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Regular Article

Demand, supply and long-term adoption: Evidence from a storage technology in West Africa☆

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ABSTRACT

Most research on technology adoption focuses on the demand side, emphasizing the role of information provision, financial incentives and nudges. Yet supply plays a critical and oft-overlooked role in facilitating the take-up of new technologies. We study the supply- and demand-side factors affecting the adoption of an improved storage technology (hermetically-sealed bags, or PICS) in Niger, which was introduced and freely distributed in West Africa in the late 2000s. Using surveys, survey experiments and a willingness-to-pay (WTP) experiment with farmers and traders, we find that PICS bags are largely profitable for small-scale farmers as compared to traditional storage technologies. Yet a majority of farmers and traders do not store in PICS bags, and average WTP is approximately 50% of the market price. There is also significant regional variation in adoption and WTP, which cannot be fully explained by differences in production or storage patterns. We find that these adoption patterns are not primarily explained by information frictions or liquidity constraints. While there is some evidence of behavioral barriers to adoption, we posit that the main explanation of these distinct equilibria is variation in supply, driven by a market structure introduced over a decade ago.

Agricultural productivity growth is an important driver of structural transformation and economic growth (Gollin et al., 2002), but has been hampered by the low adoption of modern inputs and improved practices (Emerick et al., 2016). Recognizing this, billions of dollars have been spent on developing and promoting inputs that improve soil quality (such as fertilizers) or reduce exposure to climatic risks (such as seeds). There has been less focus on inputs that reduce insect-related depreciation during storage, which increase the effective crop yield that is available to farmers for consumption or sale. While official estimates suggest that average post-harvest losses in sub-Saharan Africa are between 8 and 12%, this masks substantial heterogeneity by crop and region (FAO 2011, APHLIS). In West Africa, for example, 25 percent of cowpeas – the primary cash crop – are destroyed by the cowpea weevil (Jackai and Daoust 1986; Murdock et al., 1997).

Farmers in West Africa have traditionally used a variety of storage technologies to deal with these pests, including underground pits, airtight earthen mounds and drums and insecticides (Murdock and Baoua, 2014). Cowpea traders use many of the same techniques, and many traders sell storage inputs alongside the crop that they buy and sell. While these techniques can be effective in reducing storage losses, they have drawbacks: Airtight containers are heavy and hard to transport, and insecticides are associated with negative impacts on health outcomes (Fernandez-Cornejo et al., 1998; Sheahan et al., 2017). A newer approach to post-harvest protection is hermetic storage in bags, whereby oxygen barriers limit the growth of insects or microbes (Masters and Alvarez 2018). Recent hermetic storage technologies are triple-layer bags that suffocate weevils without insecticides. Agronomic and economic randomized control trials (RCTs) show that hermetically-sealed bags are effective in minimizing storage losses, decreasing the rate of pest infestations and increasing the duration of storage (Bakoye et al., 2020; Omotilewa et al., 2018; Channa et al., 2018).

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Strategies to increase the take-up of new technologies often involve information provision, financial incentives, and nudges (Dupas et al., 2021; Shukla et al., 2020). This is also the case for hermetic storage: Since 2007, thousands of hermetically sealed bags (the Purdue Improved Crop Storage bags, or PICS) have been freely distributed throughout West Africa, and demonstrations have been conducted in over 31,000 villages (Murdock et al., 2012). Despite these promotional efforts, PICS adoption in West Africa is estimated at only 17% (Bokar et al., 2014). Studies from the early years of PICS roll-out suggested that there was significant heterogeneity in uptake between and within cowpea-producing countries (Moussa et al., 2011; Baoua et al., 2012). Why does adoption remain so low? And what explains these regional variations in adoption?

We study these issues in the context of the cowpea sector in Niger, focusing on PICS bags. While decades of research shows that information and liquidity constraints are important barriers to adoption (Foster and Rosenzweig 2010), supply plays a critical and oft-overlooked role in facilitating take-up. As a result, we focus on both demand-side and supply-side determinants of technology adoption in our analysis.

Our empirical analysis proceeds in three steps. First, using survey data from farmers and traders across three different regions of Niger, we collect information about storage practices and beliefs. In particular, we measure farmers' and traders' expected storage losses under various storage scenarios, as well as traders' beliefs about demand and supply on local markets. Second, we experimentally measure farmers' and traders' willingness-to-pay (WTP) for PICS bags using a variant of the Becker-DeGroot-Marschak (BDM) mechanism (Becker et al., 1964). Finally, we conduct a survey experiment to test the hypothesis that the higher nominal price of PICS bags may be overly weighted in the demand decision. In particular, we randomly assigned a sample of farmers to an informational intervention designed to increase the salience of the relative price of PICS prior to eliciting their WTP.

We find that PICS bags are largely profitable for small-scale farmers as compared to traditional storage technologies, even in the short-term. Yet, a majority of farmers and traders do not store in PICS bags, with farmers' adoption ranging from 4% to 49% across regions. This geographical variation in adoption is also mirrored in WTP: average WTP is approximately 50% of the market price for PICS bags, with significant heterogeneity by region. This heterogeneity persists after controlling for a number of covariates. Yet despite this variation in demand, farmers appear to value the technology: We find those who won the bags via the WTP game still use them one year later, storing approximately 50% more cowpea. There is no correlation between the bid price, the randomly drawn price and usage.

We address a number of potential explanations for this puzzle. On the demand side, we find that simple information constraints are not the primary drivers of variation in PICS adoption, as 70% of farmers and 98% of traders have heard about PICS bags. In addition, a majority of farmers and traders believe that PICS bags offer the best protection against storage losses and have accurate beliefs about their effectiveness. Low adoption also does not seem to be driven by farmers' liquidity constraints, as the average total expenditure on traditional storage technologies is equivalent to (or greater than) that of PICS bags. Yet this fact does not seem to be "top of mind" for many farmers: When we experimentally increase the salience of recent expenditures on traditional storage methods, willingness-to-pay for PICS increases by 18–21%. Thus, while salience clearly plays a role in reducing overall demand for PICS, it does not appear to explain the regional variation in adoption.

On the supply side, we find that traders have broadly accurate beliefs about farmers' demand for PICS, and that PICS are more readily available in the high adoption region. Yet, traders appear to face liquidity and supply-chain constraints in purchasing and stocking PICS bags: Almost half of all traders only purchase in cash, and 15–25% report not knowing suppliers. This situation is, in part, due to the market structure established when PICS first entered Niger. The high-usage, high-supply region is located in an area where an exclusive importer had rights over a 10-year period (Moussa et al., 2014; Coulibaly et al., 2012), which limited distribution in other regions. Although the market liberalized in 2017, spatial differences in private sector incentives are correlated with persistent differences in the market structure and hence adoption.

Our analysis adds to an active economics literature in the area of technology adoption. In the seminal work on agricultural technology adoption, Griliches (1957) examines the diffusion of hybrid corn seeds across regions of the US during the first half of the 20th century, focusing on the interplay between supply and demand. Since then, most studies of technology adoption in lower-income countries have focused on demand-side factors, including learning about a new technology (Foster and Rosenzweig, 1995, 1996; Conley and Udry, 2010; Suri, 2011), the role of social networks (Conley and Udry, 2001; Bandiera and Rasul, 2006; Matuschke and Qaim, 2009; Maertens and Barrett, 2012; Beaman et al., 2020) and the role of subsidies in addressing externalities and credit constraints (Dupas 2014; Cohen and Dupas 2010; Foster and Rosenzweig 2010). While there is significant literature on the market for new goods that focus on the behavior of suppliers (Romer (1994), Bresnahan and Gordon, 2008) to our knowledge, there are few papers that attempt to analyze both the demand and supply-side constraints to adoption and market emergence. Recently, Dar et al. (2021) show that providing information to private input suppliers can be an important driver of farmers' seed adoption in India, whereas Omotilewa et al. (2019) find that providing a one-time subsidy to farmers can crowd-in commercial demand for an improved grain storage bag in Uganda, while highlighting the role of supply-side constraints.

Our findings also speak to the literature on storage and welfare outcomes in sub-Saharan Africa. A number of recent papers have examined the tendency of some farmers to "sell low" and "buy high" because of storage and financing constraints (Stephens and Barrett 2011; Dillon 2020), as well as a number of interventions designed to address farmers' joint storage and credit problems (Coulter and Shepherd 1995; Basu and Wong 2015; Casaburi et al., 2014; Aggarwal et al., 2018; Burke et al., 2019). Omotilewa et al. (2018) assessed the impact of PICS bags on input use and food security amongst maize farmers by distributing these bags for free. By focusing on the adoption of a storage technology for a highly perishable commodity in Sahelian West Africa, we are able to provide additional insights into its impacts upon well-being. Revealed preference evidence of welfare gains for farmers comes from the fact that those who win the chance to buy a PICS bag in the BDM game continue to use the bags one year later, and increase the quantity of stored cowpeas.

Finally, we contribute to the literature on the elicitation and use of WTP measures in assessing demand for a new technology (Berry et al., 2020; Aker et al., 2020; Hidrobo et al., 2020). We find that, while behavioral experiments could potentially increase consumers' adoption and WTP for PICS, this would still not be sufficient to reach the market price, thereby suggesting that supply-side interventions may be needed.

