village milk and cereals markets are from that benchmark. Hence the literature testing the risk-sharing hypothesis on sub-components of consumption, even on individual commodities (Bradford et al., 2022; De Weerdt and Dercon, 2006). Third, our data explicitly record consumption from government and informal transfers. A large social science literature documents interhousehold transfers of food within communities, ascribing these at least partly to risk-sharing motives (Fafchamps, 2011). This paper also speaks to that literature.

India is the world's largest milk producer, and Indians consume considerably more milk than the global average, despite below-average income (United States Department of Agriculture (USDA) Foreign Agricultural Service, 2023). This reflects the importance of regular dairy consumption as a source of protein and key minerals – e.g., calcium, magnesium, potassium –

essential to good nutrition and health, especially among vegetarians (Weaver, 2009), who comprise more than a third of India's population (United States Department of Agriculture (USDA) Foreign Agricultural Service, 2023). Milk consumption smoothing is therefore essential from a food and nutrition security perspective. But milk production varies intertemporally because dairy animals' lactation cycle is highly sensitive to local weather conditions (Key and Sneeringer, 2014; Sirohi and Michaelowa, 2007). Moreover, milk production is typically correlated with crop production and off-farm income-earning opportunities in rural villages because weather and other shocks affect many sectors simultaneously (Birthal and Negi, 2012; Pérez-Méndez et al., 2019; Thornton and Herrero, 2014). Furthermore, fluid milk is highly perishable, especially in hot tropical communities with little access to refrigeration; households cannot safely store milk for more than several hours (Bachmann, 1985; Rajendran and Mohanty, 2004).[4] The non-storability of milk implies that rural households who lack reliable access to formal financial services must smooth consumption via some combination of sales and purchases through local markets and/or informal mutual insurance by way of inter-household transfers.

Staple cereals (rice, wheat, millet, sorghum, and maize) account for most of the value of Indian farmers' annual output. In sharp contrast to milk, however, staple cereals are storable. With (typically) two harvests annually, cereal production is far more seasonal than milk production. Recognizing the importance of staple cereals consumption for food security, the Indian government distributes subsidized rice and wheat (as well as kerosene and sugar) through the world's largest food assistance program, the Public Distribution System (PDS).

Rural India thus offers an excellent empirical setting to study how rural households manage intertemporal variability in production to smooth consumption. Contrasting the two dominant sources of key daily macronutrients, which differ in their seasonality, storability, and public distribution, affords a means to explore how low-income, rural households use on-farm storage,

[4]Milk can be processed into products like butter, cheese, ghee or yogurt that are storable for somewhat longer periods. But such processing requires added inputs (especially of labor) and transformation from a liquid into a solid, obviating the health gains from fluid milk consumption in places where access to potable water remains limited. Milk can also be dried and stored as powder for really long periods, but doing so requires industrial-scale equipment far beyond the scale of individual households.

product markets, subsidized public distribution, and non-market inter-household transfers.

This is also an excellent empirical setting to explore to what extent households' relative dependence on market exchange versus informal transfers may evolve as transport infrastructure changes. The literature suggests that high trade frictions and transaction costs can impede informal risk sharing (Fitzgerald, 2012; Jack and Suri, 2014). Better road infrastructure can make distant markets and relatives more accessible. Improved access might induce either an expanded mutual insurance network through more distant relatives whose income streams are less strongly correlated with local villagers' (Munshi and Rosenzweig, 2016; Rosenzweig and Stark, 1989) or substitution away from reliance on informal transfers to smooth consumption as commodity market transactions become cheaper. It is unclear ex ante which effect will dominate. We use data on targeted, rule-based road construction and upgrading under the Pradhan Mantri Gram Sadak Yojana program as a natural experiment to study how village-level exogenous variation in road connectivity influences households' consumption smoothing patterns via informal insurance relative to commodity market transactions.

We find that Indian dairy-producing households smooth consumption, on average, around 80 percent of the variation in household milk production while they fully smooth cereals consumption relative to highly seasonal cereals production. Own storage accounts for about two-thirds of households' staple cereals consumption smoothing, with market purchases and sales responsible for most of the remaining cereals consumption smoothing, and government subsidized sales accounting for most of the rest. By contrast, nonstorable milk purchases and sales in local product markets account for roughly two-thirds of milk consumption smoothing. Informal, inter-household transfers play a quite modest role in smoothing both cereals and milk consumption. As one would expect based on household endowments, smaller farmers rely more on market purchases – implicitly financed by cash earnings – and larger, surplus-producing farmers rely more on commodity sales. Improved road access reduces consumption smoothing via informal transfers, suggesting that increased access to distant markets is more important than increased access to distant relatives or friends.

2 Data and Descriptive Statistics

2.1 The Village Dynamics Studies in South Asia Surveys

The primary data for this paper come from the Village Dynamics Studies in South Asia (VDSA) surveys. The VDSA surveys were conducted by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and focused on studying village economies in agroecologically and economically vulnerable regions of India (Walker and Ryan, 1990). An uncommon feature of the VDSA surveys was that resident field investigators were permanently posted in selected villages and visited households monthly to collect detailed data on various aspects of the household economy (Walker and Ryan, 1990). These surveys have been used to study, among other topics, long-term productivity growth and the relationship between the scale of agricultural operations and farm productivity (Foster and Rosenzweig, 2022; Merfeld, 2023; Michler, 2020).

The recent survey rounds cover 30 villages across three eastern states of Bihar, Jharkhand, and Odisha, and five states of Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, and Maharashtra in humid and semi-arid tropical regions (ICAR-ICRISAT, 2010). Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, and Maharashtra represent low rainfall semi-arid tropical (SAT) regions practicing dryland agriculture. The Eastern states of Bihar, Jharkhand, and Odisha represent rainfall-dependent humid regions.

The VDSA villages and households were purposively sampled in four steps. Districts were selected in the first stage based on the major agroclimatic regions within SAT and Humid regions. Second, smaller administrative units called talukas within districts were selected based on weather, soil, and other variables. Finally, remote villages that didn't have access to infrastructure, government programs, and outside resources were selected. The sampled villages are mapped in Appendix Figure A1. Based on the village census, households in the villages were stratified based on operational land holdings, and random household samples of equal size were then drawn from each stratum (Walker and Ryan, 1990). Appendix Table A1 describes the sampling frame and household sample. The sampling method renders the VDSA surveys not representative of the sampled regions or states, as they were strategically chosen to reflect the most vulnerable rural population within the chosen regions. However, general trends in the VDSA surveys are consistent with overall trends at the all-India level (Michler, 2020).

Credit and insurance markets are underdeveloped in these villages. Kumar et al. (2015) report that less than half of the households in the Eastern region accessed any form of credit, and only 24.4 percent used formal credit sources. Only 28.5 percent of households reported borrowing for agricultural purposes with most relying on costly informal loans. While credit access seemed to be higher in the SAT villages, over half of the households in both regions reported having no outstanding formal debt, highlighting the limited availability or use of formal financial markets. Households largely relied on credit from informal sources borrowed at a very high interest rate of 60 to 120 percent per annum (Kumar et al., 2015).

The VDSA surveys collected detailed information at a monthly frequency on household milk and cereals consumption, divided among home-produced, market-purchased, government transfers (i.e., fair price shop purchases under PDS), and transfers received from other households. The crop module of the VDSA surveys records the different crops households grow and their harvest dates. We focus on rice, wheat, maize, (finger and pearl) millet, and sorghum, the staple cereals. These crops account for around two-thirds of the total value of agricultural output from cultivation. We match cereal harvest, sales, and consumption data to create a household-level monthly panel for storable cereals.

The VDSA surveys likewise collect data on livestock herd size and milk production and sales quantities by species – i.e., buffaloes, cows, goats, and sheep. The surveys record milk unit values in the consumption module and the price at which milk was sold in the production module. 52 percent of the total milk output comes from cows, 44 percent from buffaloes, and just 4 percent from small ruminants like sheep and goats.

The monthly panel data include 1400 households for a five-year period from 2010-11 to 2014-15. Given our focus on household consumption of milk and cereals, we are particularly concerned about attrition (or missing data) in the consumption data for these two commodities. Appendix Figure A2a and Figure A2b report the extent of missing data. For milk consumption, a household is observed for an average of 44 out of the 60 months; 37 percent of households are observed for the full period, and 47 percent are observed for at least 59 months (see Appendix Figure A2a for the distribution of missing milk consumption months per household). For cereals, households are observed for an average of 57 out of 60 months; 65 percent are observed for the full period, and 80 percent are observed for at least 59 months (see Appendix Figure A2b for the distribution of missing cereal consumption months per household). To address potential bias from non-random attrition, we present estimates using inverse probability weighting (IPW), with weights constructed based on the estimated probability of observing the household in each period, conditional on baseline characteristics.

To study how a reduction in trade costs influences consumption smoothing, we exploit variation in road construction and upgrades under the Pradhan Mantri Gram Sadak Yojana (PMGSY, the Prime Minister's Village Road Construction) scheme. The PMGSY was started in the early 2000s to provide all-weather roads to unconnected villages across India. PMGSY roll-out followed a population-based rule (Asher and Novosad, 2020; Garg et al., 2023). Villages with a household population greater than 1,000 were to be connected first, followed by villages with a population greater than 500, and only then villages with a population smaller than 500.[5] Data on the timing of rural road construction and completion for each of the 30 VDSA villages come from the Socioeconomic High-resolution Rural-Urban Geographic (SHRUG) Dataset on India (Asher et al., 2021). The population-based targeted road construction under PMGSY provides exogenous variation in market access to the VDSA villages.

2.2 Descriptive Statistics

Figure 1 shows the proportion of villages connected or upgraded with PMGSY roads over the five-year period in our sample. Roughly 20 percent of the VDSA villages had roads upgraded or constructed under PMGSY before VDSA began in 2010. By 2015, this proportion had increased to more than 30 percent. Overall, we observe a greater proportion of villages with upgraded roads than with new roads. The changes in roads took place in two periods, 2010–11 and 2011–12, with no changes in PMGSY road construction in these villages after 2012.

[5] Implementation broadly followed population-based criteria (Asher and Novosad, 2020; Shamdasani, 2021).

Table 1 presents the mean and standard deviation of key variables. The data reflect the importance of India's dairy sector. In around half of the month-year observations, households report having a large dairy animal (i.e., buffalo or cattle) with an average herd size of one. Average monthly milk production was 11 liters per household member, two-thirds of which is sold in the market, on average. Almost all milk sales are local, i.e., within the village.

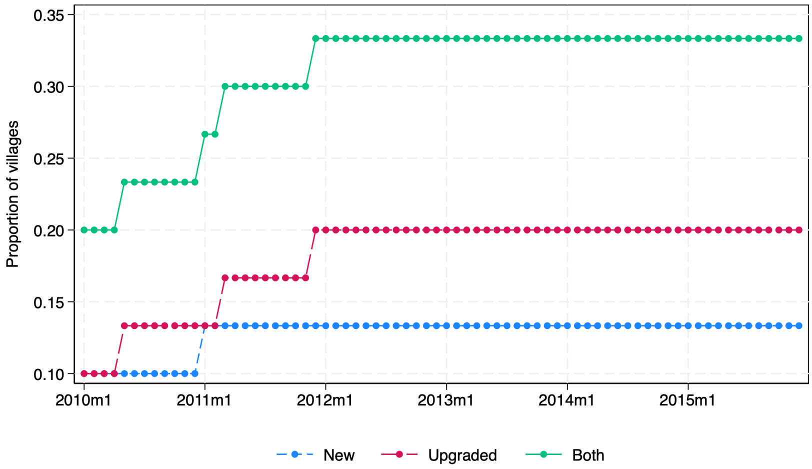


Figure 1: Variation in PMGSY road construction across VDSA villages over time.

Notes: Dates reflect village-level earliest date of road construction per SHRUG.

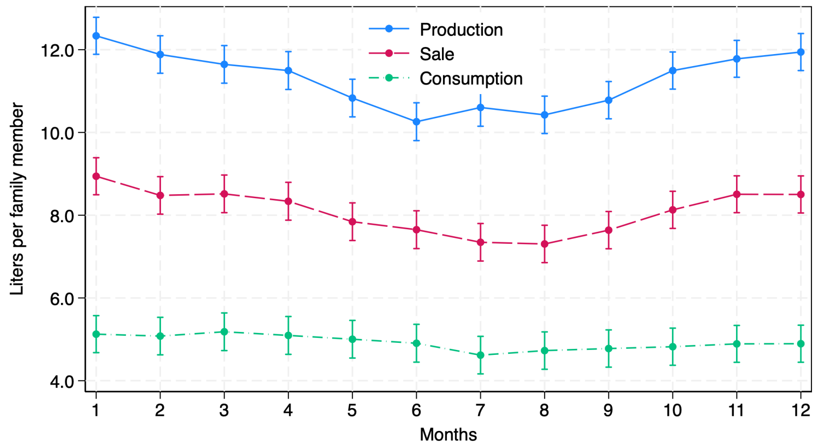
The National Institute of Nutrition (NIN) of India recommends 300 milliliters of milk consumption per adult per day, or 9 liters monthly per person. Average monthly milk consumption is just 5 liters per household member, about 55 percent of the NIN recommendations. Milk consumption is less than the NIN's recommendations in 86 percent of household-month-year cases.[6] 57 percent of milk consumed is home-produced, the rest from market purchases and informal transfers. Milk consumption from other sources, mainly informal transfers, forms a very small part of the total milk consumption. These simple descriptive statistics provide the first indication that informal transfers may play less of a role in smoothing milk consumption than commodity market participation does.

[6]The averages presented in Table 1 only consider fluid milk consumption and do not account for other milk products, such as buttermilk, butter, or ghee. Non-inclusion of these milk products could explain why Table 1 shows a minor difference of 0.4 liters per person between produced milk left after sales and home-produced milk consumed.

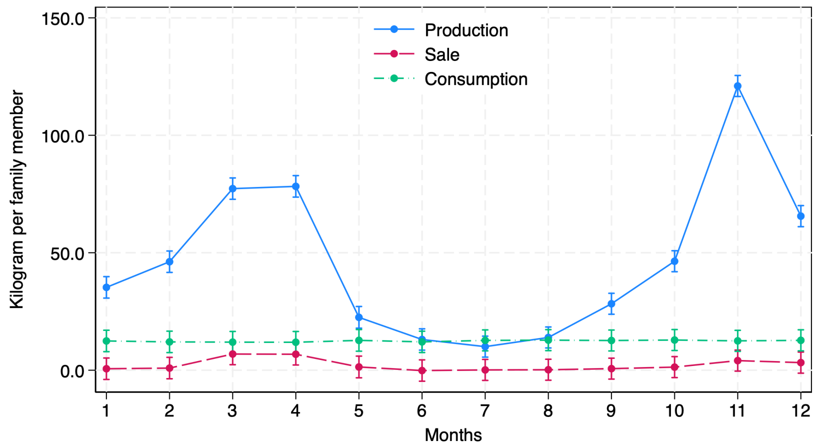
Table 1: Summary statistics

	Mean	SD	N
Per capita milk produced (lt/month)	11.30	28.09	61528
Per capita milk production value (rs/month)	277.41	674.22	61528
Per capita milk sold (lt/month)	8.10	25.05	61528
Per capita milk from home production (lt/month)	2.79	4.85	61528
Per capita milk purchased (lt/month)	2.06	2.90	61528
Per capita milk from other sources (lt/month)	0.08	0.65	61528
Total per capita milk consumption (lt/month)	4.93	4.51	61528
Dairy animal owning households	0.51	0.50	61528
Dairy animal number	0.92	1.30	61528
Monthly per capita consumption expenditure (rs)	1734.57	4137.61	61528
Number of members	4.84	2.30	61528
	Mean	SD	N
Per capita cereal produced (kg/month)	46.48	331.69	77463
Per capita cereal production value (rs/month)	750.35	8289.30	77463
Per capita cereal sold (kg/month)	2.16	50.33	77463
Per capita cereal from home production (kg/month)	4.87	5.35	77463
Per capita cereal purchased (kg/month)	3.90	4.75	77463
Per capita cereal from PDS (kg/month)	3.42	3.78	77463
Per capita cereal from other sources (kg/month)	0.26	1.43	77463
Total per capita cereal consumption (kg/month)	12.45	3.92	77463
Operated land (ha)	1.56	2.46	77463
Large farmers ($\geq$ 2 ha)	0.25	0.43	77463
Monthly per capita consumption expenditure (rs)	1568.29	3896.84	77463
Number of members	4.77	2.23	77463

Notes: This table presents means, standard deviations, and sample sizes for variables related to milk and cereal production and consumption. Sample is restricted to relevant households producing and consuming the two commodities.