The rest of this paper proceeds as follows. In Section 2 we discuss the setting in Niger. In Section 3 we describe the sample data, and in In Section 4 we present our findings. In Sections 5 and 6 we discuss the potential explanations for low and variable adoption of PICS. Section 7 concludes.

1. Setting

1.1. Cowpea production and marketing

Cowpeas are the primary cash crop for over 80 percent of households in Sahelian West Africa, with Nigeria and Niger amongst the largest cowpea producers in the world (IATA, 2018). The crop is highly susceptible to the cowpea weevil, an insect that destroys 25–30 percent of output during storage, making it a semi-perishable commodity (Jackai and Daoust, 1986; Murdock et al., 1997). In Niger, farmers and traders have typically used double-woven bags, with or without insecticides, to store cowpea (Moussa et al., 2011). While hermetically sealed, chemical-free bags (such as PICS or GrainPro bags) have proven agronomic success in minimizing storage losses, previous work suggests that adoption rates of such bags range considerably by country and by region (Moussa et al., 2014).

With only one growing season per year, cowpea markets tend to exhibit a marked degree of seasonality in prices. In Niger, the intra-annual price fluctuation of cowpea ranges from 20 to 60% (Fig. 1). Cowpeas are traded on a system of weekly markets, which range in size from 20 to 300 traders (Aker et al., 2020). A wide range of trader types participate in cowpea markets, including retailers, intermediaries and wholesalers. Traders may travel to farmers' villages to purchase output directly, or purchase at the markets.

Despite the potential for farmers to engage in inter-temporal arbitrage, data from previous studies suggests that 78% of Nigerien farmers sell a significant portion of their cowpea production in the 1–2 months immediately after the harvest (authors' calculations). As a result, a majority of households fully deplete their stocks and purchase cowpea later in the year. This translates into an average loss of US$ 80 per year, or 50–65% of average total revenue from cowpea sales. If farmers expect to store cowpeas for any period of time, they must use improved storage technologies, such as hermetic storage or insecticides, in order to avoid catastrophic crop losses.

This study focuses on three major cowpea-producing regions in Niger: Dosso, Maradi and Zinder (Fig. 2). All three regions are located in the Sahelian band, with an average of 300 mm of rainfall per year.[1] Dosso is approximately 250 km from the capital city, with Maradi and Zinder located farther east (650 and 850 km, respectively). Population density varies by region, with the highest population density in Maradi (89 individuals/km^2), followed by Dosso (67/km^2) and Zinder (24/km^2). Yet these averages mask significant intra-regional heterogeneity in population density. Households in these regions are primarily from the Hausa ethnic group, and rely upon agriculture, livestock and migration for their livelihoods. All three regions border Nigeria, the primary destination market for cowpea sales. Market density varies slightly by region, with an estimated 1040 markets in Dosso, 935 in Maradi and 830 in Zinder (SIMA, 2010).[2]

1.2. The PICS technology

Building on technologies developed in Cameroon in the late 1980s and 1990s, researchers at Purdue University developed PICS, an improved storage technology.[3] The key innovation of the hermetically-sealed bags (such as PICS) is in the triple layer of plastic bags, which induces hypoxia in the pests and ends their reproductive cycle. If used correctly, PICS bags are highly effective at eliminating losses due to the cowpea weevil without insecticides, and can last for three (or more) years if used properly. The bags were initially introduced across West Africa in the mid-2000s and were freely distributed by governmental and non-governmental organizations (NGOs) (Moussa et al., 2011). Between 2007 and 2010, PICS bag demonstrations occurred in over 31,000 villages across the region, along with a widespread radio and media campaign. By 2016, the average cost for the bag was US$ 1.60 for a 100-kg bag, as compared with US$.50 for a traditional woven bag. Storing in traditional bags also requires purchasing plastic inserts or pesticides on an annual basis, and it is unclear whether these bags can last three seasons.

Coinciding with the free distribution and information campaigns was a series of efforts to ensure the supply of PICS bags via the private sector. This initially involved the establishment of regional manufacturers of PICS bags in Burkina Faso and Nigeria, as well as financing bag orders until 2010. Between 2007 and 2016, the bags were commercially imported under an exclusive import license by a national distributor in Niger, who had informal contacts in one region (Dosso) (Coulibaly et al., 2012) and developed a distribution network of five regional wholesalers, 61 semi-wholesalers and retailers. This initial import restriction created a supply chain with relatively thicker markets in Dosso as compared to other regions (Coulibaly et al., 2012). In 2014, for example, licensed PICS distributors sold about 98,500 bags, with an estimated 80,000 PICS bags imported informally from Nigeria. The market was opened to other importers in 2017.

2. Sample and data

The data for this paper are from farmer and trader surveys in the regions of Dosso, Maradi and Zinder. The farmer surveys are used to document patterns of cowpea production, storage and sales, as well as assess their demand for using improved storage technologies. The trader surveys provide insights into traders' storage and sales patterns, as well as their use of improved storage technologies and willingness to sell them. Collectively, these surveys are designed to measure spatial variation in PICS demand and adoption, as well as collect data on factors that might help explain variation in adoption, such as cowpea production, storage practices, and beliefs about the relative effectiveness of PICS. The type and timing of each survey, along with the number of observations, is provided in Table 1.

2.1. Farmer survey

Farmers were selected from amongst participants in a series of randomized control trials (RCTs) on the impact of adult education interventions in each of the three regions. None of these prior studies were related to agriculture or storage technologies. Out of a population of 300 villages, we stratified by geography and prior treatment status to randomly select 63 villages for our sample.[4] In each village we attempted to survey all previous respondents, who had been stratified by gender, for a total of 918 intended respondents.[5] We successfully interviewed 91% of targeted respondents, for a total sample of 839 farmers (528 women, 311 men).

The farmer surveys took place in September 2016, at the beginning of the cowpea harvest. The survey asked questions about cowpea production, storage, and knowledge of and experience with PICS bags. Enumerators also elicited farmers' subjective expectations about the depreciation rates for different storage technologies, and used a variant of the Becker-DeGroot-Marschak (BDM) mechanism to measure farmers' maximum WTP for a PICS bag. The detailed description of both methodologies is included below. While average WTP may be lower before harvest, when farmers are credit-constrained, any such effect is constant across regions. The surveys were timed to ensure that questions

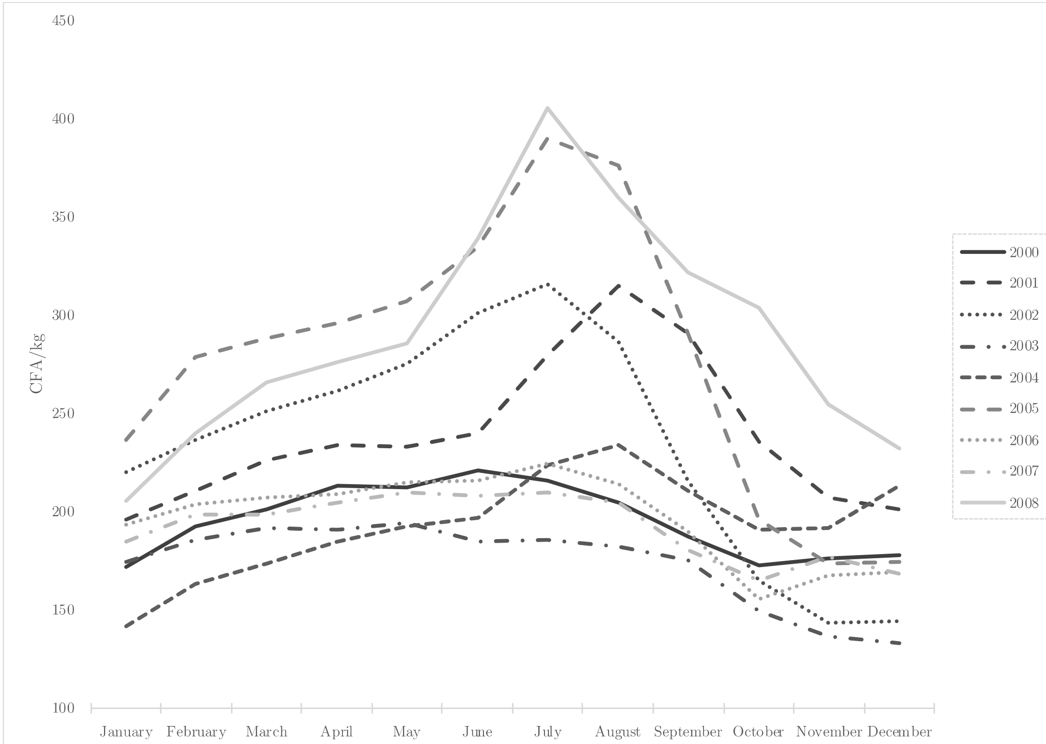
[1] In the extreme southern part of Dosso, average annual rainfall can be 600 mm, and farmers grow maize and cassava. None of our study villages are located in the extreme south.

[2] The *Systeme d'Information sur le Marche Agricole* (SIMA) conducted a census of all markets in Niger in 2010, with a total of 32,000 markets nationally. As new markets are rarely created, and few markets close, this census is a valid proxy for market density in 2016, the time of our study.

[3] "PICS bags are composed of an outer layer of ordinary woven polypropylene and two inner liners of high-density polyethylene (HDPE), 80 μm thick" (Baributsa et al., 2014). Other types of hermetic storage bags available in sub-Saharan Africa are GrainPro, ZeroFly bags, AgroZ bags and Elite Storage Bags (Masters and Alvarez 2018).

[4] Previous treatment status included any adult education program or none, and, within adult education villages, whether they participated in a mobile phone-enhanced curriculum (ABC).

[5] The original sample differed slightly by region, with 16 respondents per village (8 women and 8 men) in Dosso, and 15 respondents per village (10 women and 5 men) in Maradi and Zinder. We used this original sample in our study.



Notes: This figure shows the average monthly consumer cowpea prices (in CFA/kg) by year.

Fig. 1. Monthly Cowpea Prices in Niger, 2000-2008
Notes: This figure shows the average monthly consumer cowpea prices (in CFA/kg) by year.

regarding storage were "top of mind" for farmers.

We conducted a follow-up survey with a subset of 460 farmers across 30 villages in 2017, approximately one year later. Similar to the original sample, we stratified the 63 villages by region and treatment status before randomly choosing 10 villages per region. The survey asked questions about farmers' cowpea production, storage and marketing, as well as PICS adoption and usage. We use these data to assess changes in PICS adoption and cowpea storage over time.

2.2. *Trader survey*

During the farmer survey, respondents were asked for the names of markets where they bought and sold cowpeas, as well as where they purchased their storage technologies. Farmers identified approximately 45 markets in each region. From among these, we stratified by sub-region and selected 10 markets per region that were most-often cited, for a total sample of 30 markets.[6] Within each market, the survey team conducted a census of all cowpea traders and bag vendors. Traders were stratified by type (wholesaler, intermediary/retailer and bag seller) and approximately 10 traders were selected per market, for a total sample of 303 traders. Given the potentially different storage and sales behavior of cowpea traders and bag sellers, we control for whether the trader was a bag seller in our trader-level regressions.

The trader survey took place in November and December 2016, immediately after the annual cowpea harvest. Because traders are both potential sellers and users of PICS bags, we asked all traders a series of questions about their primary trading activities, purchase and sales markets, and the use and sales of cowpea storage technologies (including PICS). Similar to the farmer survey, we also asked about their beliefs about cowpea storage depreciation, as well as WTP for PICS bags.

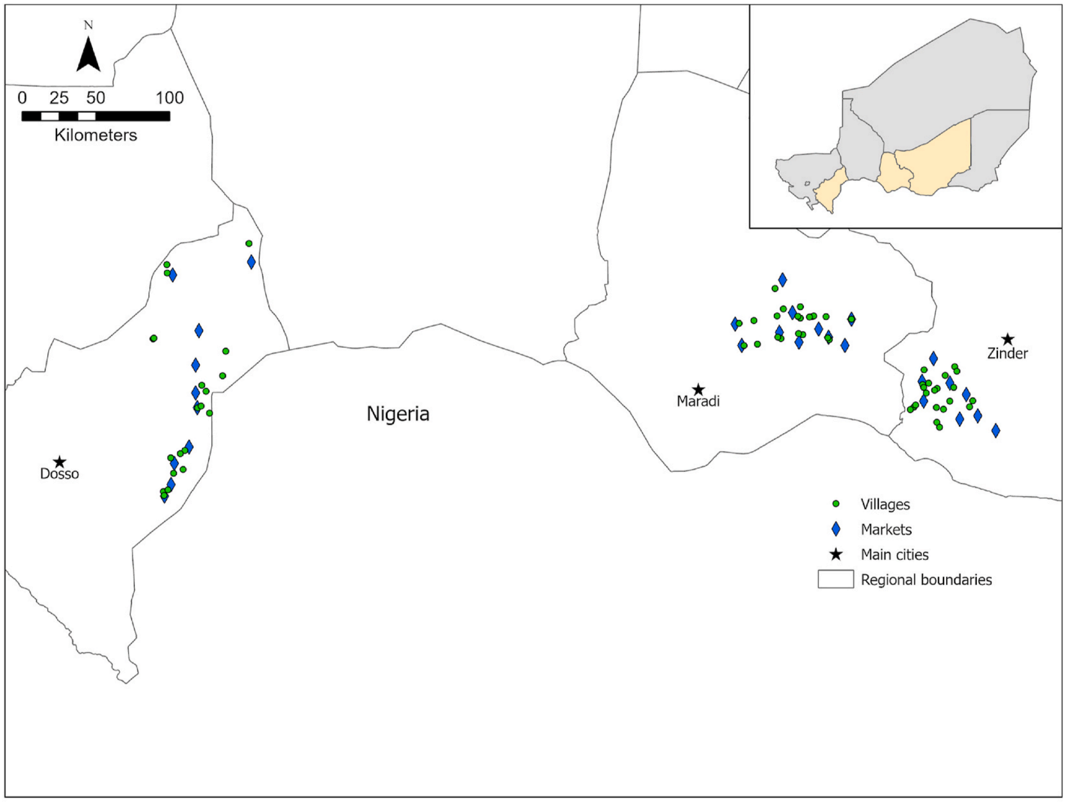
To measure traders' beliefs about demand for PICS, we presented each trader with a series of hypothetical scenarios. In each scenario we asked the respondent to imagine that he/she had 100 PICS bags to sell that day in the market where the interview was taking place. We then asked, "How many bags do you expect you would sell at price *P*," where *P* ranged from 20 to 125% of the average market price. The responses to these questions trace out each traders' beliefs about the demand curve in that market-day.[7] This is separate from the elicitation of traders' demand for PICS, which we present below.

2.3. *Willingness-to-pay experiment*

Elicitation of WTP for both farmers and traders took the form of a two-stage, incentive compatible BDM. In eliciting WTP from traders – rather than willingness-to-accept - we focused on their contribution to the demand side of the PICS market. While some respondents may have conditioned their WTP on the possibility of re-selling the bags, any such

[6] Rather than take a random sample of markets within the region, we conditioned the selection upon markets frequented by farmers for cowpea purchases or sales, in order to increase the likelihood of finding cowpea traders and bag sellers. Thus, some smaller and more remote markets may be under-represented in our sample.

[7] Price options for this exercise were chosen based on the observed market prices of each technology, ranging from 200, 250 and 300 CFA for traditional bags and from 750, 1000 and 1250 for PICS bags. Table 8 shows farmers' and traders' mean purchase prices and traders' sales prices for both traditional and PICS bags. We note that these prices are stated preferences, not revealed preferences, and hence not incentive compatible.



Notes: Each dot shows the location of a village in each region, with 21 villages and 10 markets per region, for a total of 63 villages and 30 markets.

Fig. 2. Map of Survey Regions
Notes: Each dot shows the location of a village in each region, with 21 villages and 10 markets per region, for a total of 63 villages and 30 markets.

Table 1
Survey overview.

Survey Round	Dates	Observations
Farmer Survey	09/16	918
Trader Survey	Nov–Dec 2016	303
Farmer Survey	08/17	460

Notes: Each number is the total sample size of found households by survey round. See text for additional detail.

effects would also be present outside of the experimental demand elicitation, and hence are important to capture. During our follow-up survey with a subset of respondents one year later, 77% of farmers still had the PICS bag in the following year, and only 2% had sold it.

After presenting the respondent with a PICS bag, outlining its attributes, and explaining the game, the individual was able to inspect the bag. The enumerator then revealed a sequence of hypothetical prices, ranging from 10 CFA to 5000 CFA.[8] For each price, the respondent was asked to indicate whether he or she would be willing to pay that amount, on that day, to purchase the bag. Once the respondent provided a Yes/No answer for all prices, the enumerator confirmed the highest price that the respondent was willing to pay that day. During the second stage, a price was randomly drawn from those on the list. If the respondent's maximum WTP was greater than or equal to the drawn price, a PICS bag was sold to the respondent at the drawn price. Otherwise, no sale took place. This "spot" transaction had to be completed before the team left the village that day, after a small "cooling off" period (ie, they had 1–2 h, which would have also allowed the respondent to borrow money if needed). In practice, less than 1% of respondents did not pay the drawn price if they won. No participation fee was provided.

For a respondent who fully understands the game and has no deceptive intentions, this mechanism reveals the interval containing the maximum WTP. Aggregating WTP data across respondents provides a lower bound estimate of the demand at each price.[9] This interval-identified design leads to a slight coarsening of demand curve estimates relative to a design with open-ended responses for WTP. We accepted this tradeoff because the open-ended BDM design led to greater confusion and more degenerate responses when piloted in a similar

[8] The prices used for this exercise were: 10, 250, 400, 500, 600, 750, 900, 1000, 1100, 1250, 1400 and 5000 CFA, with the highest and lowest prices meant to provide the *X* and *Y* intercepts, respectively. While the lowest price offered should have been 0 CFA, several pilots suggested that respondents felt uncomfortable with a "free" (0″) price, and so 10 CFA was used. 98% of respondents were willing to pay 10 CFA, suggesting that the non-zero price is not a primary concern.

[9] Whenever the respondent's true maximum WTP lies between two of the price options, he or she will choose the lower option, leading us to weakly underestimate maximum WTP and demand.

Table 2
Farmer summary sample.