(a) Fluid milk



(b) Staple cereals

Figure 2: Seasonality in production, sale, and consumption.

Notes: Figure (a) shows average milk production, sale, and consumption per family member. Figure (b) displays average cereal production, sale, and consumption per family member (cereals include rice, wheat, millets, sorghum and maize). Both figures present predicted values from regressions controlling for household and year fixed effects. Error bars represent 95 percent confidence intervals.

Figure 2 presents monthly averages of per capita production, sale, and consumption for milk and cereals across all households in our sample. These averages are estimated as marginal effects from regressions that control for household and year fixed effects. While milk production exhibits some seasonality, it is considerably less pronounced than that observed in cereal production. For both commodities, average production peaks during the winter and spring months, but begins to decline from April and reaches its lowest levels in the summer and monsoon months of July and August. While milk is produced round the year at varying levels, cereal production is realized only at harvest. As a result, the production of staple cereals is close to zero during the planting seasons. Cereal sales exhibit far less seasonality than production, providing the first suggestion that crop storage serves an important role in smoothing cereal consumption between the two annual harvest periods. Despite these seasonal fluctuations in production, consumption remains relatively smooth throughout the year, indicating consumption smoothing by households.

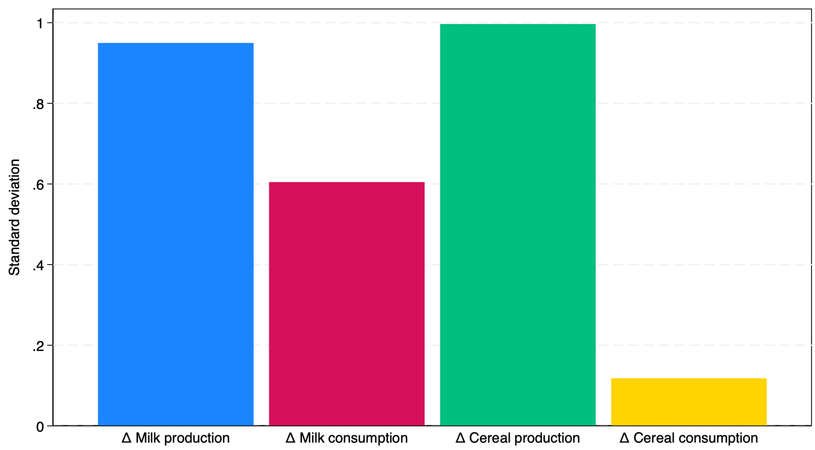


Figure 3: Variability in production and consumption of the two commodities.

Notes: The figure displays the household-level averages of the standard deviations of milk and cereals production and consumption. These standard deviations are computed from the log first-differenced per-capita production and consumption series constructed using monthly data.

Figure 3 presents household-level average variability in per capita production and consumption as preliminary evidence of consumption smoothing across the two commodities. The variability is based on first-differenced production and consumption, hence reflecting intertemporal variability. While production of both milk and cereals exhibits considerable variability, consumption is significantly more stable. Moreover, the variation in cereal consumption is substantially lower than that of milk, suggesting that consumption smoothing is higher for cereals than for milk. The next section proposes a theory-based consistent empirical framework to formally test these observations.

3 Empirical Framework

Product market transactions, storage, and informal insurance jointly enable households to smooth consumption in the face of time-varying income. In a dynamic model with complete, competitive, frictionless markets, households perfectly smooth consumption through product market transactions enabled by saving and dissaving from time–varying income – effectively the result of stochastic or seasonal production with subsequent sales (Friedman, 1956). In the presence of borrowing constraints – which are equivalent to storage subject to the constraint that stocks remain non-negative – consumption smoothing becomes imperfect (Deaton, 1991; Zimmerman and Carter, 2003). Informal insurance then offers a potentially complementary mechanism to smooth consumption in the face of idiosyncratic – i.e., household-specific – shocks and binding non-negative storage constraints. The canonical risk-sharing model predicts that with complete risk sharing, household consumption of a commodity depends only on aggregate endowments and is independent of idiosyncratic endowment shocks, thus smoothed up to fluctuations in aggregate resource availability within the insurance pool (Townsend, 1994). While extensive literatures study each of these mechanisms individually, surprisingly little work empirically explores which mechanism(s) households rely on most for consumption smoothing. That is this paper's main contribution.

In Appendix A1, we present a simple two-period partial equilibrium model in which households smooth consumption across two tradable commodities: nonstorable milk and storable cereals. Households receive stochastic endowments of both goods, which is equivalent to stochastic production, but lets us abstract from factor market decisions. Households face prospective frictions specific to each mechanism they might use to smooth consumption: transaction costs for both market transactions and informal transfers as well as storage losses. Households respond to positive endowment/production shocks by selling, storing or giving away one good so as to consume either more of the other good or more in a future period, or both. When faced with negative endowment/production shocks, households can purchase or seek transfers or consume from storage to boost current consumption. As discussed in Appendix A1.2.3, households' optimal consumption allocations of each commodity then depend on all endowments, market and transfer frictions, and storage costs. A key insight of this integrated modeling framework is that market transactions enable partial consumption smoothing even in the presence of frictions and may be preferred to informal transfers under certain conditions, especially if storage is infeasible. This theoretical structure guides the empirical approach that follows.

3.1 Consumption smoothing with multiple commodities

We study a setting in which households might engage in storage, informal transfers, and/or market transactions in an effort to smooth consumption of multiple goods. If utility is not additively separable, a household's consumption of any particular good generally depends on its endowment/production of all tradable commodities that enter the utility function (Townsend, 1994).

We propose to start with the following empirical specifications to test for incomplete risk-sharing and consumption smoothing in milk and cereals:

$$c_{mivt} = \alpha_1 + \beta_1 y_{mivt} + \delta_1 y_{givt} + \psi_{mvt} + \epsilon_{1ivt} \quad (1)$$

$$c_{givt} = \alpha_2 + \delta_2 y_{mivt} + \beta_2 y_{givt} + \psi_{gvt} + \epsilon_{2ivt} \quad (2)$$

where subscripts i, v, and t refer to household, village, and time, respectively, and $c_{mivt} = \Delta \ln(C_{mivt})$ and $c_{givt} = \Delta \ln(C_{givt})$ denote seasonally differenced log consumption of milk and cereals, respectively. Similarly, $y_{mivt} = \Delta \ln(Y_{mivt})$ and $y_{givt} = \Delta \ln(Y_{givt})$ represent seasonally differenced log production of milk and cereals, respectively. The village-time fixed effects, ψ reflect village mean consumption of each good. Given the monthly frequency of our data and the highly seasonal nature of agricultural production, we prefer seasonally differenced specifications. In this specification, the β and δ coefficients reflect how consumption of each good covaries with the different income components after controlling for village mean consumption. If there is complete risk pooling, then each $\beta = \delta = 0$.

Equations (1) and (2) depart from standard empirical tests of risk sharing by incorporating household-specific production shocks for both commodities. This allows us to examine inter-commodity smoothing behavior. If households use product markets to convert commodities into money, effectively exchanging one commodity for another, then a positive shock to milk production may also increase cereal consumption. We therefore expect milk production shocks to be positively correlated with cereal consumption, and similarly, cereal production shocks to be positively associated with milk consumption.

We also estimate several variants of these baseline specifications, including models with lags and leads of production shocks, to test whether past or future production realizations influence the estimated β coefficients. In addition, we control for seasonally differenced household size and total consumption expenditure to assess whether changes in family size or overall income affect consumption smoothing. We will also include changes in annual stocks of storable commodities, such as cereals and pulses, to examine whether stock fluctuations influence consumption smoothing behavior. Finally, we include village-time fixed effects which effectively control for fluctuations in the aggregate resource base. Under complete risk pooling, household-level consumption should track the village period mean and be independent of household-specific fluctuations in production (Townsend, 1994).

3.2 Consumption smoothing channels

We follow the method of Asdrubali et al. (1996) and Asdrubali et al. (2020) to quantify the contribution of different channels to a household's consumption smoothing. We start with the simpler case of milk, for which we can rule out storage and government transfers as infeasible. When we apply this method to staple cereals below, we incorporate those two options. Consider the following identity:

$$C_{ivt} \equiv Y_{ivt} + P_{ivt} - S_{ivt} + O_{ivt} \tag{3}$$

where C_{ivt} denotes consumption, Y_{ivt} is production, P_{ivt} represents purchases, S_{ivt} is the quantity sold, and O_{ivt} refers to consumption from other sources, primarily transfers from other households. We define two additional measures, $Y_{ivt}^{P} = Y_{ivt} + P_{ivt}$, the sum of milk produced and milk purchased from the market, i.e., gross household-level milk availability, and $Y_{ivt}^{S} = Y_{ivt} + P_{ivt} - S_{ivt}$, which is net household-level milk availability, i.e., milk production and market purchases net of milk sales. All quantities are expressed in per household member terms. Given these measures, household i's per-person milk production is simply

$$Y_{ivt} = \left(\frac{Y_{ivt}}{Y_{ivt}^{P}}\right) \times \left(\frac{Y_{ivt}^{P}}{Y_{ivt}^{S}}\right) \times \left(\frac{Y_{ivt}^{S}}{C_{ivt}}\right) \times C_{ivt} \tag{4}$$

With some algebraic manipulation (see Appendix Section A2), equation (4) leads to the following identity:

$$\beta = 1 - \beta^{P} - \beta^{S} - \beta^{O} \tag{5}$$

Equation (5) expresses β as the residual after consumption smoothing achieved via purchases and sales of milk, indicated by β^{P} and β^{S}, respectively, while β^{O} captures consumption smoothing achieved via informal transfers among households. In the case of cereals, we add β^{B} and β^{G} to reflect storage and government transfers, respectively.

Given this structure, the null hypothesis of autarky or no consumption smoothing implies $\beta = 1$. If $\beta < 1$, then the estimate $(1 - \beta)$ can be interpreted as the degree of risk-sharing within the village (Asdrubali et al., 1996, 2020; Jalan and Ravallion, 1999). The β's in equation (5) can be estimated as coefficients from the following system of equations:

$$y_{ivt} - y_{ivt}^{P} = \tau^{P} + \beta^{P} y_{ivt} + X_{ivt}\Gamma^{P} + \psi_{vt} + \varepsilon_{ivt}^{P} \tag{6}$$

$$y_{ivt}^{P} - y_{ivt}^{S} = \tau^{S} + \beta^{S} y_{ivt} + X_{ivt}\Gamma^{P} + \psi_{vt} + \varepsilon_{ivt}^{S} \tag{7}$$

$$y_{ivt}^{S} - c_{ivt} = \tau^{O} + \beta^{O} y_{ivt} + X_{ivt}\Gamma^{P} + \psi_{vt} + \varepsilon_{ivt}^{O} \tag{8}$$

$$c_{ivt} = \tau + \beta y_{ivt} + X_{ivt}\Gamma^{P} + \psi_{vt} + \varepsilon_{ivt} \tag{9}$$

All equations include village–time fixed effects and the control vector X, which incorporates production of cereals as well as relevant household-level covariates. Equation (9) corresponds to the modified risk-sharing regression in equations (1). Although equations (6)–(9) describe the decomposition for milk, an analogous set of equations can be derived for staple cereals. In the case of cereals, the decomposition additionally includes storage and government transfers (through the fair price shops) as additional smoothing channels.

The parameters on production in this system of equations are assumed to be homogeneous. But we can let them vary across households by interacting with observables that may reflect heterogeneity. For example, a household with greater production scale will more likely sell than purchase milk and cereals for home consumption. This implies that the channels through which larger farmers with surpluses and smaller farmers with deficits smooth consumption may differ. Moreover, larger landowners may be wealthier and face lower transfer frictions due to better social standing and greater credibility in reciprocating transfers (Townsend, 1994; Udry, 1994). While the literature has traditionally focused on caste or social group based differentiation to capture transfer frictions, in this setting, land size and caste are highly correlated. Lower caste households are generally landless or smallholders, while wealthier farmers typically belong to upper caste groups. Land based differentiation therefore also reflects social affiliation based transfer frictions.

3.3 Trade costs, prices, storage and smoothing channels

The transaction costs of participating in milk or cereals markets – and of informal transfers with distant kin or friends – may vary over time and among villages. Reduced transaction costs due to better road infrastructure may thereby change households' incentives and interact with production scale and seasonality in complex ways. Whether improved connectivity with communities outside one's village boosts informal insurance or consumption smoothing through market participation is an empirical question.

As Appendix A1.2.2 shows, the scope for inter-commodity consumption smoothing through market transactions is influenced by transaction costs. We first estimate regressions where the price differential between buying and selling a good is regressed on the PMGSY road dummy.

This allows us to assess whether the construction of rural roads reduces transaction costs, narrowing the price gap. A smaller buy-sell price differential due to rural road improvements that reduce transaction costs, reflected in a narrowing of the price differential, should in turn facilitate increased reliance on market transactions for consumption smoothing, all else equal.

We also directly examine how annual storage behavior responds to lower transaction costs. As discussed in Appendix A1.2.2, a reduction in transaction costs would generally reduce storage incentives making market transactions more attractive and thereby reducing the need for precautionary storage. However, this relationship also depends on the presence of other frictions and hence is empirically ambiguous.

Finally, to test how consumption smoothing channels evolve with changes in market frictions we characterize the parameters in the system of equations (6)-(9) as:

$$\begin{aligned}\beta^k &= \delta + \theta^H LO_i + \theta^R ROAD_{vt} + \theta^W WINTER_m \\ &\quad + \gamma^{LR} LO_i \times ROAD_{vt} + \gamma^{LW} LO_i \times WINTER_m \\ &\quad + \gamma^{LRW} LO_i \times ROAD_{vt} \times WINTER_m \end{aligned} \tag{11}$$

where $k \in \{P, S, O\}$, LO_i is an indicator for farm households whose 2010 baseline operated area is larger than 2 hectares, indicating larger landowners with a greater scale of milk and cereal production.[7] $ROAD$ is a dummy variable that captures village-level variation in road construction or upgradation under the PMGSY, and $WINTER$ is a dummy variable that takes value 1 for October, November, December, January, February, and March, reflecting seasonality in production.

[7]Farmers operating more than 2 hectares of land own dairy herds that are, on average, three times larger than those of smaller landholders.

4 Estimation Results

Table 2 presents the estimates from the modified risk-sharing tests. The leftmost column presents the conventional Townsend-type risk-sharing test specification, which includes only own production shocks. We then sequentially add production shocks of the other commodity, changes in household size, total consumption expenditure, and annual changes in stocks as additional regressors. To account for potential bias due to non-random attrition, we also present specifications that apply inverse probability weights (IPW).[8] The last specification of each commodity additionally includes village time fixed effects to control for village-level aggregate shocks and correlated time trends. The estimated β coefficients for milk and cereals are robust to the inclusion of controls for production of the other commodity, additional household covariates, and changes in stocks of storable commodities. The results are also not sensitive to sample attrition, as applying inverse probability weights (IPW) leaves the estimates virtually unchanged. An important observation is that, once the variables are first-differenced, village-specific aggregate shocks are effectively differenced out. Consequently, the inclusion of village–time fixed effects has little impact on the estimated degree of risk sharing.

[8] Estimates of the likelihood of milk and cereal consumption being observed as a function of baseline household characteristics are reported in Appendix Table A2.

Table 2: Production shocks and consumption smoothing

	(1) Milk	(2) Milk	(3) Milk	(4) Milk	(5) Milk	(6) Milk	(7) Cereal	(8) Cereal	(9) Cereal	(10) Cereal	(11) Cereal	(12) Cereal
Δym	0.198***	0.198***	0.190***	0.195***	0.190***	0.189***		0.001	-0.003	-0.003	-0.003	0.000
	(0.028)	(0.028)	(0.027)	(0.028)	(0.027)	(0.030)		(0.003)	(0.003)	(0.003)	(0.003)	(0.001)
Δyg		-0.003*	-0.004**	-0.003*	-0.004**	-0.001	0.001	0.001	0.001	0.001	0.001	-0.000
		(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Δ Log family size			-0.533***	-0.544***	-0.535***	-0.543***			-0.324***	-0.322***	-0.323***	-0.352***
			(0.036)	(0.038)	(0.036)	(0.036)			(0.028)	(0.028)	(0.028)	(0.027)
Δ Log MPCE			0.199***	0.204***	0.199***	0.193***			0.116***	0.116***	0.116***	0.079***
			(0.032)	(0.032)	(0.033)	(0.024)			(0.018)	(0.017)	(0.018)	(0.008)
Δ Log cereal stocks					0.008	0.006					0.003	0.005**
					(0.010)	(0.005)					(0.003)	(0.002)
Δ Log pulses stocks					-0.020**	-0.009					0.006	-0.003
					(0.009)	(0.005)					(0.007)	(0.003)
Observations	45578	45578	45578	44879	45566	45531	62583	62583	62583	61639	62568	62568
Village-Time FE	No	No	No	No	No	Yes	No	No	No	No	No	Yes
IPW	No	No	No	Yes	No	No	No	No	No	Yes	No	No

Notes: Dependent variables are seasonally differenced log per capita milk and staple cereal consumption. Δym and Δyg denote seasonally differenced log per capita milk and cereal production, respectively. Δ Log family size and Δ Log MPCE refer to the seasonally differenced logs of family size and monthly per capita consumption expenditure, respectively. Δ log cereal stocks and Δ log pulses stocks indicate annual changes in stocks of these commodities. Figures in parentheses report standard errors clustered at the village level. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Across specifications, we find that roughly 20 percent of variation in household milk production passes through to the household's own milk consumption; put differently, households' consumption smooth about 80 percent of the variation in (nonstorable) own production. In contrast, cereal consumption is largely uncorrelated with own production shocks, suggesting complete consumption smoothing. We find that cross-commodity endowment shocks are generally weakly related to both milk and cereal consumption. For cereals, the estimated effects are statistically and economically negligible; for milk, the effects are statistically different from zero but economically tiny, suggesting limited substitution or spillover effects across commodities in response to production fluctuations. We explore these spillovers more later when we introduce heterogeneity by road access, seasonality, and scale of production.

As discussed in Appendix A1.2.3, in a more general setting, consumption may also depend on future output realizations that determine household beliefs about expected permanent income. This implies that both past and future production shocks could be correlated with current consumption. To test this hypothesis, we add lags and leads of production shocks to Equations (1) and (2). Appendix Figure A3 presents the estimates from these regressions. For milk, we observe that the effect of current production shocks is strongest, while the coefficients on lags and leads are small and statistically insignificant. This suggests that milk consumption responds contemporaneously to production shocks, with little anticipatory or delayed adjustment. For cereals, all estimated coefficients are statistically indistinguishable from zero, consistent with the hypothesis of complete consumption smoothing.

4.1 Decomposing consumption smoothing channels

The incomplete consumption smoothing result in milk mirrors many prior studies that find considerable consumption smoothing but incomplete risk sharing within villages (e.g., Murgai et al. (2002); Townsend (1994); Vanderpuye-Orgle and Barrett (2009)). But what mechanisms do households use to smooth consumption? Especially given the complete consumption smoothing we see in cereals, that question remains underexplored, especially for households lacking good access to financial services.

Table 3: Consumption smoothing channels in milk

Proportion of production smoothed	(1) Purchases	(2) Sales	(3) Transfers	(4) Residual
	0.367***	0.343***	0.095***	0.195***
	(0.024)	(0.041)	(0.025)	(0.028)
1. H_0: $1 - \beta = 0$		0.805***		
		(0.028)		
2. H_0: $\beta^P - \beta^S = 0$		0.024		
		(0.058)		
3. H_0: $\beta^P - \beta^O = 0$		0.272***		
		(0.038)		
4. H_0: $\beta^S - \beta^O = 0$		0.248***		
		(0.055)		
5. H_0: $\beta^P + \beta^S - \beta^O = 0$		0.615***		
		(0.052)		
Observations		44,838		

Notes: All specifications are estimated with inverse probability weighting (IPW) and control for the seasonally differenced log change in household size and the change in log per capita consumption expenditure. Standard errors clustered at the village level are reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 3 presents the β estimates from Equations (6) - (9) estimated as a system with standard errors clustered at the village level using the conditional mixed processes (CMP) suite of commands in Stata.[9] The estimates in columns 1 to 3 represent consumption smoothing achieved from milk purchases, sales, and transfers, respectively. The estimate in the last column is the residual, indicating again that, on average, household milk consumption smooths out around 80 percent of variation in household milk production ($1 - \beta = 0.805$).

Per columns 1 and 2, roughly two-thirds of the variation in milk production gets smoothed via milk market purchases and sales. We cannot reject the null that commodity market purchases and sales are equally important to consumption smoothing, consistent with perishable fluid milk markets being highly local such that purchases roughly equal sales in any given period. In total, market sales and purchases account for around 88 percent of the total consumption smoothing. Informal transfers account for less than 13 percent (0.095/0.805) of total consumption

[9] The adding up constraint in Equation (5) is satisfied automatically due to identity (3) and the linear system of equations in (6) - (9).

smoothing, significantly less than market transactions.

The Table 3 results could reflect the nature of the commodity, as milk is highly perishable and nonstorable and not available through the PDS in the government-subsidized fair price shops. We therefore replicate the analysis for staple cereals, which are storable, unlike milk, and for which a major government transfer program exists. Staple cereals production varies even more seasonally than does milk production, yet consumption is strikingly stable throughout the year (Figure 2b). We decompose the cereal consumption smoothing channels similarly to what we did for milk. We just add storage and government transfers — in the form of rice and wheat distributed to eligible poor households at highly subsidized prices through PDS — as additional smoothing channels that do not exist for milk.[10]

Table 4: Consumption smoothing channels in staple cereals

Proportion of production smoothed by	(1) Purchases	(2) Sales	(3) Govt	(4) Informal	(5) Storage	(6) Residual
	0.175***	0.017***	0.119***	0.003***	0.686***	0.001
	(0.020)	(0.006)	(0.015)	(0.001)	(0.017)	(0.001)
1. H_0: $\beta^P - \beta^S = 0$			0.158***			
			(0.022)			
2. H_0: $(\beta^P + \beta^S) - (\beta^G + \beta^O) = 0$			0.070**			
			(0.031)			
3. H_0: $\beta^B - (\beta^P + \beta^S + \beta^G + \beta^O) = 0$			0.374***			
			(0.034)			
Observations			61,629			

Notes: Cereals include rice, wheat, millets, sorghum and maize. All specifications are estimated with inverse probability weighting (IPW) and control for the seasonally differenced log change in household size and the change in log per capita consumption expenditure. Standard errors clustered at the village level are reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

As Table 4 shows, in contrast to milk, cereal consumption is statistically indistinguishable from fully smoothed with more than two-thirds of the smoothing coming through own storage

[10] For cereals, consumption (C) is given by $C = Y + P - S + G + O + B$, where Y denotes production, P denotes purchases, S denotes sales, G denotes government transfers, O denotes informal transfers, and B denotes storage (net of depreciation). The production variance decomposition for cereals can thus be written as $\beta = 1 - \beta^P - \beta^S - \beta^G - \beta^O - \beta^B$, where β is the partial correlation of cereals production with consumption, and each component β^P, β^S, β^G, β^O, and β^B represents the contribution of purchases, sales, government transfers, informal transfers, and storage, respectively, in smoothing cereals consumption against production shocks.

(column 5). More than 60 percent of the remaining consumption smoothing occurs through market purchases and sales, with purchases far more important than sales, reflecting the fact that most households are net buyers of staple cereals, as is typical of smallholder agriculture worldwide (Barrett, 2008). Informal transfers again account for only a very small (just 0.3 percent) share of consumption smoothing, although government transfers are important, accounting for roughly 12 percent of total cereals consumption smoothing.

These results are striking. Even without good financial services access, rural Indian households achieve a high degree of within-village consumption smoothing, especially in staple cereals, mainly through storage and market transactions. Even a government food assistance program as massive as India's PDS – the world's largest – contributes relatively little to smoothing consumption of its headline products. And informal inter-household transfers are relatively tiny. Rural households mainly smooth consumption through commodity markets and storage, although government and informal transfers seem to draw most researchers' attention.

4.2 Roads, trade costs, scale of production and prices

Theory suggests that the relative frictions households face in using product markets, informal transfers, or storage guide their choice among consumption smoothing mechanisms. We can explore this by studying the relationship between road construction and household-level trade and marketing costs. In competitive spatial equilibrium, the difference between prevailing sales and purchase prices reflects the marketing costs incurred by marginal transactors (Samuelson, 1952). Interventions like road improvements can reduce those margins by shortening travel distances and reducing costs. So we assess whether improved road infrastructure reduces the costs associated with product trade and general travel. We then test how it affects consumption smoothing. Table 5 presents the estimated effects of road connectivity on household transportation and trade expenses.

Households in villages with access to new roads report significantly shorter distances to the markets where they sell their produce, suggesting improved physical access to commercial centers. The mean effect is large, a reduction of 11.4 kilometers, slightly more than half the

Table 5: Roads, marketing costs and travel expenditures

	Output sales transport distance and per unit cost				Travel expenditure	
	(1) Distance (km)	(2) Distance (km)	(3) Cost (rs)	(4) Cost (rs)	(5) Exp. (rs)	(6) Exp. (rs)
$ROAD$	-2.70		22.71		-64.32	
	(4.26)		(30.26)		(77.64)	
$ROADN$		-11.43***		-5.01		-100.93**
		(3.17)		(7.33)		(36.80)
Observations	4529	4529	4047	4047	80109	80109
Mean of dep. var	22.65	22.65	24.14	24.14	369.27	369.27

Notes: All regressions include village fixed effects and time fixed effects. $ROAD$ indicates rural road construction or upgrades under the PMGSY, while $NROAD$ captures newly constructed rural roads under the PMGSY. Standard errors clustered at the village level are reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

baseline mean. Furthermore, new roads are associated with a (statistically insignificant) decline in self-reported marketing costs for agricultural output. On the expenditure side, we observe a statistically significant 27 percent reduction in travel-related expenses relative to baseline, indicating that new roads are also associated with lower costs of general mobility. These findings are consistent with the hypothesis that new road infrastructure reduces trade frictions and lowers both output-marketing-related transaction costs and general travel expenditures.

Consumption smoothing arises due to both predictable, seasonal variation in output and prices and to stochastic variation around those seasonal patterns. As just demonstrated, storage plays a key role in smoothing consumption of non-perishable commodities like cereals. When the costs of storage are high – as for perishables like fluid milk – market exchange provides an attractive alternative if marketing margins are not excessive. But as road infrastructure develops, commodity market transactions become more lucrative for sellers and imported products more attractive for buyers, potentially making markets more appealing as a means of consumption smoothing relative to storage. Of course, road improvements can also make informal transfers over space easier, so it's an open, empirical question whether road improvements impact the mechanisms rural households use to smooth consumption.

Table 6 presents the estimates from the price differential regressions for milk and cereals. Note that prices are only observed when a household both buys and sells the respective good.

Table 6: Roads, buy-sell price differential and stocks of foodgrains

	Monthly price differential		Seasonal price differential		Annual stocks per person		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Milk	Milk	Cereals	Cereals	Cereals (kg)	Pulses (kg)	Value (rs)
$ROAD$	0.06		-0.07				
	(0.04)		(0.06)				
$LO \times ROAD$	0.01*		0.02				
	(0.01)		(0.04)				
$NROAD$		0.07**		-0.14***	-153.38	-4.37	-1641.45**
		(0.03)		(0.04)	(97.15)	(6.78)	(660.12)
$LO \times NROAD$		0.02**		0.02***	-71.10***	-2.92***	-295.38***
		(0.01)		(0.00)	(8.91)	(0.40)	(10.76)
Mean of dep. var	0.005	0.005	0.352	0.352	278.677	24.280	3647.519
Month FE	Yes	Yes	No	No	No	No	No
Season FE	No	No	Yes	Yes	No	No	No
Crop FE	No	No	Yes	Yes	No	No	No
IPW	Yes	Yes	Yes	Yes	No	No	No
Observations	24052	24052	5230	5230	6735	6735	6735

Notes: The dependent variables in columns (1) to (4) are the log difference between buying and selling price. Milk prices are reported at a monthly frequency, while cereal prices are available at the agricultural season level. Price differential regressions are estimated using inverse probability weights to adjust for attrition and recover representativeness of the baseline sample by accounting for the likelihood of remaining in the panel. Dependent variables in columns (5) and (6) are per person stocks of cereals and pulses at annual frequency. Dependent variable in column (7) is the per-person total value of stocks at annual frequency. LO is an indicator for large farmers who operated more than 2 hectares of land at baseline (2010). $ROAD$ indicates rural road construction or upgrades under the PMGSY, while $NROAD$ captures newly constructed rural roads under the PMGSY. All regressions include household and year fixed effects. Standard errors clustered at the village level are reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

While most households report purchase prices, sale prices are available only when a sale occurs. As a result, selection into sales is a significant source of potential bias. To account for non-random selection into milk and cereal sales that may affect the estimated marketing margins, we estimate price differential regressions using inverse probability weights. These weights are constructed from a first-stage regression predicting the likelihood of observing a price differential – i.e., of a household both buying and selling within a given month – as a function of baseline observable household characteristics. The estimates from this model for milk and cereals are reported in Appendix Table A3.

Column (2) of Table 6 shows that the milk price differential increases with the construction of new roads with the increase being slightly larger for households with greater landholdings. In contrast, the cereal price differential decreases following new roads with the reduction being smaller for larger landowners (column (4)). The narrowing of margins in cereals aligns with the hypothesis that improved roads lower trade costs and enhance market integration. The widening of milk price differentials is somewhat puzzling. It may reflect induced changes in market structure, such as increased bargaining asymmetries or shifts in buyer power, that are infeasible to explore in these data.