	All Mean (s.d.)	Dosso Mean (s.d.)	Maradi Mean (s.d.)	Zinder Mean (s.d.)	N
Panel A (Socio-Demographic)					
Female (=1)	.63 (.48)	.53 (.5)	.69 (.46)	.68 (.47)	839
Age in years	39 (13)	44 (13)	41 (12)	35 (11)	839
Household owns cell phone (=1)	.31 (.46)	.41 (.49)	.25 (.43)	.24 (.42)	839
Panel B (Cowpea Production and Storage)					
Household harvested cowpea (=1)	.96 (.2)	.97 (.18)	1 (0)	.92 (.28)	839
Quantity of cowpea harvested (kg), unconditional	160 (206)	241 (251)	179 (199)	74 (90)	839
Sold cowpea after 2015–2016 harvest (=1), unconditional	.74 (.44)	.77 (.42)	.92 (.29)	.55 (.5)	805
Bought cowpea after 2015–2016 harvest (=1)	.59 (.49)	.53 (.5)	.46 (.5)	.74 (.43)	839
Household stored cowpea (=1), unconditional	.82 (.38)	.81 (.39)	.92 (.37)	.73 (.47)	918
Quantity (kg) of cowpea stored, unconditional	76 (118)	117 (148)	86 (116)	35 (49)	839
Household stored cowpea for more than 6 months	.77 (.42)	.76 (.43)	.82 (.4)	.75 (.44)	691
Share of cowpea lost in post-harvest storage	.08 (.18)	.06 (.15)	.06 (.15)	.12 (.19)	689
Panel C (Types of Storage)					
Stored in Traditional bags	.40 (.49)	.27 (.45)	.66 (.44)	.23 (.42)	691
Stored in PICS bags	.22 (.42)	.49 (.50)	.13 (.33)	.04 (.18)	691
Stored in Plastic Jugs	.5 (.5)	.44 (.50)	.30 (.46)	.79 (.40)	691
Total amount (CFA) spent on cowpea storage per 100 kg	3721 (6409)	3354 (6409)	2567 (5513)	5169 (7133)	691
Amount (CFA) spent per 100 kg for storing only in normal bag	1448 (1599)	1127 (1153)	1306 (1369)	1864 (2593)	192
Amount (CFA) spent per 100 kg for storing only in a PICS bag	1795 (1823)	1657 (1521)	2237 (2488)	1612 (2027)	124
Amount (CFA) spent per 100 kg for storing only in plastic jugs	5814 (6919)	4967 (4922)	5163 (6095)	6271 (7909)	264
Panel D (PICS Storage)					
Respondent has heard about PICS bag	.69 (.46)	.96 (.20)	.65 (.49)	.52 (.5)	838
Respondent had used PICS bag at some point	.27 (.45)	.57 (.50)	.18 (.38)	.07 (.23)	838
Price per PICS bag paid	1067 (277)	1100 (270)	926 (292)	1006 (0)	143
WTP for PICS bags	564 (376)	745 (366)	503 (366)	430 (321)	828

Column 1 shows the mean and s.d. for the entire farmer sample. Columns 2–4 show the means and s.d. for the farmer sample each region.

setting.[10]

2.4. Elicitation of subjective expectations

In an effort to better understand farmers' and traders' perceptions of the depreciation rates of different storage technologies, we used a standardized set of questions to elicit subjective expectations about cowpea losses over a 9-month period. In particular, respondents were presented with the following scenario: "Suppose that you have 10 tia (25 kg) of cowpea to store at harvest time. Using technology *X*, what quantity of cowpea do you expect will survive until the cold season (which is roughly 3 months later)? What quantity will survive until the hot season (6 months)? And what quantity will survive until the rainy season (9 months)?" We asked these questions three times, for the following choices of *X*: traditional bags only, traditional bags with the addition of pesticides or plastic inserts, and PICS bags.

2.5. Behavioral experiment

A recent line of literature has explored the role of attribute salience as an influence on WTP and uptake (Bordalo et al., 2013; Gabaix 2014; Karlan et al., 2016). The central idea in that literature is that certain product attributes may be more salient than others at the time of purchase, such that the more salient attributes receive greater weight in the purchasing decision. As a result, nudging consumers to consider otherwise less salient attributes can increase the adoption of profitable technologies (Karlan et al., 2016). PICS bags are more expensive to purchase than traditional bags, although they can be more cost effective overall because they last longer and do not require complementary inputs. If the higher PICS sticker price is more salient than the total per kg storage cost at the time of purchase, farmers' demand for PICS may be lower than it would be upon full consideration of all attributes.

To determine whether price salience affects demand for PICS bags, we randomly assigned a subset of farmers to an information treatment. The sample of farmers was first stratified by village and gender before randomly assigning approximately 1/8th to the treatment and the rest to the control.[11] For treated farmers, the enumerator provided individualized information about the total value of self-reported storage costs that the respondent had incurred over the previous three years (the expected useful life of a PICS bag). This information was calculated on the spot, using the farmers' responses to previous survey questions. For farmers that used traditional storage methods, the three-year total cost of storage inputs is a more appropriate comparison with the PICS bag price than is the market price of a traditional woven bag.[12] The information treatment was provided immediately prior to the WTP elicitation.

3. Results: adoption of and WTP for improved storage technologies

In this section, we present survey evidence on farmers' and traders' cowpea storage practices (Sections 4.1. and 4.2), with Section 4.3.

[10] We considered a number of methodologies when determining WTP, knowing that the valuation can be sensitive to the method chosen. While BDM can be complex, TIOLI can be "unusual in environments where fixed, posted prices are rare and bargaining common", as is the case in our context (Berry et al., 2020). Berry et al. (2020) find that demand is lower under BDM than TIOLI, but that the difference is small in magnitude. This may suggest that our estimates are lower bounds.

[11] Given the fixed sample size, we conducted power calculations to estimate the optimal treatment allocation, while at the same time ensuring that we had a sufficient sample to measure WTP in the control group.

[12] The information treatment also changed the example price used to demonstrate the BDM elicitation method from 250 CFA to 900 CFA, both of which are below the market price of PICS in all locations. While we cannot distinguish the effects of this anchoring treatment from those of the cost summary treatment, both relate to the role of salience and priming. We place more stock in the cost summary treatment, because it was more overt, and was tailored to each respondent based on their prior answers.

Table 3
Trader summary sample.

	All Mean (s.d.)	Dosso Mean (s.d.)	Maradi Mean (s.d.)	Zinder Mean (s.d.)	N
Panel A (Socio-Demographic)					
Age in years	48 (13)	52 (13)	46 (13)	46 (11)	303
Trading is principal occupation (=1)	.98 (.13)	.99 (.1)	1 (0)	.96 (.2)	303
No. of years as trader	17 (11)	18 (12)	15 (10)	18 (9.8)	303
Total markets	4.2 (1.8)	4.5 (1.9)	3.7 (1.8)	4.5 (1.7)	303
Trader has paid employees (=1)	.77 (.42)	.73 (.45)	.81 (.39)	.77 (.42)	303
No. of employees	3.1 (3.7)	3.2 (2.1)	3.3 (5.7)	2.8 (1.7)	234
Panel B (Production and Storage)					
Trader sells any cowpea storage products	.46 (.5)	.42 (.5)	.4 (.49)	.55 (.5)	303
Trader sold cowpea (=1)	.77 (.42)	.75 (.44)	.82 (.38)	.74 (.44)	303
Trader bought and sold cowpea since last harvest (=1)	.77 (.42)	.76 (.43)	.82 (.38)	.74 (.44)	303
Trader has stored cowpea (=1)	.93 (.26)	.89 (.31)	.93 (.26)	.96 (.2)	234
Quantity of cowpea trader currently has in stock (in kg)	2815 (5330)	2639 (4038)	3055 (6241)	2730 (5446)	234
Trader lost cowpea to weevils (=1)	.16 (.37)	.1 (.31)	.12 (.32)	.26 (.44)	217
Trader lost cowpea to rats (=1)	.12 (.33)	.16 (.37)	.052 (.22)	.17 (.38)	217
Panel C (Types of Storage)					
Cowpea stored in Normal bag (=1)	.73 (.44)	.4 (.49)	.97 (.16)	.79 (.41)	217
Trader stored in PICS (=1)	.36 (.48)	.81 (.4)	.13 (.34)	.18 (.39)	217
Cowpea stored in Jug (=1)	.21 (.41)	.18 (.38)	.091 (.29)	.38 (.49)	217
Total storage costs since the previous harvest (CFA)	41,812 (124,340)	40,581 (90,378)	35,903 (74,339)	48,871 (180,729)	303
Panel D (PICS Use)					
Trader has heard of PICS bag (=1)	.98 (.13)	.99 (.1)	.98 (.14)	.98 (.14)	303
Have used PICS bag at some point (=1), unconditional	.64 (.48)	.95 (.22)	.49 (.5)	.49 (.5)	303
Number of PICS bags bought	44 (84)	50 (94)	15 (16)	41 (66)	78
Trader used PICS for sales (=1)	.65 (.48)	.69 (.46)	.64 (.49)	.58 (.5)	189
Traders' WTP for PICS bag	754 (271)	785 (222)	726 (261)	752 (320)	300

Column 1 shows the mean and s.d. of the overall trader survey sample. Columns 2–4 show the means and s.d. by region.

providing calculations of the profitability of switching to PICS bags. We then present the WTP analysis and regional demand curves for PICS (Section 4.4) before assessing the correlates of regional differences in PICS demand (Section 4.5).