Table 6 also presents estimates of how annual stocks change following the construction of new roads. Notably, cereal stocks decline after new roads are built, especially among larger farmers. This pattern is consistent with the interpretation that improved road connectivity reduces transaction costs and shrinks the autarkic region, particularly for larger landholders, inducing some substitution of market exchange for storage as a means of consumption smoothing. As market access improves, storage becomes less attractive for households, holding storage technology (and thus loss rates) constant. While annual stocks decline due to reduced trade costs, storage remains an important channel for smoothing intra-year consumption.

4.3 Seasonality, scale of production, roads, and consumption smoothing

Does the reliance on different consumption smoothing channels vary with household production scale and road connectivity? We next consider how consumption smoothing responses differ across households by the scale of production, seasonality, and access to rural roads. While our earlier estimates are robust to inverse probability weighting (IPW), attrition may still be systematically related to road access (see Appendix Table A4). To address potential attrition bias and ensure representativeness based on baseline household characteristics, we apply IPW adjustments. In addition, we include village-time fixed effects to control for village-level changes that may be correlated with road construction.

Our theoretical setup indicates that the extent to which households rely on market exchange, storage, and transfers to smooth consumption depends on the full vector of household endowments across goods and over time, as well as on market prices, transaction costs, transfer frictions, storage costs, and discounting. These forces jointly determine the degree to which households can smooth consumption intertemporally, across households, and across commodities. Given this complexity, it is useful to begin with simpler variants of the consumption regressions. Appendix Tables A5 and A6 present estimates from these baseline specifications.

Appendix Table A5 examines heterogeneity in milk consumption smoothing by allowing the effects to vary with baseline dairy herd size, which proxies for the scale of production. The top panel reports estimates using the combined measure that captures both road upgrades and new construction, while the bottom panel isolates the impact of newly built PMGSY roads by using only the new-construction measure. Households with larger baseline herd sizes rely less on market purchases, consistent with the notion that larger dairy farmers experience greater and more frequent milk surpluses. With new road access, these households rely less on milk sales for smoothing during lean periods and instead increase smoothing via sales during the winter when production is higher (Table A5 lower panel).

Appendix Table A6 presents analogous heterogeneity results for cereals, using operating land size as a proxy for the scale of production. As with the previous table, the top panel reports estimates using the combined road-improvement measure, and the bottom panel restricts attention to newly constructed PMGSY roads. Larger farmers rely less on government transfers for consumption smoothing, reflecting their lower likelihood of eligibility for PDS benefits. New road construction also reduces households' reliance on cereal consumption smoothing through

PDS. Similarly, new roads diminish the limited role of informal transfers for these households. Interestingly, improved road connectivity enhances the role of storage in consumption smoothing, especially among larger farmers, suggesting greater ability to engage in seasonal spatial arbitrage once households can access new roads.

Road access can also shape how smoothing channels in one commodity respond to production shocks in another. To examine these cross-commodity interactions, we allow production shocks in both milk and cereals to interact with household production scale, the winter-season indicator, and road access. Because operated land and herd size are positively correlated, we report heterogeneity results using operated land as the measure of production scale. Importantly, the correlation between milk and cereal production shocks is low (0.02), indicating that monthly fluctuations in the two commodities are largely independent and thus suitable for identifying cross-commodity smoothing responses.

Table 7: Production scale, new roads, seasonality and consumption smoothing

	Fluid milk				Staple cereals					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	β^P	β^S	β^O	β	β^P	β^S	β^G	β^O	β^B	β
Δym	0.400***	0.343***	0.048**	0.209***	0.014	-0.001	0.004	0.003	-0.018**	-0.001
	(0.034)	(0.055)	(0.018)	(0.036)	(0.009)	(0.001)	(0.006)	(0.002)	(0.007)	(0.003)
$\Delta ym \times LO$	0.007	-0.022	0.025	-0.010	-0.014	0.001	-0.002	-0.006*	0.019	0.004
	(0.034)	(0.048)	(0.031)	(0.021)	(0.019)	(0.004)	(0.009)	(0.003)	(0.016)	(0.003)
$\Delta ym \times NROAD$	-0.012	-0.005	0.055*	-0.037	-0.028***	0.002	0.005	0.001	0.020**	-0.001
	(0.046)	(0.093)	(0.031)	(0.105)	(0.009)	(0.002)	(0.014)	(0.004)	(0.008)	(0.006)
$\Delta ym \times WINTER$	-0.008	0.006	0.012	-0.010	-0.010	-0.003	-0.004	-0.002	0.017**	0.000
	(0.008)	(0.008)	(0.011)	(0.012)	(0.008)	(0.003)	(0.006)	(0.002)	(0.006)	(0.003)
$\Delta ym \times LO \times NROAD$	-0.040	-0.100**	-0.002	0.142***	0.037*	0.002	0.081***	0.005	-0.054	-0.051***
	(0.046)	(0.047)	(0.035)	(0.046)	(0.019)	(0.005)	(0.017)	(0.004)	(0.033)	(0.018)
$\Delta ym \times LO \times WINTER$	-0.013	-0.007	-0.008	0.028*	0.020	-0.003	-0.006	0.006*	-0.023	0.004
	(0.014)	(0.013)	(0.015)	(0.015)	(0.024)	(0.005)	(0.014)	(0.004)	(0.016)	(0.004)
$\Delta ym \times LO \times NROAD \times WINTER$	0.034	0.068***	-0.098*	-0.004	0.013	-0.004	-0.038	-0.009***	0.030	0.002
	(0.030)	(0.020)	(0.049)	(0.048)	(0.038)	(0.005)	(0.025)	(0.003)	(0.023)	(0.016)
Δyg	-0.007	0.003	0.009	-0.005	0.168***	0.018	0.133***	0.002	0.684***	-0.008**
	(0.006)	(0.007)	(0.006)	(0.007)	(0.031)	(0.011)	(0.026)	(0.001)	(0.031)	(0.003)
$\Delta yg \times LO$	0.008	-0.001	-0.013*	0.006	0.017	0.006	-0.052**	0.001	0.016	0.008**
	(0.007)	(0.007)	(0.007)	(0.007)	(0.019)	(0.014)	(0.024)	(0.002)	(0.030)	(0.003)
$\Delta yg \times NROAD$	0.003	0.006	-0.002	-0.007	-0.057*	-0.014**	-0.060**	-0.005**	0.131***	0.004**
	(0.005)	(0.007)	(0.006)	(0.005)	(0.031)	(0.006)	(0.029)	(0.002)	(0.025)	(0.001)
$\Delta yg \times WINTER$	0.006	-0.003	-0.010*	0.007	0.035*	-0.001	0.005	0.004*	-0.051**	0.008**
	(0.006)	(0.007)	(0.006)	(0.007)	(0.018)	(0.009)	(0.012)	(0.002)	(0.019)	(0.003)
$\Delta yg \times LO \times NROAD$	-0.007	0.012	-0.041***	0.036***	-0.024	-0.003	-0.014	-0.002	0.055*	-0.010**
	(0.008)	(0.014)	(0.014)	(0.008)	(0.022)	(0.012)	(0.028)	(0.002)	(0.029)	(0.005)
$\Delta yg \times LO \times WINTER$	-0.012*	0.007	0.014*	-0.009	-0.026	-0.004	0.002	-0.004*	0.042*	-0.007*
	(0.007)	(0.008)	(0.008)	(0.009)	(0.019)	(0.013)	(0.019)	(0.002)	(0.023)	(0.004)
$\Delta yg \times LO \times NROAD \times WINTER$	0.008	-0.039***	0.076***	-0.045***	0.018	0.000	0.007	0.003***	-0.024	-0.001
	(0.010)	(0.010)	(0.005)	(0.008)	(0.012)	(0.013)	(0.018)	(0.001)	(0.019)	(0.004)
Observations	43525	43525	43525	43525	43524	40979	40979	40979	40978	40978

Notes: Cereals include rice, wheat, millets, sorghum and maize. All specifications are estimated with inverse probability weighting (IPW) and control for seasonally differenced the log change in household size, the change in log per capita consumption expenditure, and village time trends. yg and ym denote seasonally differenced log per person household production of cereals and milk, respectively. LO is a dummy indicating farm households operating greater than 2 hectares of land in the baseline. $NROAD$ captures new rural road construction under the $PMGSY$. $WINTER$ is a dummy variable that takes values 1 for October through March. Figures in parentheses are standard errors robust to the intra-village correlation of residuals. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 7 presents estimates specifically focusing on new road construction.[11] Given that there is a strong positive correlation between herd size and land size, we only focus on baseline operated land size (*LO* dummy) as the production scale measure. We observe that milk consumption smoothing through sales declines for larger farmers following the construction of new roads. Similarly, smoothing through transfers also diminishes for large farmers during the winter season. Interestingly, overall consumption smoothing in milk appears to decline for larger farmers after new roads become operational.

Some cross-commodity effects emerge. Milk consumption smoothing via transfers in response to cereal production shocks improves for large farmers once new roads are in place, for example. However, this pattern reverses in the winter season. Overall, the ability of large farmers to smooth milk consumption in response to cereal shocks worsens with new roads, but this effect is offset in the winter months.

For cereals, we find that larger farmers generally rely less on government transfers for consumption smoothing. Among smaller farmers, the construction of new roads is associated with a decline in smoothing through market transactions, government transfers, and informal transfers. Interestingly, this decline appears to be offset by an increase in smoothing via own stocks. This may seem contrary to our earlier finding that annual stocks are negatively correlated with new road construction. The explanation may be that, although overall annual stocks decline, households may increasingly use available stocks to manage within-year fluctuations in production.

We also observe cross-commodity effects in cereal consumption smoothing. Specifically, smoothing through purchases in response to milk production shocks declines with the construction of new roads, while smoothing through cereal stocks in response to milk shocks increases. This suggests that new roads may alter the way households buffer consumption not only from

[11] Appendix Table A7 reports heterogeneity estimates using the combined road measure, allowing interactions by season and production scale. We also examine cross-commodity effects by interacting road access with production shocks for both commodities. While there is some evidence that milk consumption smoothing through transfers responds not only to own-commodity shocks but also to cereal production fluctuations, we do not find strong effects of reduced trade costs attributable to PMGSY road construction.

shocks to the same commodity but also from shocks to other related commodities.

The presence of cross-commodity effects observed for the two commodities highlights the interconnectedness of rural consumption portfolios. The decline in cereal purchases in response to milk shocks coupled with increased reliance on cereal stocks suggests that rural households adapt their consumption smoothing strategies in response to changing relative prices and production realizations. New roads may thus reduce the transaction costs of responding to shocks, but can also induce shifts in the relative effectiveness or attractiveness of different smoothing mechanisms. Such nuanced and context-specific effects however are difficult to predict theoretically and highlight the value of our empirical analysis in uncovering such patterns.

Farmers can mitigate the impact of milk production shocks on consumption through alternative income streams or financial transfers that do not perfectly co-move with milk production. Appendix Table A8 examines the relationship between milk production shocks and such alternative income channels. Some statistically significant correlations exist between gifts and loans and cereal production shocks after new roads get built (Appendix Table A9). Similarly, savings and investment behaviors appear correlated with cereal production shocks following road construction. These patterns, however, do not indicate systematic use of these instruments for potential consumption smoothing and suggest that our main results are unlikely to be primarily driven by these alternative channels.

5 Conclusions

This paper explores how households in rural India smooth consumption of fluid milk and staple cereals. We unpack the different channels through which rural households insulate consumption of these essential commodities from intertemporal fluctuations in their own production. We do that by integrating models of market participation, informal risk sharing, and storage, and then demonstrating a method to decompose consumption smoothing among different channels.

We observe a high degree of consumption smoothing in milk and complete consumption smoothing within villages in cereals. Commodity market transactions – sales and purchases – are the dominant channel through which households smooth milk consumption, more than three times (and statistically significantly) more important than informal transfers for consumption smoothing. Storage is the primary mechanism for smoothing cereal consumption, followed by market transactions. Even with the massive government food assistance program, the PDS, public transfers represent a small portion of consumption smoothing, and informal transfers are a negligible contributor. We also uncover evidence of cross-commodity spillovers, where production shocks in one good affect the consumption of the other.

We find that improved road infrastructure lowers commodity trade frictions, as evident from reduced buy-sell price margins for cereals, shorter travel distances to markets, and reduced travel expenditures. New roads reduce households' already modest reliance on informal transfers without appreciably changing the overall extent of consumption smoothing. As rural villages become better integrated into the broader national and global economy, markets – not transfers among increasingly accessible distant relations and friends – increasingly insulate consumption from production shocks while cereals producers also use their own storage more to smooth consumption even while they reduce overall stockholding, indicating improved timing of spatial arbitrage.

These findings have special relevance if future changes in climate make local weather more unpredictable and household level agricultural production more volatile. Commodity markets offer a crucial medium through which rural households can insulate consumption from increasing production volatility. While considerable attention has appropriately been paid to the role of financial inclusion and informal insurance networks in cushioning rural households against risk, researchers must not overlook the central role that product markets play in facilitating risk management and consumption smoothing.

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Appendix

A1 Markets, Transfers and Consumption

A1.1 Model Setup

In this section, we develop a simple model to illustrate how product market transactions, inter-household transfers, and storage interact with each other as different channels of consumption smoothing. The framework is intentionally parsimonious and serves as a guide for the empirical analysis. To maintain tractability, we introduce several simplifying assumptions.

Assume a community with two households existing for only two periods. Each household consumes two goods, milk (m) and cereals (c). Households are indexed by $h \in \{1, 2\}$. Each household derives utility from the consumption of both goods in both periods.

So as to avoid also modeling factor markets, we assume that there is no production and each household receives exogenous endowments of milk and cereals. One could complicate the model by adding in stochastic production, where the random component is, in effect, the exogenous endowment. In the current period (period 1), household h has endowments ω^h_{1m} and ω^h_{1c} of the two goods. Endowments in the future period (period 2) are uncertain today and state-contingent and are given by $\omega^h_{2m}(s)$ and $\omega^h_{2c}(s)$ for each state $s = \{1, \dots, S\}$. A household's intertemporal preferences are represented by:

$$\mathbb{E}[U^h] = u(m^h_1, c^h_1) + \beta \sum_{s=1}^{S} \pi_s u(m^h_2(s), c^h_2(s))$$

where $u(\cdot)$ is an additively separable logarithmic utility function, $u(m, c) = \log m + \log c$. Households discount future utility at rate β, where $\beta \in (0, 1]$. Since future consumption is state-contingent, expected utility is computed over all possible states with π_s denoting the probability of state s occurring in period 2.

Milk is perishable and must be consumed within the same period. Cereals, however, can be stored from period 1 to period 2 at a cost. Let x^h denote household h's cereals storage in period 1 for consumption in period 2. Storage involves a proportional cost $\delta \in [0, 1)$, so only $(1 - \delta)x^h$ is available in the next period.

Milk and cereals can be traded in external markets at fixed, exogenous prices p_m and p_c. This is a simplifying partial equilibrium assumption given that our primary interest is to study how different frictions influence consumption smoothing.

Market transactions are subject to proportional transaction costs τ. To buy a good $g \in \{m, c\}$, the effective price is:

$$p^b_g = (1 + \tau)p_g$$

To sell the same good, the effective price is:

$$p^s_g = (1 - \tau)p_g$$

The transaction cost wedge τ captures trading frictions in both goods. We assume τ is identical for both buyers and sellers.

Households can also engage in informal transfers of milk and cereals. If household h sends $t_{gt}^{h,O}$ (outgoing) units of good g in period t to the other household, the recipient receives only $\alpha t_{gt}^{h,I}$ (incoming), where $\alpha \in (0, 1]$. These frictions reflect transaction losses or costs of accessing informal networks.

Transfers are governed by social norms, such as kinship ties or communal insurance, and are enforced without default. Transfers are purely for consumption and cannot be resold in markets. Thus, transfers do not enter the household's budget constraint. This restriction prevents arbitrage between market and informal channels and ensures that transfers function only as risk-sharing instruments. This implies that market transactions and transfers are distinct consumption smoothing channels. Transfers are also static in the sense that they do not generate future repayment obligations.

Since our focus is on the interplay between different frictions in consumption smoothing, we make simplifying assumptions that households cannot borrow, lend, or save money across periods, and that no formal financial institutions exist. As a result, intertemporal smoothing is only possible through the storage of cereals while market transactions and informal transfers facilitate consumption smoothing within each period.

The period 1 budget constraint for each household h is:

$$p_m^b m_1^{h,+} - p_m^s m_1^{h,-} + p_c^b c_1^{h,+} - p_c^s c_1^{h,-} \leq p_m^s \omega_{1m}^h + p_c^s(\omega_{1c}^h - x^h)$$

where $m_1^{h,+}$ and $c_1^{h,+}$ are quantities of milk and cereals purchased, $m_1^{h,-}$ and $c_1^{h,-}$ are quantities sold, and x^h is the quantity of cereals stored. The left-hand side represents the cost of net market purchases. The right-hand side represents the value of available endowments at selling prices net of storage.

In period 2, endowments are state-contingent. The period 2 budget constraint for household h in state s is:

$$p_m^b m_2^{h,+}(s) - p_m^s m_2^{h,-}(s) + p_c^b c_2^{h,+}(s) - p_c^s c_2^{h,-}(s) \leq p_m^s \omega_{2m}^h(s) + p_c^s \left(\omega_{2c}^h(s) + (1-\delta)x^h\right)$$

Net consumption of each good is determined from endowments after choosing storage, market transactions, and transfers. The consumption identities are:

$$\begin{aligned}
m_1^h &= \omega_{1m}^h + m_1^{h,+} - m_1^{h,-} + \alpha t_{m1}^{h,I} - t_{m1}^{h,O} \\
c_1^h &= \omega_{1c}^h + c_1^{h,+} - c_1^{h,-} + \alpha t_{c1}^{h,I} - t_{c1}^{h,O} - x^h \\
m_2^h(s) &= \omega_{2m}^h(s) + m_2^{h,+}(s) - m_2^{h,-}(s) + \alpha t_{m2}^{h,I}(s) - t_{m2}^{h,O}(s) \\
c_2^h(s) &= \omega_{2c}^h(s) + c_2^{h,+}(s) - c_2^{h,-}(s) + \alpha t_{c2}^{h,I}(s) - t_{c2}^{h,O}(s) + (1-\delta)x^h
\end{aligned}$$

We impose transfer balance. For $h \neq h'$, and for all $g \in \{m, c\}$ and all s:

$$t_{g1}^{h,I} = \alpha t_{g1}^{h',O}$$
$$t_{g2}^{h,I}(s) = \alpha t_{g2}^{h',O}(s)$$

Sales must not exceed available resources. For all h and s:

$$m_1^{h,-} \leq \omega_{1m}^h, \quad c_1^{h,-} \leq \omega_{1c}^h - x^h$$
$$m_2^{h,-}(s) \leq \omega_{2m}^h(s), \quad c_2^{h,-}(s) \leq \omega_{2c}^h(s) + (1-\delta)x^h$$

We also impose following non-negativity constraints:

$$m_t^{h,+},\ m_t^{h,-},\ c_t^{h,+},\ c_t^{h,-} \geq 0 \quad \forall t$$
$$t_{gt}^{h,I},\ t_{gt}^{h,O} \geq 0 \quad \forall g, t$$
$$x^h \geq 0$$

Given this structure, each household $h \in \{1,2\}$ chooses market transactions, transfer quantities, and storage levels to maximize expected utility $\mathbb{E}[U^h]$, subject to budget constraints, consumption identities, transfer balance, feasibility, and non-negativity constraints. We develop key insights from the model with special cases.

A1.2 Special cases

A1.2.1 Informal transfers without market transactions

We start with solving for optimal consumption in cases where markets are not available. We will illustrate the case without storage first and then add the possibility of storage.

(a) Without storage

If the only smoothing mechanism available is bilateral transfers between the two households, then each period's optimization problem can be solved independently. We first consider the optimal consumption allocation in period 1. Assume household 1 is milk-rich and cereal-poor, while household 2 is cereal-rich and milk-poor:

$$\omega_{1m}^1 > \omega_{1m}^2, \quad \omega_{1c}^1 < \omega_{1c}^2$$

Household 1 transfers milk to household 2 ($t_{m1}^{1,O} > 0$), and household 2 transfers cereals to household 1 ($t_{c1}^{2,O} > 0$). Let:

$$t_m \equiv t_{m1}^{1,O}, \quad t_c \equiv t_{c1}^{2,O}$$

denote the quantities of milk and cereals transferred in period 1. Due to transfer frictions, the recipient receives only a fraction $\alpha \in (0, 1]$ of what is sent:

$$t^{2,I}_{m1} = \alpha t_m, \quad t^{1,I}_{c1} = \alpha t_c$$

Substituting into the period 1 consumption identities yields:

$$\begin{aligned} m^1_1 &= \omega^1_{1m} - t_m, & c^1_1 &= \omega^1_{1c} + \alpha t_c \\ m^2_1 &= \omega^2_{1m} + \alpha t_m, & c^2_1 &= \omega^2_{1c} - t_c \end{aligned}$$

Similar to Townsend (1994) we now solve the social planner's problem. In the absence of information asymmetries and with symmetric households, this planner's solution is equivalent to a decentralized Nash bargaining outcome with equal weights. The planner chooses (t_m, t_c) to maximize the sum of utilities:

$$\begin{aligned} \max_{t_m, t_c} \quad & \log(\omega^1_{1m} - t_m) + \log(\omega^1_{1c} + \alpha t_c) \\ & + \log(\omega^2_{1m} + \alpha t_m) + \log(\omega^2_{1c} - t_c) \end{aligned}$$

subject to:

$$0 \leq t_m \leq \omega^1_{1m}, \quad 0 \leq t_c \leq \omega^2_{1c}$$

Solving the first-order conditions yields optimal transfers:

$$\begin{aligned} t^*_m &= \frac{\alpha\omega^1_{1m} - \omega^2_{1m}}{2\alpha} \\ t^*_c &= \frac{\alpha\omega^2_{1c} - \omega^1_{1c}}{2\alpha} \end{aligned}$$

Substituting back into the consumption expressions, we get:

$$\begin{aligned} m^1_1 &= \omega^1_{1m} - t^*_m = \frac{\alpha\omega^1_{1m} + \omega^2_{1m}}{2\alpha}, & c^1_1 &= \omega^1_{1c} + \alpha t^*_c = \frac{\omega^1_{1c} + \alpha\omega^2_{1c}}{2}, \\ m^2_1 &= \omega^2_{1m} + \alpha t^*_m = \frac{\omega^2_{1m} + \alpha\omega^1_{1m}}{2}, & c^2_1 &= \omega^2_{1c} - t^*_c = \frac{\alpha\omega^2_{1c} + \omega^1_{1c}}{2\alpha}. \end{aligned}$$

The resulting equilibrium allocations are familiar. As $\alpha \to 1$, transfer frictions vanish and consumption converges to the average of total endowments:

$$m_1^1 = m_1^2 = \frac{\omega_{1m}^1 + \omega_{1m}^2}{2}, \quad c_1^1 = c_1^2 = \frac{\omega_{1c}^1 + \omega_{1c}^2}{2}$$

As $\alpha \to 0$, the interior feasibility conditions fail and both transfers bind at zero. Households are then in autarky and each consumes only its own endowment.

A similar logic applies to period 2, though consumption is now state-contingent.[12] If $\alpha = 1$ and transfers are positive in each state, both households perfectly share risk in period 2 as well. The key difference between the two periods is that in period 1, transfers redistribute initial endowment differences, while in period 2, they smooth consumption across uncertain realizations.

Because utility is additively separable across periods and goods, the planner's solution implies that optimal consumption in each period depends only on aggregate endowments in that period. However, when $\alpha < 1$, frictions in transfers prevent full smoothing and lead to incomplete risk-sharing.

(b) With storage

We now also allow households to store cereals from period 1 to period 2, subject to cost, $\delta \in [0, 1)$. Milk remains perishable. In the interests of algebraic tractability we keep the same transfer pattern as the previous case in both periods. We also keep endowments deterministic in period 2. These simplifications allow closed-form solutions and highlight the tradeoff between transfers and storage for smoothing. Final period 1 consumption is therefore:

$$\begin{aligned} m_1^1 &= \omega_{1m}^1 - t_m, & c_1^1 &= \omega_{1c}^1 + \alpha t_c - x^1, \\ m_1^2 &= \omega_{1m}^2 + \alpha t_m, & c_1^2 &= \omega_{1c}^2 - t_c - x^2. \end{aligned}$$

Period 2 consumption is:

$$\begin{aligned} m_2^1 &= \omega_{2m}^1 - t_m, & c_2^1 &= \omega_{2c}^1 + \alpha t_c + (1-\delta)x^1, \\ m_2^2 &= \omega_{2m}^2 + \alpha t_m, & c_2^2 &= \omega_{2c}^2 - t_c + (1-\delta)x^2. \end{aligned}$$

We analyze the interaction between storage and pre-arranged transfer networks. The Planner's objective is to maximize social welfare with equal weights:

$$\max_{t_m, t_c, x^1, x^2} \quad \sum_{h=1}^{2} \left[\log(m_1^h) + \log(c_1^h) + \beta\Big(\log(m_2^h) + \log(c_2^h) \Big) \right]$$

[12]To obtain closed form expressions for optimal transfers, we have to solve the planner's problem assuming a fixed direction of transfer in each good and state and look for the interior solution. More generally, the direction of transfer would be endogenously determined by relative endowments in each state but this can lead to multiple corner solutions without a closed form. The key implications of how transfer frictions impede risk-sharing, however, remain unchanged.

subject to the consumption identities and non-negativity constraints:

$$t_m \geq 0, \quad t_c \geq 0, \quad x^1 \geq 0, \quad x^2 \geq 0.$$

Under perfect transfer efficiency ($\alpha = 1$) and costless storage ($\delta = 0$), perfect smoothing occurs across households and time. In this first-best equilibrium, the solution is symmetric ($x^1 = x^2 = x$). Period 1 consumption is:

$$m_1^1 = m_1^2 = \frac{\omega_{1m}^1 + \omega_{1m}^2}{2},$$
$$c_1^1 = c_1^2 = \frac{\omega_{1c}^1 + \omega_{1c}^2}{2} - x,$$

and period 2 consumption is:

$$m_2^1 = m_2^2 = \frac{\omega_{2m}^1 + \omega_{2m}^2}{2},$$
$$c_2^1 = c_2^2 = \frac{\omega_{2c}^1 + \omega_{2c}^2}{2} + x.$$

Let total storage be $X = 2x$. The optimal storage level solves:

$$\frac{1}{\frac{\omega_{1c}^1+\omega_{1c}^2}{2} - \frac{X}{2}} = \beta \frac{1}{\frac{\omega_{2c}^1+\omega_{2c}^2}{2} + \frac{X}{2}},$$

subject to feasibility. In this equilibrium, transfers equalize consumption across households, and storage smooths consumption over time.[13] These findings can also be extended to the case with stochastic endowments, where transfers will smooth consumption across households and over states, and storage will smooth consumption over time.

When transfer frictions are present ($\alpha < 1$), this perfect symmetry breaks down. Consumption is no longer equalized, leading to different marginal utilities for each household. This results in asymmetric storage decisions ($x^1 \neq x^2$). The interaction between transfers and storage becomes complex and non-separable. The general implication, however, is that higher transfer frictions increase reliance on ex-ante storage as a substitute for imperfect risk-sharing. If storage costs are not too high, households in communities with weak insurance networks (low α) will tend to store more cereals as a precautionary measure.

[13]To obtain closed-form solutions, we make the strong simplifying assumption that period 2 endowments are deterministic and that the optimal transfer pattern from period 1 is fixed and repeated in period 2. This abstracts from the state-contingent nature of risk-sharing.

A1.2.2 Product market without transfers

We now assume that there are no transfers but households can trade in the market at fixed prices. We again first solve for the case without storage so as to pin down intuition.

(a) Product markets without storage

If neither transfers nor storage are feasible, then households can only smooth consumption through product market trade, which is subject to proportional transaction costs $\tau > 0$. Given the absence of storage, additively separable utility, and fixed market prices, we can solve each period's optimization problem independently.[14]

Each household h chooses quantities of milk and cereals to buy or sell to maximize utility. Let $m_t^{h,+}$ and $m_t^{h,-}$ denote purchases and sales of milk, respectively, and similarly for cereals. Then the household's optimization problem in period 1 is:

$$\max_{m_1^h, c_1^h} \log(m_1^h) + \log(c_1^h)$$

subject to the period budget constraint,

$$(1+\tau)p_m m_1^{h,+} + (1+\tau)p_c c_1^{h,+} \leq (1-\tau)p_m m_1^{h,-} + (1-\tau)p_c c_1^{h,-}$$

consumption identities,

$$\begin{aligned} m_1^h &= \omega_{1m}^h + m_1^{h,+} - m_1^{h,-}, \\ c_1^h &= \omega_{1c}^h + c_1^{h,+} - c_1^{h,-}. \end{aligned}$$

and non-negativity constraints. This yields the Lagrangian:

$$\begin{aligned} \mathcal{L} = &\log(\omega_{1m}^h + m_1^{h,+} - m_1^{h,-}) + \log(\omega_{1c}^h + c_1^{h,+} - c_1^{h,-}) \\ &+ \lambda_1^h \left[(1-\tau)(p_m m_1^{h,-} + p_c c_1^{h,-}) - (1+\tau)(p_m m_1^{h,+} + p_c c_1^{h,+}) \right] \\ &+ \sum_{g \in \{m,c\}} \left(\mu_g^{h,+} g_1^{h,+} + \mu_g^{h,-} g_1^{h,-} \right) \end{aligned}$$

Let λ_1^h denote the Lagrange multiplier on the budget constraint and μ_1^h's be the multipliers for non-negativity constraints. Based on the first order conditions, trade occurs only when the marginal rate of substitution justifies paying the transaction cost. Specifically:

[14] Given the symmetry of the setup, we do not lose much by focusing on the allocation for a single household in a single period.

$$\begin{aligned}
\text{Buy milk if} \quad & \frac{1}{m_1^h} > (1+\tau)p_m\lambda_1^h \\
\text{Sell milk if} \quad & \frac{1}{m_1^h} < (1-\tau)p_m\lambda_1^h \\
\text{Buy cereals if} \quad & \frac{1}{c_1^h} > (1+\tau)p_c\lambda_1^h \\
\text{Sell cereals if} \quad & \frac{1}{c_1^h} < (1-\tau)p_c\lambda_1^h
\end{aligned}$$

Based on the trade conditions above and

$$\frac{c_1^h}{m_1^h} = \frac{(1+\tau)p_m}{(1-\tau)p_c}$$

we can derive the no trade condition:

$$\frac{1}{\kappa} \leq \frac{p_m m_1^h}{p_c c_1^h} \leq \kappa$$

where $\kappa \equiv \frac{1+\tau}{1-\tau}$ denotes the price distortion ratio. In this case, the household simply consumes its own endowments:

$$m_1^h = \omega_{1m}^h, \quad c_1^h = \omega_{1c}^h$$

Note that the interval depends upon τ. An increase in transaction cost will widen the no-trade autarky interval; reduced transaction costs promote market-based exchange.