3.1. Farmers' cowpea production and storage

Table 2 presents the summary statistics for the farmer study sample. Approximately 30% of households own a mobile phone, with relatively higher rates of adoption in Dosso as compared with the other regions. As described above, the proportion of males and females varies slightly by region, with more female respondents in Maradi and Zinder (68%), as compared to Dosso (53%) (Panel A). As a result of this sampling difference, we condition on gender for the rest of the table and farmer-level regressions, although the results are largely similar using unconditional means.

96% of respondents in our sample harvested cowpea during the previous agricultural season, producing an average of 160 kg (Panel B). While 74% of households sold cowpea, approximately 60% bought cowpea at some point. 82% percent of households stored cowpea, storing approximately half of what they had produced. The duration of storage was significant: 77% of respondents stored until the rainy season, a period of at least six months. Average storage losses were 8 percent, with a majority of farmers reporting no storage losses and 1% losing the entire harvest. These rates of depreciation vary by the storage technology used, with storage losses of 8.7 percent for normal bags and plastic jugs and less than 2 percent for PICS (not shown). The relatively low average rate of storage losses reflects the widespread use of traditional methods to kill or deter pests (without which losses would have been much greater) (Murdock and Baoua, 2014). The primary reason for storage losses was the cowpea weevil (18%), followed by rats (5%).

The summary statistics show marked differences by region, with relatively higher levels of production and storage in Dosso and lower levels in Zinder.[13] Self-reported cowpea storage losses are similar in Dosso and Maradi (at 6%), yet double in Zinder (12%).[14] The relatively low rates of storage losses are reflected in farmers' storage behavior: Farmers use a variety of traditional methods to protect their crop. Overall, farmers either store in a normal 100-kg bag (40%) – adding pesticides or plastic inserts – or plastic jugs (50%), both of which are relatively effective in killing the cowpea weevil (Panel C). The dominant storage technologies also differ by region: farmers in Maradi primarily use normal bags, whereas farmers in Zinder primarily use plastic jugs. Average pesticide usage is 56%, ranging from 35% in Dosso to 77% in Maradi. On average, farmers spent US$ 6.76 per 100 kg to store their cowpeas, with the highest expenses in Zinder.[15]

We also find substantial variation across regions in PICS adoption. During the previous agricultural season, 22% of farmers had used a PICS bag, ranging from 4% in Zinder to 49% in Dosso (Panel D).[16] We also find that large shares of farmers are aware of PICS bags, ranging from 52% in Zinder to 96% in Dosso. In Dosso, just over half of farmers had

[13] As our sample areas are generally within the same latitude, we posit that the differences in production are primarily due to farm size, as well as random rainfall shocks within in a given year. Average farm sizes in this sub-region of Dosso are larger than those in this sub-region of Zinder, although we do not have accurate measures of farm size. While cowpea production was similar in Dosso for 2016/2017, production in Zinder increased from 74 kg to 100 kg.

[14] Storage losses are only comparable over a set period of time, and farmers encountering higher depreciation rates may choose to sell earlier. While we do not know the timing of cowpea sales, we can compare storage losses for those households that did not sell any of their 2015–2016 cowpea harvest. Among this sub-group, storage losses range from 7% in Dosso to 14% in Zinder.

[15] The regional differences in pesticide usage and storage expenditures are correlated with the types of storage technologies used. Normal bags require pesticides to kill the cowpea weevil, whereas plastic jugs do not, as they can create a hermetic seal. The per-kg price per plastic jugs – which only come in 20-kg units – is approximately four times the per-kg price of PICS bags.

[16] Storage patterns do not differ for farmers storing more/less than 100 kg (not shown).

used PICS at some point, compared to 1 out of 5 in Maradi and 1 out of 14 in Zinder.[17] The average price paid for the bags was approximately $US2, with few differences by region.

3.2. Traders' adoption of storage technologies

Table 3 shows the summary statistics for traders. All traders in our sample are male. The average trader has 17 years of experience and operates across five markets. Approximately half of traders classify themselves as semi-wholesalers and have three paid employees (Panel A). Unsurprisingly, over 90% of the traders store cowpea for some period, storing an average of 320 kg, approximately 8 times more than farmers (Panel B).

Like farmers, traders primarily store in traditional bags (with pesticides or plastic liners) or plastic jugs. Traders in Dosso are less likely to store in traditional bags than those in Maradi and Zinder, whereas traders in Zinder are most likely to use plastic jugs. The quantities of bags purchased are substantial, ranging from 115 to 200 bags (Panel C).

In contrast to farmers, nearly all traders have heard of PICS bags (Panel D). Yet less than half of traders in Maradi and Zinder have ever used PICS to store cowpeas, compared with 95% of Dosso traders. While PICS adoption rates among traders in the past year are higher than farmers, they are still low and variable, ranging from 13 to 81%. Similar to farmers, we find substantial variation across regions in both PICS adoption: During the previous agricultural season, 80% of traders had stored in PICS bags in Dosso, as compared with 13% and 18% in Maradi and Zinder, respectively.

3.3. Profitability of switching to PICS

Based upon these storage patterns, a key question is whether switching to PICS bags would be profitable for small-scale farmers. From a profitability perspective, PICS bags have three advantages. First, they reduce the rate of crop depreciation, as per numerous RCTs and self-reported storage losses in our sample. Second, they do not require complementary inputs, such as plastic liners and insecticides, the latter of which has negative health effects (Sheahan et al., 2017). And third, they may have longer expected durability. Nonetheless, we note that farmers may reuse some of their normal bags or plastic jugs, which would reduce the expected profitability of switching to PICS.[18]

We use a semi-parametric approach to compare simulations of farmers' expected storage costs using traditional technologies (normal bags and plastic jugs, considered separately) with the counterfactual cost of switching to PICS over several time periods. The net gain in profits from switching to PICS are shown in Fig. 3. Overall, our approach simulates "business-as-usual" storage costs over three seasons for farmers that do not switch to PICS, allowing for group-specific output distributions and heterogeneity in both the share of output stored and the cost of storing a particular quantity. We allow for the fact that farmers may re-use traditional technologies, and conservatively assume that a farmer that switches to PICS must do so entirely. Further details about this methodology are outlined in Appendix A.1.

Using this approach, we find that switching to PICS is profitable for 72% of farmers currently using traditional bags after one year, 96% of farmers after two years, and almost all farmers after three years. These percentages would be even higher if we allowed farmers to partially adopt PICS in the counterfactual. The results are similar for those currently using plastic jugs: switching to PICS would be profitable for 75% of farmers after the first year, 93% of farmers after two years, and 98% of farmers after three years. Despite the seeming flexibility and durability of the 20 kg plastic jugs, farmers incur substantial expenses each year. Overall, these results suggest that a majority of farmers in our sample would maximize the net value of their cowpea production and storage by using PICS, and that PICS is the dominant storage technology for cowpea farmers in all study regions.[19]

3.4. WTP for PICS bags

3.4.1. Farmers

From the above, it is evident that farmers and traders have a need for a storage technology that prevents pest-related losses. Under these circumstances, what are farmers and traders willing to pay for a PICS bag? Our incentive-compatible BDM elicitation method generates region-specific demand curves for farmers and traders, which are shown in Fig. 4A–D.

Fig. 4A shows the demand curves implied by the WTP elicitation for all farmers within the sample, whereas Fig. 4B shows separate demand curves by region. Overall, average WTP for the entire sample is 564 CFA (US$ 1), slightly more than half of the sales price on most markets. This is consistent with other studies on WTP for PICS in East Africa (Masters and Alvarez 2018), which found that average WTP was 50% of the market price. Uptake of PICS bags drops significantly at modest increases in prices: while demand only drops by 12 percentage points when the price increases from 10 CFA to 250 CFA (US$ 0.50), it drops by an additional 30 percentage points when increasing from 250 to 500 CFA, the latter of which is still about 500 CFA below the prevailing cost. Yet, perhaps the most striking aspect of Fig. 4B is the regional variation in farmer WTP. At any price, more farmers in Dosso are willing to pay for a PICS bag than in either of the other two regions. The gaps are significant: At a price of 100 CFA, farmer demand in Dosso is greater than the sum of farmer demand from Maradi and Zinder combined. Farmers in Maradi exhibit demand greater than or equal to that of farmers in Zinder at almost any price.[20]

On average, 77% of households who won the WTP game and purchased the PICS bag still owned the bag one year later, with relatively similar rates by region. Fig. 5 shows that there is no difference in the likelihood of usage by the maximum WTP; almost all of the coefficients are not statistically significant. As the bid price could be endogenous to later usage, we use the exogenous variation in price generated by the WTP game to assess the correlation between the randomly drawn price and usage one year later. Regressions of whether the household still owned the bag one year later on the bid and randomly drawn prices are shown in Table A1. Overall, the coefficient is close to zero and not statistically significant, suggesting that there is no relationship between the price bid, the price paid and later usage. In fact, farmers who won the PICS bag during the BDM game stored approximately 50% more cowpea than those who had not won and stored for longer (Table A2).

3.4.2. Traders

Fig. 4C and D shows equivalently-defined PICS demand curves for traders. Overall, average WTP for the entire sample is 784 CFA (US$ 1.57), approximately 83% of the market price. Unlike farmers, demand

[17] If farmers most likely to adopt PICS bags were selectively learning about the technology by searching for new storage options, we would have expected the highest rate of use, conditional on awareness, to be in the region with the lowest level of awareness. That is not the case.

[18] In addition to reusing old bags or jugs, each of these technologies could have multiple uses (e.g., to store other crops or water) after cowpea storage. We do not account for these in our analyses.

[19] Regional variation in expected profitability from switching to PICS is not sufficient to explain regional differences in adoption. Across all farmers using traditional technologies, switching to PICS would be profitable in the first year for 75% of those in Maradi, 76% in Zinder, and 85% in Dosso. Those figures rise to 94–96% in all regions after two years, and 99% in all regions after three years.

[20] No respondent answered "Yes"" when asked whether they would pay 5000 CFA, the maximum price, which therefore bounds the demand curve (the points associated with a price of 5000 CFA are not depicted).

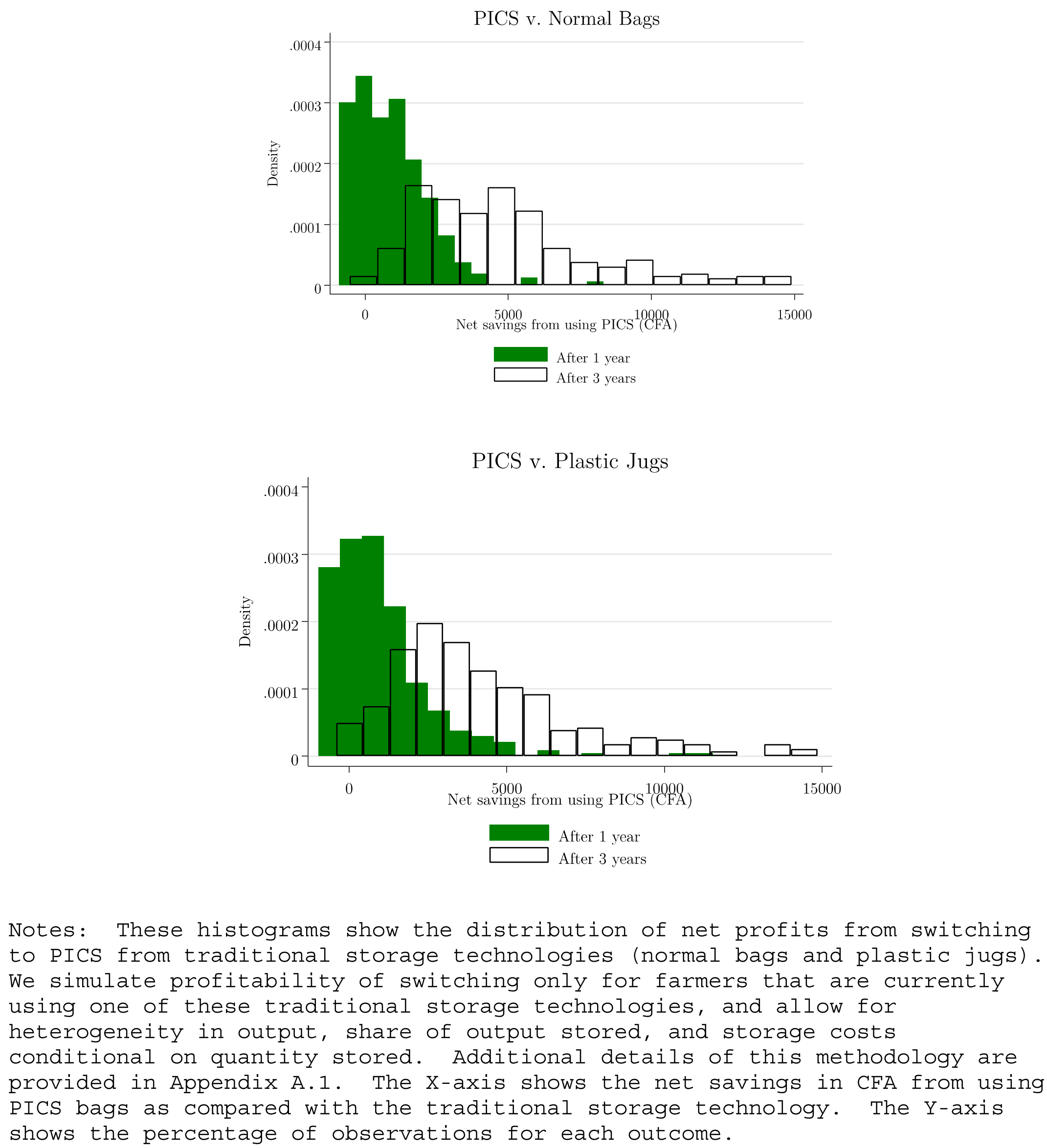


Fig. 3. Profitability of switching to PICS Bags from Traditional Storage Technologies
Notes: These histograms show the distribution of net profits from switching to PICS from traditional storage technologies (normal bags and plastic jugs). We simulate profitability of switching only for farmers that are currently using one of these traditional storage technologies, and allow for heterogeneity in output, share of output stored, and storage costs conditional on quantity stored. Additional details of this methodology are provided in Appendix A.1. The X-axis shows the net savings in CFA from using PICS bags as compared with the traditional storage technology. The Y-axis shows the percentage of observations for each outcome.

is less elastic at lower prices: Uptake drops by 13 percentage points when prices increase from 10 CFA to 500 CFA. Similar to farmers, there is inter-regional variation in trader demand, but it is less pronounced: The exception is in the range of prices just below the current market price, for which 900 CFA is a safe lower bound. As the price falls below 900 CFA, Dosso traders become dramatically more willing to buy the bags; traders in the other regions do not exhibit a similar level of demand to those in Dosso until the price falls to 400 CFA.

3.5. Correlates of regional WTP

Regional variation in WTP could be due to socio-economic differences in the composition of the regional samples, cowpea production and storage or exposure to PICS bags. For example, if women are more credit-constrained or are less likely to be responsible for cowpea storage than men, then the higher WTP in Dosso could be due to differences in the gender composition of our sample. If PICS demand is related to output quantity, then regional variation in output could drive variation in PICS adoption. To examine whether these and other factors are responsible for regional variation in farmer WTP, we use the following estimation:

$$maximum\ WTP_{iv} = \partial + \propto female_i + \theta maradi_r + \lambda zinder_r + \beta X_i + u_{iv} \tag{1}$$

where *maximum* WTP_{iv} is the maximum amount that farmer i in village *v* is willing to pay for a PICS bag during the BDM game (in CFA); $female_i$ is a binary variable if the respondent is female; $maradi_r$ is a binary variable for if the respondent lives in the Maradi region, 0 otherwise; $zinder_r$ is a binary variable for the Zinder region, 0 otherwise; and X_i are other individual characteristics potentially correlated with an individual's WTP. Standard errors are corrected for heteroscedasticity and clustered at the village level.

The results of these regressions are shown in Table 4. Column 1 conditions on region and gender. Female farmers have significantly lower WTP than male farmers, with the average female farmer willing to