To get closed form expressions for consumption, we assume that the household sells cereals ($c_1^{h,-} > 0$) and buys milk ($m_1^{h,+} > 0$), which implies that there are no milk sales ($m_1^{h,-} = 0$) or cereal purchases ($c_1^{h,+} = 0$) so long as $\tau > 0$. The budget constraint becomes:

$$(1+\tau)p_m m_1^{h,+} = (1-\tau)p_c c_1^{h,-}$$

The consumption identities are:

$$\begin{aligned}
m_1^h &= \omega_{1m}^h + m_1^{h,+} \\
c_1^h &= \omega_{1c}^h - c_1^{h,-}
\end{aligned}$$

The optimal consumption bundle when selling cereals to buy milk is:

$$m_1^h = \frac{(1-\tau)p_c\omega_{1c}^h + (1+\tau)p_m\omega_{1m}^h}{2(1+\tau)p_m}$$

$$c_1^h = \frac{(1-\tau)p_c\omega_{1c}^h + (1+\tau)p_m\omega_{1m}^h}{2(1-\tau)p_c}$$

Thus as $\tau \to 0$, the price distortion ratio $\kappa \to 1$, and the allocation converges to the first-best:

$$m_1^h = \frac{p_m\omega_{1m}^h + p_c\omega_{1c}^h}{2p_m}, \quad c_1^h = \frac{p_m\omega_{1m}^h + p_c\omega_{1c}^h}{2p_c}$$

Market access essentially allows households to reallocate their consumption bundles by trading endowments. When a household sells one good (e.g., cereals), it generates income to buy other goods (e.g., milk). Transaction costs distort this trade in two ways. First, they reduce effective income from sales. Second, they increase effective purchase prices per unit purchased. These frictions reduce the gains from trade, in extreme cases leading to a no trade equilibrium, i.e., autarky.

(b) With storage

Assume now that households can engage in market transactions and also store cereals from period 1 to period 2. Given that there are no transfers, we only focus on one household's problem. For simplicity, we again assume that the household sells cereals ($c_t^{h,-} > 0$) and buys milk ($m_t^{h,+} > 0$).[15] The household can also store cereals $x^h \geq 0$ at a cost δ. The household maximizes expected intertemporal utility:

$$\max_{\substack{m_1^{h,+}, c_1^{h,-}, x^h, \\ m_2^{h,+}(s), c_2^{h,-}(s)}} \left\{ \log(m_1^h) + \log(c_1^h) + \beta \sum_s \pi_s \left[\log(m_2^h(s)) + \log(c_2^h(s)) \right] \right\}$$

subject to the period 1 budget constraint,

$$(1+\tau)p_m m_1^{h,+} \leq (1-\tau)p_c c_1^{h,-}$$

and the period 2 budget constraint,

$$(1+\tau)p_m m_2^{h,+}(s) \leq (1-\tau)p_c c_2^{h,-}(s)$$

The consumption identities are thus,

[15] Note that buying and selling decisions would be endogenous when endowments are uncertain. For tractability, we consider only states of the world where the household engages only in milk purchases and cereals sales. This assumption allows for closed form solutions while preserving the main insights.

$$
\begin{aligned}
m_1^h &= \omega_{1m}^h + m_1^{h,+} \\
c_1^h &= \omega_{1c}^h - c_1^{h,-} - x^h \\
m_2^h(s) &= \omega_{2m}^h(s) + m_2^{h,+}(s) \\
c_2^h(s) &= \omega_{2c}^h(s) - c_2^{h,-}(s) + (1-\delta)x^h
\end{aligned}
$$

with feasibility constraints,

$$
\begin{aligned}
c_1^{h,-} &\leq \omega_{1c}^h - x^h \\
c_2^{h,-}(s) &\leq \omega_{2c}^h(s) + (1-\delta)x^h \\
x^h &\geq 0
\end{aligned}
$$

We set up the Lagrangian:

$$
\begin{aligned}
\mathcal{L} = &\log(m_1^h) + \log(c_1^h) + \beta \sum_s \pi_s \left[\log(m_2^h(s)) + \log(c_2^h(s))\right] \\
&+ \lambda_1 \left[(1-\tau)p_c c_1^{h,-} - (1+\tau)p_m m_1^{h,+}\right] \\
&+ \sum_s \lambda_2(s) \left[(1-\tau)p_c c_2^{h,-}(s) - (1+\tau)p_m m_2^{h,+}(s)\right]
\end{aligned}
$$

and derive the first-order conditions:

$$
\begin{aligned}
\frac{1}{m_1^h} &= \lambda_1(1+\tau)p_m, \\
\frac{1}{c_1^h} &= \lambda_1(1-\tau)p_c, \\
\frac{\beta\pi_s}{m_2^h(s)} &= \lambda_2(s)(1+\tau)p_m, \\
\frac{\beta\pi_s}{c_2^h(s)} &= \lambda_2(s)(1-\tau)p_c, \\
\frac{1}{c_1^h} &= \beta(1-\delta)\,\mathbb{E}\left[\frac{1}{c_2^h(s)}\right].
\end{aligned}
$$

from which we derive, for period 1:

$$
\frac{c_1^h}{m_1^h} = \frac{(1-\tau)p_c}{(1+\tau)p_m}
$$

and similarly for period 2:

$$\frac{c_2^h(s)}{m_2^h(s)} = \frac{(1-\tau)p_c}{(1+\tau)p_m}$$

Given x^h, optimal consumption is given by the following expressions:

$$\begin{aligned}
m_1^h &= \frac{(1+\tau)p_m\omega_{1m}^h + (1-\tau)p_c(\omega_{1c}^h - x^h)}{2(1+\tau)p_m}, \\
c_1^h &= \frac{(1+\tau)p_m\omega_{1m}^h + (1-\tau)p_c(\omega_{1c}^h - x^h)}{2(1-\tau)p_c}, \\
m_2^h(s) &= \frac{(1+\tau)p_m\omega_{2m}^h(s) + (1-\tau)p_c(\omega_{2c}^h(s) + (1-\delta)x^h)}{2(1+\tau)p_m}, \\
c_2^h(s) &= \frac{(1+\tau)p_m\omega_{2m}^h(s) + (1-\tau)p_c(\omega_{2c}^h(s) + (1-\delta)x^h)}{2(1-\tau)p_c}.
\end{aligned}$$

The expressions show that the decision to store cereals alters the household's intertemporal wealth profile. This allows storage to serve as a mechanism for smoothing the consumption of both storable and nonstorable goods.

To see how storage will respond to change in frictions, we consider the deterministic case of fixed period 2 endowments. The Euler equation simplifies to

$$\frac{1}{c_1^h} = \beta(1-\delta)\frac{1}{c_2^h} \tag{10}$$

Using this simplified Euler equation, we get the following optimal storage condition:

$$x^h = \max\left\{0,\ \frac{\beta(1-\delta)\left[(1+\tau)p_m\omega_{1m}^h + (1-\tau)p_c\omega_{1c}^h\right] - \left[(1+\tau)p_m\bar{\omega}_{2m}^h + (1-\tau)p_c\bar{\omega}_{2c}^h\right]}{(1-\tau)p_c(1-\delta)(1+\beta)}\right\}.$$

The effect of transaction costs on optimal storage in general is ambiguous. On one hand, higher trade frictions increase the cost of intertemporal smoothing via markets as households would earn less from selling cereals and pay more when buying milk. This would make storage relatively more attractive, increasing the incentive to store cereals for future use. On the other hand, higher trade frictions also reduce households' effective purchasing power from trade, tightening their resource constraint. This would lower the amount of cereals available for storage. Which effect dominates depends on the discount factor, storage costs and the distribution of endowments across periods.[16] For patient households with low storage losses, storage is likely to rise with τ, whereas for poorer liquidity constraint households with higher storage costs, higher trade frictions may instead reduce storage.

[16] If the corner solution binds, changes in trade frictions will not affect storage.

A1.2.3 Consumption smoothing with transfers and market transactions

We discuss another simple case to illustrate how relative frictions across transfers and market trade affect household decisions for smoothing consumption. In response to an adverse production shock, a household can either receive transfers from another household or purchase from the market, each subject to frictions.

Let the household require one additional unit of consumption. The cost of obtaining this unit depends on the smoothing channel. For market purchases, the household must pay $(1+\tau)$ units of cereal per unit consumed, where $\tau \in [0,1)$ is the ad valorem transaction cost. For transfers, the other household must send $\frac{1}{\alpha}$ units to deliver 1 unit of effective consumption, where $\alpha \in (0,1]$ captures transfer efficiency. If $\alpha < 1$, some portion of the transfer is lost due to frictions.

Comparing the cost of smoothing via the two channels, transfers are preferred iff:

$$\frac{1}{\alpha} < 1+\tau \quad \Rightarrow \quad \alpha > \frac{1}{1+\tau};$$

markets are preferred otherwise. This provides a simple threshold rule. Households choose the cheaper of the two smoothing options based on the relative strength of frictions associated with market versus non-market exchange. When transaction costs are high and transfers are efficient (α close to 1), households rely more on informal transfers. But if transaction costs are low market purchases may be a more attractive option.

A1.2.4 The implications of integrating market and non-market exchange with storage

These special cases help build intuition on how the costs of storage, market, and non-market exchange influence the mechanisms used for consumption smoothing. Higher trade costs (τ) reduce households' ability to smooth consumption through market transactions by making buying more expensive (paying $(1+\tau)p_g$) and selling less profitable (receiving only $(1-\tau)p_g$). A higher τ therefore takes households closer to market autarky for moderate endowment imbalances. Households might rely on storage as an alternative consumption smoothing mechanism if storage costs are not too high. Or they might rely on informal, non-market transfers when the relative frictions favor that mechanism, i.e., $\alpha > \frac{1}{1+\tau}$.

The implication is that in remote communities with high market transaction costs, we expect households to depend more on storage and informal transfers. As the costs of market exchange fall, we expect some substitution of product market exchange for informal transfers, storage, or both. Interventions that lower transaction costs, like new roads connecting communities to the nearest town/market, can enhance market-based consumption smoothing. By lowering τ, households can more easily engage in intertemporal and cross-good consumption smoothing.

Empirically, this model implies that consumption allocations for each good depend upon the full vector of household endowments across goods and time, market prices, transaction costs, transfer frictions, storage costs, and the discount factor. These factors jointly determine the extent to which households can smooth consumption intertemporally, across households, and across commodities, as well as the extent to which households rely on market exchange, storage and transfers to consumption smooth. While the direction of these effects is intuitive in simplified cases, in the general setting, the net effects are theoretically ambiguous as they depend on nonlinear interactions between multiple frictions, the set of constraints that bind, and corner solutions. This theoretical ambiguity motivates our empirical framework for quantifying the real world relative importance of each smoothing mechanism and studying how consumption from different channels responds to exogenous variation in transaction costs.

A2 Production variance decomposition

To decompose milk production variance, we take logs and seasonal first differences of Equation (4) on both sides:

$$\begin{aligned}\Delta \ln(Y_{ivmt}) = {} & \Delta \ln(Y_{ivmt}) - \Delta \ln(Y^P_{ivmt}) \\ & + \Delta \ln(Y^P_{ivmt}) - \Delta \ln(Y^S_{ivmt}) \\ & + \Delta \ln(Y^S_{ivmt}) - \Delta \ln(C_{ivmt}) \\ & + \Delta \ln(C_{ivmt})\end{aligned} \tag{A1}$$

Multiplying both sides by $\Delta \ln(Y_{ivmt})$ and taking expectations, we obtain:

$$\begin{aligned}\mathrm{Var}(\Delta \ln(Y_{ivmt})) = {} & \mathrm{Cov}(\Delta \ln(Y_{ivmt}) - \Delta \ln(Y^P_{ivmt}), \Delta \ln(Y_{ivmt})) \\ & + \mathrm{Cov}(\Delta \ln(Y^P_{ivmt}) - \Delta \ln(Y^S_{ivmt}), \Delta \ln(Y_{ivmt})) \\ & + \mathrm{Cov}(\Delta \ln(Y^S_{ivmt}) - \Delta \ln(C_{ivmt}), \Delta \ln(Y_{ivmt})) \\ & + \mathrm{Cov}(\Delta \ln(C_{ivmt}), \Delta \ln(Y_{ivmt}))\end{aligned} \tag{A2}$$

Dividing both sides by $\mathrm{Var}(\Delta \ln(Y_{ivmt}))$, we get:

$$\begin{aligned}1 = {} & \frac{\mathrm{Cov}(\Delta \ln(Y_{ivmt}) - \Delta \ln(Y^P_{ivmt}), \Delta \ln(Y_{ivmt}))}{\mathrm{Var}(\Delta \ln(Y_{ivmt}))} \\ & + \frac{\mathrm{Cov}(\Delta \ln(Y^P_{ivmt}) - \Delta \ln(Y^S_{ivmt}), \Delta \ln(Y_{ivmt}))}{\mathrm{Var}(\Delta \ln(Y_{ivmt}))} \\ & + \frac{\mathrm{Cov}(\Delta \ln(Y^S_{ivmt}) - \Delta \ln(C_{ivmt}), \Delta \ln(Y_{ivmt}))}{\mathrm{Var}(\Delta \ln(Y_{ivmt}))} \\ & + \frac{\mathrm{Cov}(\Delta \ln(C_{ivmt}), \Delta \ln(Y_{ivmt}))}{\mathrm{Var}(\Delta \ln(Y_{ivmt}))}\end{aligned} \tag{A3}$$

Using lowercase notation to denote log seasonal first differences:

$$\begin{aligned}1 = {} & \frac{\mathrm{Cov}(y_{ivmt} - y^P_{ivmt}, y_{ivmt})}{\mathrm{Var}(y_{ivmt})} + \frac{\mathrm{Cov}(y^P_{ivmt} - y^S_{ivmt}, y_{ivmt})}{\mathrm{Var}(y_{ivmt})} \\ & + \frac{\mathrm{Cov}(y^S_{ivmt} - c_{ivmt}, y_{ivmt})}{\mathrm{Var}(y_{ivmt})} + \frac{\mathrm{Cov}(c_{ivmt}, y_{ivmt})}{\mathrm{Var}(y_{ivmt})}\end{aligned} \tag{A4}$$

These terms are regression coefficients and can be written concisely as:

$$1 = \beta^P + \beta^S + \beta^O + \beta \tag{A5}$$

Cereal production variance can be decomposed in a similar way with storage and government transfers as additional smoothing channels.