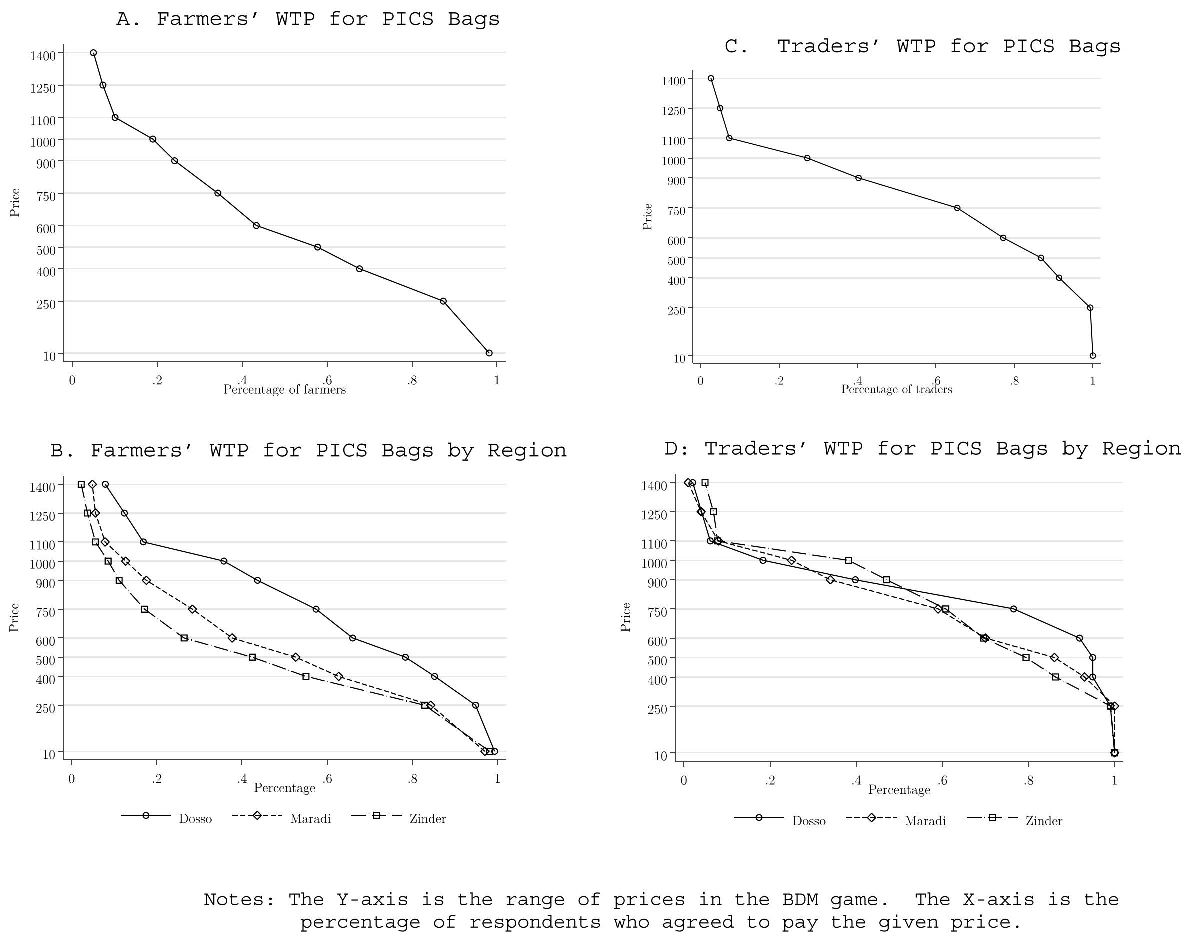


Fig. 4. A. Farmers' WTP for PICS Bags. Fig. 4B. Farmers' WTP for PICS Bags by Region. Fig. 4C. Traders' WTP for PICS Bags. Fig. 4D: Traders' WTP for PICS Bags by Region
Notes: The *Y*-axis is the range of prices in the BDM game. The *X*-axis is the percentage of respondents who agreed to pay the given price.

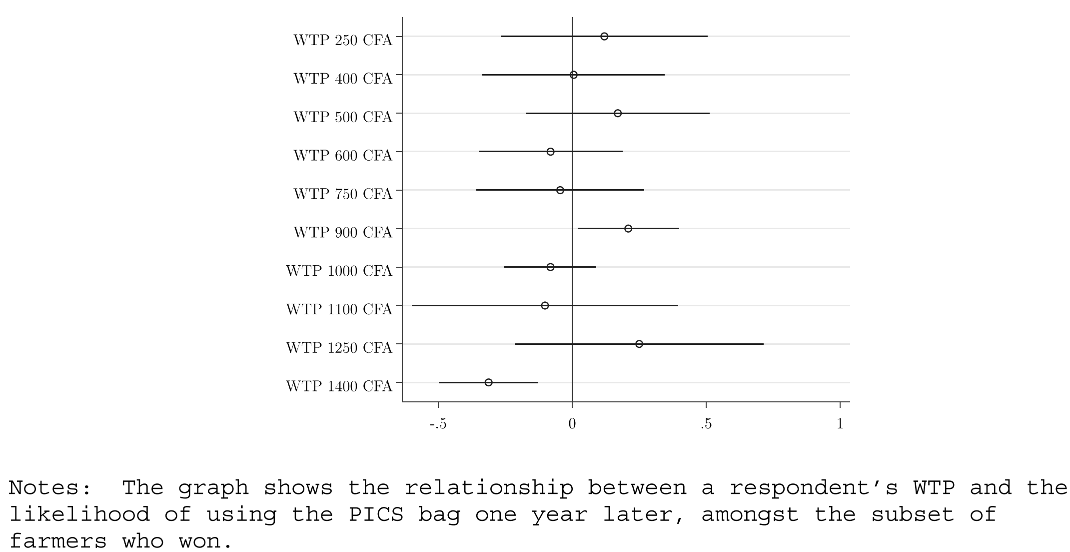


Fig. 5. WTP and Usage One Year Later
Notes: The graph shows the relationship between a respondent's WTP and the likelihood of using the PICS bag one year later, amongst the subset of farmers who won.

pay 24% less than the average male farmer in Dosso. Regional differences in WTP are significant and of substantial magnitude, as was evident in Fig. 4.

Column 2 examines whether spatial variation in WTP persists after controlling for a number of variables, such as age, cell phone ownership, cowpea production and storage and prior experience with PICS bags. While some of these variables may be endogenous, they provide some insights into the correlates of WTP. Only mobile phone ownership and prior PICS usage have a statistically significant correlation with farmers' WTP. While the coefficients on the region fixed effects are attenuated,

Table 4
Correlates of willingness to pay (WTP) for PICS bags.

	(1)	(2)	(3)
	Farmer Max WTP for PICS bag (CFA) Coeff (s.e.)	Farmer Max WTP for PICS bag (CFA) Coeff (s.e.)	Trader WTP for PICS bag (CFA) Coeff (s.e.)
Maradi (=1)	−210*** (35)	−156*** (34)	−20 (40)
Zinder (=1)	−285*** (34)	−233*** (39)	−4.7 (49)
Female (=1)	−203*** (25)	−160*** (38)	
Age of respondent		−1.5 (.97)	−2 (1.6)
Respondent owns a cell phone (=1)		60* (33)	
Quantity of cowpea harvested (kg) in 2015/2016		.082 (.091)	
Quantity of cowpea stored (in 100 kg units)		9.5 (18)	
3 month subj. depreciation rate, traditional bags		−28 (50)	−91 (54)
3 month subj. depreciation rate, trad bags + pesticides		−51 (93)	−110 (78)
3 month subj. depreciation rate, PICS bags		−137 (131)	
Used PICS		80** (36)	126*** (35)
Cowpea lasted in storage until just beore the rainy season, unconditional		−14 (28)	
Total amount spent on cowpea storage, unconditional		.012 (.015)	.00019* (.000094)
Household stored cowpea in jug only		42 (30)	
Respondent owns a cell phone			−46 (41)
Trader has stored cowpea since the last harvest, unconditional			89* (44)
Trader sells any storage products			−11 (31)
Mean in Dosso	839	839	785
No. of Observations	828	827	300
R squared	0.20	0.23	0.10
P-Value Maradi = Zinder	0.03	0.04	0.75

Column 1 shows the results of a regression of farmers' maximum WTP on binary variables for region. Column 2 controls for region and other controls. Column 3 shows the results of a regression of traders' maximum WTP on binary variables for region, as well as other controls. S.e. are clustered at the village level and corrected for heteroskedasticity.* ** and *** are statistically significant at the 10, 5 and 1 percent levels, respectively.

the regional gap in WTP is still significant between Maradi/Zinder and Dosso, representing between 19 and 28% of the average WTP.[21] This suggests that observable differences in the composition of the sample across regions are not the driver of regional variation in PICS adoption.

We conduct the same exercise for our trader sample (Column 3). The regression has similar controls as those in the farmer regression, with the exception of gender, as all traders were male. Consistent with the results in Fig. 4, regional differences in traders' WTP are not statistically significant. The only statistically significant correlates of WTP are whether the trader has stored cowpeas since the last harvest, storage expenses and prior experience with PICS bags. On average, traders are willing to pay 17% more for a PICS bag if they have previously used the bag, and 11% more if they have stored since the prior harvest.(Column 3).[22]

4. Demand-side mechanisms: information, beliefs, behavioral biases and liquidity

If farmers know about PICS bags and they are profitable, what explains the levels and variation in adoption? In this section, we consider some of the key potential explanations, first focusing on farmers' and traders' information beliefs about the technology (Section 5.1) and liquidity constraints (Section 5.2) before turning to behavioral biases (Section 5.3.).

4.1. *Knowledge and beliefs about relative storage technologies*

Slow learning and belief-updating are important barriers to agricultural technology adoption (Foster and Rosenzweig 2010). Although a majority of farmers and traders had heard about PICS bags, a potential explanation for low levels of adoption is that they do not believe in its effectiveness. To assess this issue, we use data from the elicitation of farmers' and traders' subjective beliefs about the technology.

The results from this exercise are shown in Table 5.[23] Farmers indicate that PICS bags have the lowest depreciation rate, followed by traditional bags with pesticides and traditional bags alone. In fact, farmers estimate that almost 90% of the entire amount stored would be lost at the end of nine months by using a traditional bag without some complementary input (Table 5, Panel A). By contrast, farmers estimate that 24% of cowpea would be lost by using traditional bags with pesticides, with relatively similar rates by region.[24] There is notable consistency in beliefs about these technologies across regions, although with slight variation for PICS. While farmers in Dosso estimate their losses at 4% after 9 months, farmers in Mardi and Zinder estimate these losses at 12 and 14%, respectively.

The results are similar for traders: Traders estimate the highest depreciation rates for traditional bags and the lowest depreciation rates for PICS bags, without a statistically significant difference by region (Table 5, Panel B). The greatest regional variation is associated with traditional bags with pesticides. Traders in Dosso estimate that they would lose a significant portion of their stock after 9 months, with lower perceived losses amongst traders in Maradi and Zinder. With the exception of Dosso, traders across all regions are more optimistic about PICS bags than farmers.

[21] Including additional controls, such as the interaction between gender and region or the square of age, does not affect the regional coefficients nor increase the adjusted-R^2.