A3 Figures

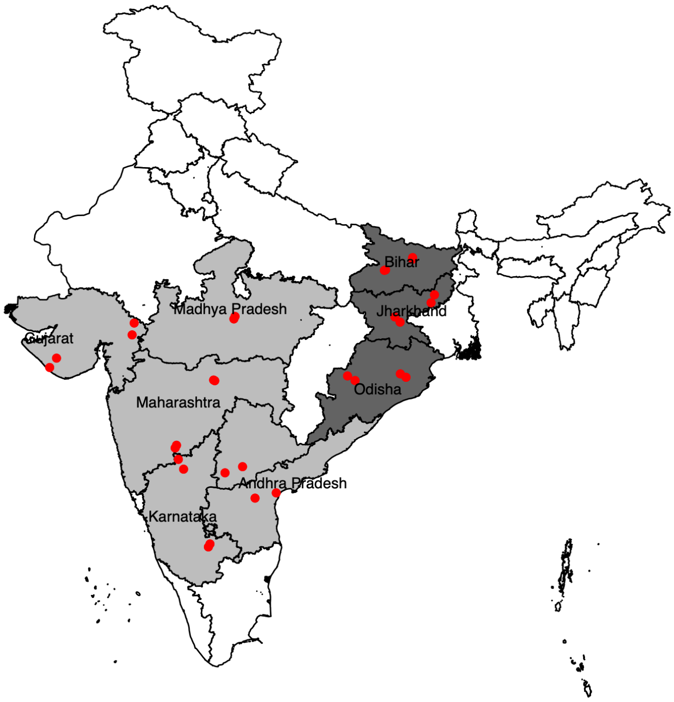
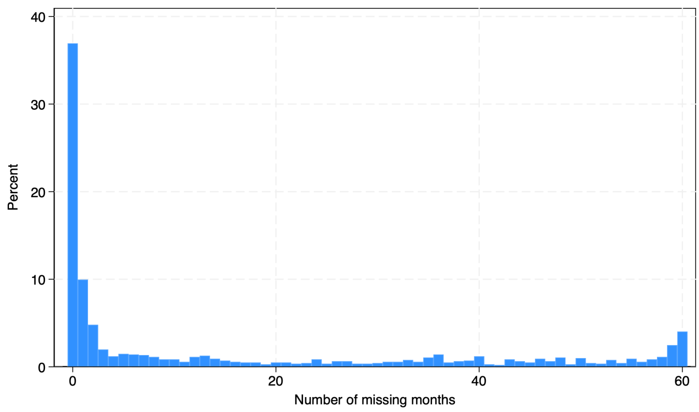
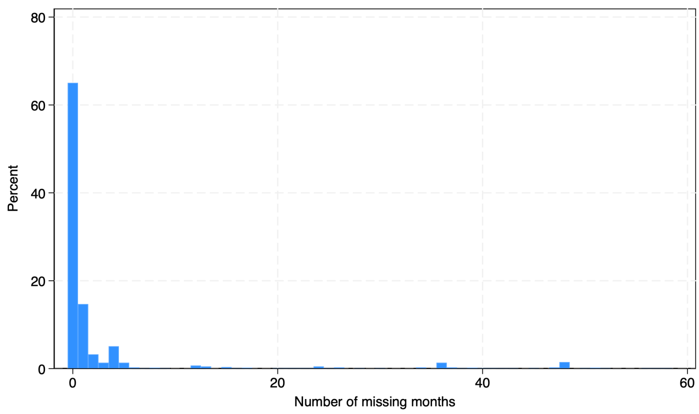


Figure A1: Locations of 30 sampled villages across 8 states of India



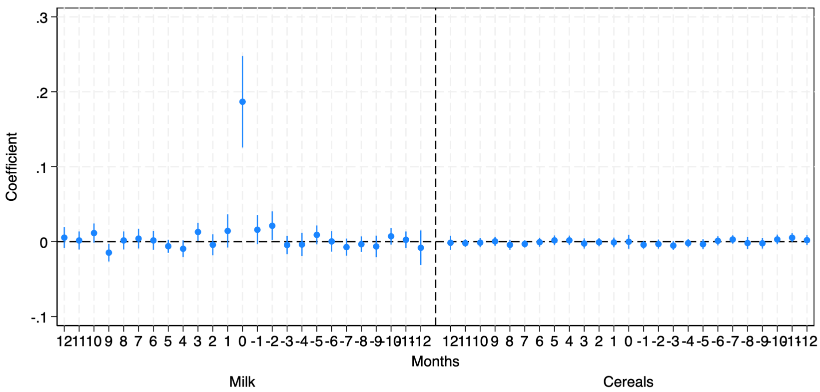
(a) Fluid milk



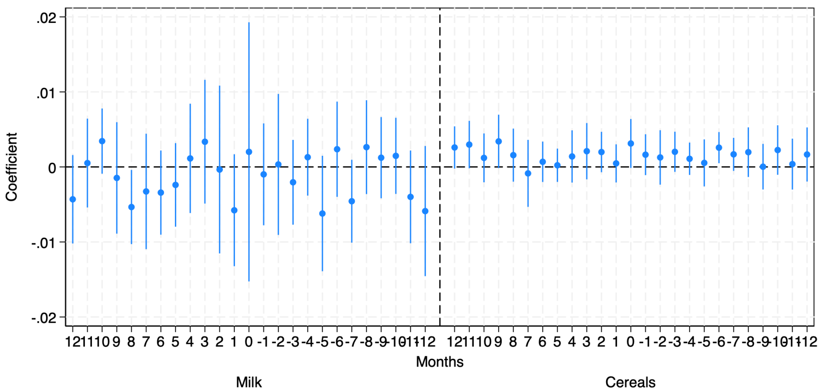
(b) Staple cereals

Figure A2: Distribution of missing months per household

Notes: The distribution of the number of missing months per sample household (maximum duration is 60 months).



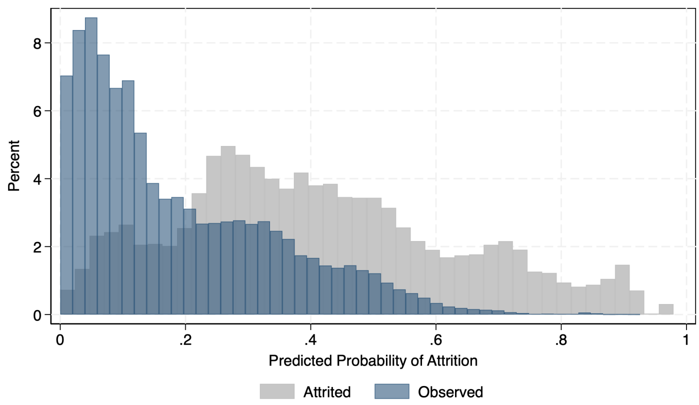
(a) Fluid milk consumption



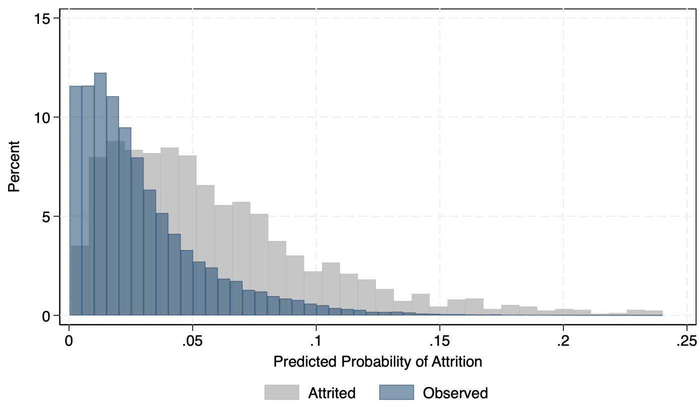
(b) Staple cereals consumption

Figure A3: Lead and lagged production shocks and consumption smoothing

Notes: The figure plots the estimated coefficients of 12-month lead and lagged log differenced milk and cereal production per person with 95% confidence intervals.



(a) Fluid milk



(b) Staple cereals

Figure A4: Estimated attrition probability

Notes: The figure plots the predicted probabilities from a logit model for observed milk and cereal consumption and production for the sample based on observed household characteristics and month and year fixed effects.

A4 Tables

Table A1: VDSA Sampling Frame

Region	State	District	Village	Households in Village	Sample
Semi-Arid Tropics	Andhra Pradesh	Mahbubnagar	Aurepalle	984	70
	Andhra Pradesh	Mahbubnagar	Dokur	545	50
	Andhra Pradesh	Prakasam	JC Agraharam	382	40
	Andhra Pradesh	Prakasam	Pamidipadu	1214	40
	Maharashtra	Akola	Kanzara	319	62
	Maharashtra	Akola	Kinkhed	189	52
	Maharashtra	Solapur	Kalman	660	61
	Maharashtra	Solapur	Shirapur	546	89
	Karnataka	Bijapur	Kapanimbargi	320	40
	Karnataka	Bijapur	Markabbinahalli	392	40
	Karnataka	Tumkur	Belladamadugu	276	40
	Karnataka	Tumkur	Tharati	401	40
	Gujarat	Junagadh	Karamdi Chingariya	240	40
	Gujarat	Junagadh	Makhiyala	789	40
	Gujarat	Panchmahal	Babrol	750	40
	Gujarat	Panchmahal	Chatha	289	40
	Madhya Pradesh	Raisen	Papda	164	40
	Madhya Pradesh	Raisen	Rampura Kalan	359	40
Eastern	Bihar	Patna	Arap	1166	40
	Bihar	Patna	Baghakole	503	40
	Bihar	Darbhanga	Inai	590	40
	Bihar	Darbhanga	Susari	644	40
	Jharkhand	Dumka	Dumariya	202	40
	Jharkhand	Dumka	Durgapur	126	40
	Jharkhand	Ranchi	Dubaliya	211	40
	Jharkhand	Ranchi	Hesapiri	96	40
	Odisha	Bolangir	Ainlatunga	307	40
	Odisha	Bolangir	Bilaikani	171	40
	Odisha	Dhenkanal	Sogar	428	40
	Odisha	Dhenkanal	Chandrasekharpur	302	40

Note: The table provides details regarding the number of households in each village and the number of households surveyed under the VDSA project.

Source: https://web.archive.org/web/20220522133130/http://vdsa.icrisat.ac.in/vdsa-desgImplementation.aspx

Table A2: Correlates of milk and cereal consumption being observed

	(1) Milk	(2) Cereals
main		
Log dairy animals	-1.052***	-0.159**
	(0.026)	(0.062)
Log land owned	0.034	0.504***
	(0.021)	(0.049)
Log MPCE	2.029***	0.197***
	(0.031)	(0.043)
Log Number of members	1.734***	1.105***
	(0.033)	(0.069)
Log milk prod/pc	0.739***	0.197***
	(0.011)	(0.024)
Log cereal prod/pc	0.001	0.045***
	(0.007)	(0.016)
Log wages/pc	-0.008	0.038***
	(0.006)	(0.012)
Year FE	Yes	Yes
Month FE	Yes	Yes
Observations	80760	80760

Notes: The dependent variable is a binary indicator equal to 1 if the milk or cereal consumption is observed for the household, and 0 otherwise. The probability is modeled using logit regression as a function of baseline (2010) household characteristics. Robust standard errors in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Table A3: Correlates of buy-sell price differential being observed

	(1) Milk	(2) Cereals
observed		
Log dairy animals	0.895**	0.314**
	(0.366)	(0.145)
Log land owned	-0.102	-0.227
	(0.120)	(0.167)
Log MPCE	0.101	-0.445**
	(0.183)	(0.193)
Log Number of members	0.934***	0.553**
	(0.226)	(0.220)
Log milk prod/pc	0.789***	-0.033
	(0.091)	(0.067)
Log cereal prod/pc	0.151***	0.410***
	(0.033)	(0.056)
Log wages/pc	-0.037	0.005
	(0.030)	(0.022)
Month FE	Yes	No
Season FE	No	Yes
Crop FE	No	Yes
Observations	70399	32350

Notes: The dependent variable is a binary indicator equal to 1 if the milk or cereal price differential is observed for the household, and 0 otherwise. The probability is modeled using a logit regression as a function of baseline (2010) household characteristics. Standard errors in parentheses are robust to the intra-village correlation of residuals. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Table A4: New roads and the likelihood of missing milk and cereal consumption

	(1) Fluid milk	(2) Staple cereals
$NROAD$	-0.095***	-0.000*
	(0.020)	(0.000)
$WINTER$	-0.015**	-0.000
	(0.007)	(0.000)
$NROAD\times$ WINTER	-0.004	0.000
	(0.012)	(0.000)
$NROAD\times$ LO	-0.010	0.000
	(0.009)	(0.000)
$WINTER\times$ LO	0.015**	0.000
	(0.006)	(0.000)
$NROAD\times$ WINTER $\times$ LO	-0.023	-0.000
	(0.019)	(0.000)
Observations	80079	80079

Notes: The dependent variable is a binary indicator equal to 1 if milk or cereal consumption is missing for the household, and 0 otherwise. *LO* is an indicator to denote households with greater than 2 hectares of operated area in the baseline. $NROAD$ captures new rural road construction under the $PMGSY$. $WINTER$ is a dummy variable that takes values 1 for October through March. Standard errors in parentheses are robust to the intra-village correlation of residuals. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

Table A5: Production scale, roads, seasonality and consumption smoothing for milk

	(1) β^P	(2) β^S	(3) β^O	(4) β
Δy	0.464***	0.320***	0.047***	0.169***
	(0.042)	(0.055)	(0.014)	(0.034)
$\Delta y \times HS$	-0.030***	0.016	0.015	-0.001
	(0.010)	(0.015)	(0.011)	(0.010)
$\Delta y \times ROAD$	-0.084	-0.021	-0.015	0.119
	(0.057)	(0.109)	(0.051)	(0.118)
$\Delta y \times WINTER$	-0.004	0.011	0.000	-0.007
	(0.008)	(0.009)	(0.011)	(0.014)
$\Delta y \times HS \times ROAD$	-0.004	-0.005	-0.007	0.017
	(0.014)	(0.021)	(0.019)	(0.028)
$\Delta y \times HS \times WINTER$	-0.008	-0.006	0.008	0.006
	(0.007)	(0.004)	(0.007)	(0.009)
$\Delta y \times HS \times ROAD \times WINTER$	0.014*	0.003	-0.008	-0.009
	(0.007)	(0.009)	(0.009)	(0.009)
Observations	43517	43517	43517	43517

	(1) β^P	(2) β^S	(3) β^O	(4) β
Δy	0.442***	0.313***	0.038**	0.208***
	(0.038)	(0.053)	(0.017)	(0.043)
$\Delta y \times HS$	-0.029***	0.018	0.014	-0.003
	(0.009)	(0.013)	(0.009)	(0.011)
$\Delta y \times NROAD$	0.013	0.024	0.043	-0.079
	(0.042)	(0.089)	(0.035)	(0.100)
$\Delta y \times WINTER$	-0.006	0.011	0.000	-0.005
	(0.009)	(0.009)	(0.011)	(0.016)
$\Delta y \times HS \times NROAD$	-0.026*	-0.037**	0.001	0.062***
	(0.014)	(0.017)	(0.021)	(0.017)
$\Delta y \times HS \times WINTER$	-0.005	-0.007*	0.006	0.006
	(0.007)	(0.004)	(0.007)	(0.009)
$\Delta y \times HS \times NROAD \times WINTER$	0.003	0.023***	-0.001	-0.026
	(0.009)	(0.007)	(0.024)	(0.019)
Observations	43517	43517	43517	43517

Notes: All specifications are estimated with inverse probability weighting (IPW) and control for the seasonally differenced log change in household size, the change in log per capita consumption expenditure, and village time trends. y denotes seasonally differenced log per-person household production of milk. HS is the herd size of dairy animals owned by the household in the baseline. $ROAD$ captures new or upgraded rural road construction under the $PMGSY$. $NROAD$ captures new rural road construction under the $PMGSY$. $WINTER$ is a dummy variable that takes values 1 for October through March. Figures in parentheses are standard errors robust to the intra-village correlation of residuals. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table A6: Production scale, roads, seasonality and consumption smoothing for cereals

	(1) β^P	(2) β^S	(3) β^G	(4) β^O	(5) β^B	(6) β
Δy	0.184***	0.014	0.113***	0.002	0.691***	-0.005
	(0.032)	(0.010)	(0.022)	(0.001)	(0.035)	(0.003)
$\Delta y \times LO$	0.018	0.003	-0.042	0.000	0.016	0.005
	(0.026)	(0.013)	(0.027)	(0.001)	(0.031)	(0.003)
$\Delta y \times ROAD$	-0.077**	0.015	0.074	-0.002	-0.007	-0.003*
	(0.037)	(0.014)	(0.044)	(0.003)	(0.045)	(0.002)
$\Delta y \times WINTER$	0.037*	-0.006	-0.000	0.003*	-0.039*	0.006
	(0.018)	(0.012)	(0.014)	(0.002)	(0.019)	(0.004)
$\Delta y \times LO \times ROAD$	-0.021	0.028	-0.018	-0.002	0.019	-0.007*
	(0.029)	(0.038)	(0.039)	(0.004)	(0.063)	(0.004)
$\Delta y \times LO \times WINTER$	-0.036	0.005	0.013	-0.004*	0.029	-0.006
	(0.023)	(0.015)	(0.023)	(0.002)	(0.022)	(0.004)
$\Delta y \times LO \times ROAD \times WINTER$	0.059**	-0.032	-0.029	0.002	-0.013	0.014***
	(0.022)	(0.034)	(0.031)	(0.003)	(0.037)	(0.003)
Observations	45764	45764	45764	45764	45764	45764

	(1) β^P	(2) β^S	(3) β^G	(4) β^O	(5) β^B	(6) β
Δy	0.162***	0.020	0.145***	0.002	0.676***	-0.005
	(0.030)	(0.014)	(0.026)	(0.001)	(0.030)	(0.003)
$\Delta y \times LO$	0.025	0.005	-0.062**	-0.000	0.027	0.005
	(0.019)	(0.017)	(0.024)	(0.001)	(0.029)	(0.003)
$\Delta y \times NROAD$	-0.031	-0.013*	-0.062**	-0.005***	0.111***	-0.001
	(0.031)	(0.007)	(0.028)	(0.002)	(0.033)	(0.001)
$\Delta y \times WINTER$	0.033*	-0.005	0.006	0.004*	-0.043**	0.006
	(0.018)	(0.012)	(0.013)	(0.002)	(0.019)	(0.004)
$\Delta y \times LO \times NROAD$	-0.040	-0.004	-0.012	-0.001	0.062*	-0.006
	(0.027)	(0.014)	(0.025)	(0.002)	(0.036)	(0.004)
$\Delta y \times LO \times WINTER$	-0.027	-0.000	0.006	-0.004*	0.028	-0.004
	(0.019)	(0.015)	(0.019)	(0.002)	(0.023)	(0.004)
$\Delta y \times LO \times NROAD \times WINTER$	0.021	-0.002	0.012	0.001	-0.037	0.005
	(0.016)	(0.013)	(0.018)	(0.001)	(0.032)	(0.005)
Observations	45764	45764	45764	45764	45764	45764

Notes: Cereals include rice, wheat, millets, sorghum, and maize. All specifications are estimated with inverse probability weighting (IPW) and control for the seasonally differenced log change in household size, the change in log per capita consumption expenditure, and village time trends. y denotes seasonally differenced log per person household production of cereals. LO is a dummy indicating farm households operating greater than 2 hectares of land in the baseline. $ROAD$ captures new or upgraded rural road construction under the $PMGSY$. $NROAD$ captures new rural road construction under the $PMGSY$. $WINTER$ is a dummy variable that takes values 1 for October through March. Figures in parentheses are standard errors robust to the intra-village correlation of residuals. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table A7: Production scale, roads, seasonality and consumption smoothing

	Fluid milk				Staple cereals					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	β^P	β^S	β^O	β	β^P	β^S	β^G	β^O	β^B	β
Δym	0.420***	0.332***	0.068***	0.181***	0.011	-0.001	0.005	0.002	-0.015*	-0.001
	(0.037)	(0.058)	(0.018)	(0.029)	(0.010)	(0.001)	(0.007)	(0.003)	(0.007)	(0.003)
$\Delta ym \times LO$	0.004	0.023	0.003	-0.030	-0.016	0.004	0.004	-0.006	0.013	0.005
	(0.036)	(0.047)	(0.027)	(0.023)	(0.021)	(0.005)	(0.008)	(0.003)	(0.018)	(0.003)
$\Delta ym \times ROAD$	-0.081	0.042	-0.048	0.087	-0.006	0.003	-0.000	0.003	-0.002	0.001
	(0.051)	(0.106)	(0.045)	(0.105)	(0.013)	(0.002)	(0.010)	(0.003)	(0.011)	(0.005)
$\Delta ym \times WINTER$	-0.008	0.006	0.012	-0.010	-0.010	-0.003	-0.004	-0.002	0.016**	0.000
	(0.008)	(0.009)	(0.010)	(0.011)	(0.008)	(0.003)	(0.006)	(0.002)	(0.006)	(0.003)
$\Delta ym \times LO \times ROAD$	-0.003	-0.213**	0.066	0.150*	0.023	-0.010	-0.015	0.001	0.012	-0.013*
	(0.064)	(0.078)	(0.107)	(0.084)	(0.031)	(0.006)	(0.030)	(0.005)	(0.026)	(0.007)
$\Delta ym \times LO \times WINTER$	-0.013	0.005	-0.008	0.016	0.031	-0.002	-0.018	0.007	-0.024	0.004
	(0.014)	(0.011)	(0.015)	(0.012)	(0.027)	(0.005)	(0.012)	(0.004)	(0.018)	(0.004)
$\Delta ym \times LO \times ROAD \times WINTER$	0.019	-0.005	-0.024	0.010	-0.037	-0.005	0.048**	-0.004	0.004	0.001
	(0.022)	(0.033)	(0.031)	(0.027)	(0.029)	(0.008)	(0.023)	(0.004)	(0.024)	(0.007)
Δyg	-0.009	0.005	0.011*	-0.007	0.192***	0.013	0.102***	0.001	0.696***	-0.007**
	(0.006)	(0.006)	(0.006)	(0.007)	(0.033)	(0.008)	(0.022)	(0.001)	(0.037)	(0.003)
$\Delta yg \times LO$	0.007	-0.003	-0.015**	0.011*	0.007	0.003	-0.031	0.001	0.007	0.008**
	(0.007)	(0.007)	(0.007)	(0.006)	(0.026)	(0.010)	(0.026)	(0.002)	(0.033)	(0.003)
$\Delta yg \times ROAD$	0.005	-0.004	-0.006	0.004	-0.094**	0.013	0.081*	-0.001	0.002	-0.001
	(0.004)	(0.005)	(0.005)	(0.006)	(0.038)	(0.013)	(0.048)	(0.003)	(0.048)	(0.002)
$\Delta yg \times WINTER$	0.006	-0.003	-0.010*	0.007	0.040**	-0.003	-0.004	0.003	-0.046**	0.008**
	(0.006)	(0.008)	(0.006)	(0.007)	(0.017)	(0.010)	(0.012)	(0.002)	(0.020)	(0.003)
$\Delta yg \times LO \times ROAD$	0.003	0.002	-0.005	-0.000	-0.001	0.031	-0.038	-0.003	0.018	-0.008*
	(0.010)	(0.009)	(0.013)	(0.016)	(0.026)	(0.037)	(0.040)	(0.004)	(0.065)	(0.004)
$\Delta yg \times LO \times WINTER$	-0.012*	0.010	0.012*	-0.009	-0.033	0.001	0.009	-0.004*	0.041*	-0.010***
	(0.007)	(0.008)	(0.006)	(0.007)	(0.022)	(0.013)	(0.020)	(0.002)	(0.024)	(0.004)
$\Delta yg \times LO \times ROAD \times WINTER$	0.001	-0.015	0.026	-0.012	0.046**	-0.031	-0.018	0.003	-0.011	0.013***
	(0.010)	(0.012)	(0.016)	(0.017)	(0.021)	(0.035)	(0.030)	(0.003)	(0.038)	(0.003)
Observations	43525	43525	43525	43525	43524	40979	40979	40979	40978	40978

Notes: Cereals include rice, wheat, millets, sorghum, and maize. All specifications are estimated with inverse probability weighting (IPW) and control for the seasonally differenced log change in household size, the change in log per capita consumption expenditure, and village time trends. yg and ym denote seasonally differenced log per person household production of cereals and milk, respectively. LO is a dummy indicating farm households operating greater than 2 hectares of land in the baseline. $ROAD$ captures new or upgraded rural road construction under the $PMGSY$. $WINTER$ is a dummy variable that takes values 1 for October through March. Figures in parentheses are standard errors robust to the intra-village correlation of residuals. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table A8: Milk production shocks, transfers, transactions and other income streams

	Gifts		Loans		Land		Savings		Durables		
	(1) Given	(2) Recieved	(3) Taken	(4) Paid	(5) Purchased	(6) Sold	(7) Deposits	(8) Withdraw	(9) Purchased	(10) Sold	(11) Earned
Δy	-0.055	0.011	-0.051*	0.003	0.003	-0.000	0.027*	-0.013*	0.005	-0.000	-0.022
	(0.036)	(0.033)	(0.027)	(0.022)	(0.003)	(0.002)	(0.013)	(0.007)	(0.014)	(0.003)	(0.020)
$\Delta y \times LO$	0.065	0.033	0.036	-0.014	-0.003	-0.010	-0.033	0.008	0.006	-0.003	0.002
	(0.039)	(0.034)	(0.038)	(0.056)	(0.007)	(0.009)	(0.031)	(0.013)	(0.025)	(0.007)	(0.042)
$\Delta y \times NROAD$	0.034	-0.036	-0.161	-0.018	-0.001	0.000	0.015	0.041*	0.013	0.000	-0.004
	(0.038)	(0.037)	(0.100)	(0.028)	(0.003)	(0.002)	(0.024)	(0.023)	(0.042)	(0.002)	(0.101)
$\Delta y \times WINTER$	0.056	0.004	-0.001	0.007	-0.006*	-0.000	-0.027	0.012	-0.010	-0.001	0.030
	(0.050)	(0.035)	(0.031)	(0.030)	(0.003)	(0.002)	(0.020)	(0.008)	(0.022)	(0.002)	(0.028)
$\Delta y \times LO \times NROAD$	0.128	0.288*	0.124**	0.440***	-0.000	-0.007	-0.002	-0.037	0.081	-0.001	0.154
	(0.079)	(0.143)	(0.055)	(0.075)	(0.007)	(0.011)	(0.147)	(0.025)	(0.087)	(0.008)	(0.150)
$\Delta y \times LO \times WINTER$	-0.072	-0.065	-0.029	-0.020	-0.009	-0.002	0.002	0.000	0.010	0.014*	-0.081*
	(0.060)	(0.049)	(0.041)	(0.051)	(0.010)	(0.012)	(0.040)	(0.019)	(0.034)	(0.007)	(0.047)
$\Delta y \times LO \times NROAD \times WINTER$	-0.119	-0.081	0.036	-0.370**	0.013	0.002	-0.029	0.017	-0.100	-0.010	0.016
	(0.103)	(0.131)	(0.051)	(0.163)	(0.009)	(0.011)	(0.061)	(0.019)	(0.165)	(0.007)	(0.194)
Observations	62590	62590	62590	62590	62590	62590	62590	62590	62590	62590	62590

Notes: All dependent variables are seasonally differenced log per capita transactions. Δy denotes seasonally differenced log per person household production of milk. LO is an indicator to denote households with greater than 2 hectares of operated area in the baseline. $NROAD$ captures new rural road construction under the $PMGSY$. $WINTER$ is a dummy variable that takes values 1 for October through March. All regressions include the change in household size and the change in log consumption per member as control variables. Figures in parentheses are standard errors robust to the intra-village correlation of residuals. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table A9: Cereal production shocks, transfers, transactions and other income streams

	Gifts		Loans		Land		Savings		Durables		
	(1) Given	(2) Recieved	(3) Taken	(4) Paid	(5) Purchased	(6) Sold	(7) Deposits	(8) Withdraw	(9) Purchased	(10) Sold	(11) Earned
Δy	-0.003	-0.060	-0.038	-0.018	0.003	-0.004	-0.037	-0.013	0.051	0.001	-0.005
	(0.034)	(0.049)	(0.026)	(0.027)	(0.005)	(0.003)	(0.025)	(0.014)	(0.032)	(0.001)	(0.016)
$\Delta y \times LO$	0.010	0.032	0.075***	0.026	0.006	0.001	0.021	0.007	-0.059	-0.009	0.011
	(0.027)	(0.046)	(0.025)	(0.041)	(0.012)	(0.009)	(0.030)	(0.014)	(0.035)	(0.006)	(0.026)
$\Delta y \times NROAD$	-0.034*	-0.086***	0.004	-0.061***	0.006**	0.002	0.011	-0.014	0.070**	-0.002	0.009
	(0.018)	(0.020)	(0.014)	(0.021)	(0.002)	(0.002)	(0.016)	(0.010)	(0.026)	(0.001)	(0.022)
$\Delta y \times WINTER$	0.019	0.103*	0.040	0.059*	-0.012**	0.002	0.051*	0.015	-0.048	0.001	-0.005
	(0.033)	(0.060)	(0.033)	(0.033)	(0.006)	(0.004)	(0.028)	(0.016)	(0.040)	(0.001)	(0.015)
$\Delta y \times LO \times NROAD$	-0.007	0.059	-0.109**	-0.048	-0.014	0.091	-0.011	0.023*	0.093	0.011*	-0.116***
	(0.028)	(0.072)	(0.052)	(0.122)	(0.010)	(0.106)	(0.046)	(0.013)	(0.073)	(0.006)	(0.033)
$\Delta y \times LO \times WINTER$	-0.009	-0.087	-0.072	-0.069	0.012	-0.001	-0.014	0.003	0.061	0.008	0.004
	(0.035)	(0.060)	(0.044)	(0.047)	(0.014)	(0.012)	(0.029)	(0.026)	(0.044)	(0.007)	(0.028)
$\Delta y \times LO \times NROAD \times WINTER$	-0.063	0.013	0.168***	0.198	-0.001	-0.076	-0.083	-0.023	-0.167***	-0.019**	0.155***
	(0.068)	(0.098)	(0.050)	(0.157)	(0.011)	(0.114)	(0.095)	(0.023)	(0.054)	(0.009)	(0.040)
Observations	62590	62590	62590	62590	62590	62590	62590	62590	62590	62590	62590

Notes: All dependent variables are seasonally differenced log per capita transactions. Δy denotes seasonally differenced log per person household production of cereals. LO is an indicator to denote households with greater than 2 hectares of operated area in the baseline. $NROAD$ captures new rural road construction under the $PMGSY$. $WINTER$ is a dummy variable that takes values 1 for October through March. All regressions include the change in household size and the change in log consumption per member as control variables. Figures in parentheses are standard errors robust to the intra-village correlation of residuals. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.