[22] Despite the numerous controls in Columns 2 and 3, and the relative stability of the regional coefficients, we may be concerned that there is significant unobserved regional heterogeneity omitted from these regressions. In fact, the covariates only explain 23% of the variation in total WTP for farmers and 10% for traders (Columns 2 and 3, respectively). Using the approach outlined in Oster (2019), we calculate the bias-adjusted coefficients for Maradi and Zinder and show that the upper and lower bounds are still negative for farmers.

[23] The results are similar if we restrict the analysis to those farmers and traders who had previously heard of PICS bags.

[24] We note that the depreciation rate for traditional bags plus other inputs is 7%, exactly equal to the rate of losses observed in the data. This suggests that farmers are basing their beliefs about existing technologies on their own experience.

Table 5
Beliefs about storage technologies.

	(1) All Mean (s.d.)	(2) Dosso Mean (s.d.)	(3) Maradi Mean (s.d.)	(4) Zinder Mean (s.d.)	(5) N
Panel A: Farmers					
9 month subj. depreciation rate, traditional bags	.88 (.18)	.92 (.17)	.92 (.15)	.81 (.2)	839
9 month subj. depreciation rate, trad bags + pesticides	.24 (.29)	.24 (.31)	.22 (.3)	.26 (.25)	839
9 month subj. depreciation rate, PICS	.1 (.21)	.04 (.13)	.12 (.24)	.16 (.24)	839
Panel B: Traders					
9 month subj. depreciation rate, traditional bags	.97 (.12)	.97 (.1)	.98 (.11)	.95 (.14)	303
9 month subj. depreciation rate, trad bags + pesticides	.27 (.32)	.36 (.33)	.21 (.32)	.24 (.29)	303
9 month subj. depreciation rate, PICS	.023 (.11)	.016 (.12)	.012 (.071)	.042 (.13)	237

Column 1 shows the mean and s.d. of the full sample, whereas Columns 2–4 show the means and s.d. for each region. Panel A shows beliefs for the farmer sample, Panel B for the trader sample.

One of the key takeaways from Table 5 is that knowledge and beliefs about PICS bags diffuse easily and uniformly amongst farmers and traders in both high and low-adoption regions. The slightly greater confidence in PICS exhibited by Dosso traders suggests that learning-by-doing provides some additional information. This feature of PICS differs from many agricultural technologies, such as hybrid seeds, agro-chemicals or planting techniques, for which learning may be slowed by the stochastic nature of the production process and the large number of observed and unobserved factors that affect output. Overall, this suggests that beliefs in the poor quality of the technology are not responsible for variable PICS adoption.

4.2. Liquidity constraints

Liquidity constraints are often cited as a barrier to technology adoption, and hence are a potential concern in this context. If farmers were credit-constrained at the time of the survey, this may have resulted in lower average WTP. While possible, we do not think that liquidity constraints are the primary explanation for low and differential WTP for several reasons. First, the average WTP was 564 CFA, and the average drawn price for respondents whose bids were successful was 370 CFA. Amongst those who won, no one refused to purchase the bag, suggesting that the respondent was able to obtain the necessary funds for the purchase price. Second, households' average expenditures on other storage technologies the previous year is roughly equivalent to the market price of PICS bags. And finally, while Niger is one of the most financially excluded countries in the world, other research has shown that farmers borrow and save from informal networks, and are often able to mobilize small amounts from these sources (Aker et al., 2020). Thus, this suggests that farmers are able to mobilize resources to pay for cowpea storage, and in theory could pay for PICS bags.

4.3. Cost salience

Even if PICS bags are equivalent to – or less than – the price of traditional technologies, the higher "sticker price" of bags may be more salient than the total per kg storage cost at the time of purchase. As a result, farmers' demand for PICS may be lower than if farmers made this full calculation.

To answer this question, we rely upon the data from the information experiment (Table 6). Overall, average WTP amongst male Dosso farmers in the control group is 550 CFA, close to the average WTP in the sample. Yet respondents assigned to the *information* intervention were willing to pay 99 CFA more than those who were not, an increase of almost 20% (Column 1). These results are robust to controlling for other correlates of adoption (Column 2). The impact of the information intervention is primarily driven by respondents in Dosso (Column 3); in Zinder, those assigned to the intervention had lower WTP, despite the fact that storage costs were higher than the cost of a traditional bag or plastic jug. The information intervention seems to be more salient for

Table 6
Information experiment.

	(1) Respondent Max WTP Coeff (s.e.)	(2) Respondent Max WTP Coeff (s.e.)	(3) Respondent Max WTP Coeff (s.e.)	(4) Respondent Max WTP Coeff (s.e.)
Assigned to information experiment (=1)	99** (37)	117*** (39)	155** (65)	69 (53)
Marketing message*Maradi			42 (94)	
Marketing message*Zinder			−158* (82)	
Marketing message*Female				95 (66)
Maradi (=1)	−213*** (35)	−170*** (36)	−178*** (40)	−171*** (37)
Zinder (=1)	−286*** (34)	−216*** (38)	−199*** (42)	−219*** (38)
Female (=1)	−196*** (25)	−176*** (25)	−178*** (25)	−191*** (28)
Cowpea lasted in storage until just beore the rainy season, unconditional		−.83 (25)	4.7 (25)	1.7 (25)
Additional controls	No	Yes	Yes	Yes
Mean WTP if Marketing Message = 0	549	549	549	549
No. of Observations	828	827	827	827
R squared	0.21	0.22	0.23	0.22

Column 1 shows the results of a regression of farmers' maximum WTP on binary variables for the information experiment and region. Column 2 controls for the information experiment, region and other controls. Columns 3 and 4 interact the information treatment with region and gender, respectively. S.e. are clustered at the village level and corrected for heteroskedasticity.* ** and *** are statistically significant at the 10, 5 and 1 percent levels, respectively.

females than males, although the effect is not statistically significant at conventional levels (Column 4). Overall, these results suggest that some behavioral biases may be at play in terms of depressing overall WTP. However, they cannot fully explain the levels and variation in WTP across regions.

5. Supply-side mechanisms: liquidity, beliefs and market structure

Section 5 suggests that demand-side information, beliefs, liquidity and cost salience on the cannot fully explain the low and varied levels of technology adoption. In this section, we investigate the role that the private sector plays, first by focusing on traders' supply of PICS bags (Section 6.1), their beliefs about demand (Section 6.2) and liquidity constraints (Section 6.3) before turning to a key challenge: market

Table 7
Supply of PICS bags.

	All Mean (s.d.)	Dosso Mean (s.d.)	Maradi Mean (s.d.)	Zinder Mean (s.d.)	N
Panel A: PICS Sales					
Trader sold PICS last year	.2 (.4)	.31 (.46)	.089 (.29)	.2 (.4)	303
Trader sells PICS today	.12 (.32)	.24 (.43)	.02 (.14)	.098 (.3)	303
Price for PICS bag today	1006 (88)	979 (66)	1125 (177)	1045 (96)	36
Sale of PICS bag in other markets now	.78 (.42)	.71 (.46)	1 (0)	.9 (.32)	36
Number of PICS sellers on market	1.3 (1.3)	2.5 (1.1)	.47 (.85)	.81 (1.1)	281
Trader bought PICS in cash	.47 (.51)	.29 (.46)	.5 (.71)	.9 (.32)	36
Trader bought PICS in Nigeria	.53 (.51)	.63 (.49)	.5 (.71)	.3 (.48)	36
Time between order and delivery was immediate	.53 (.51)	.63 (.49)	.5 (.71)	.3 (.48)	36
Panel B: Reasons for Lack of Sales					
Do not know PICS	.088 (.28)	0 (0)	.11 (.31)	.14 (.35)	226
Do not know suppliers	.15 (.36)	.063 (.24)	.21 (.41)	.16 (.37)	226
Not enough money	.093 (.29)	.19 (.39)	.035 (.19)	.078 (.27)	226
Insufficient demand for PICS	.14 (.35)	.047 (.21)	.14 (.35)	.22 (.42)	226
Too many sellers	.0088 (.094)	.016 (.13)	.012 (.11)	0 (0)	226
Too expensive	.22 (.42)	.047 (.21)	.27 (.45)	.31 (.47)	226

Column 1 shows the mean and s.d. of the full sample, whereas Columns 2–4 show the means and s.d. for each region.

structure (Section 6.4.).

5.1. Traders' supply of PICS bags

Table 7 shows the supply of PICS bags on local markets (Panel A). Given that not all traders in our sample sold storage technologies, we also show these means for the sample restricted to those who sell our storage technologies in Table A3. Within the full sample, 20% of traders sold PICS bags in the past year, with 12% selling on the day of our visit. These figures increase to 43% and 26%, respectively, if the sample is restricted to those selling storage technologies. Consistent with the demand-side results, sales of PICS bags varied significantly by region, with the smallest number of traders selling PICS bags in Maradi and the highest number in Dosso. Conditional on selling PICS, the average price of these bags was 1000 CFA, or US$ 2, with some variation by region. Overall, traders estimated that there were approximately 1.3 other sellers in the market, with the highest density of sellers in Dosso (over 2) as compared with Maradi and Zinder (less than 1). Amongst those who sold PICS, approximately half of traders bought them via cash, ranging from 30% in Dosso to 90% in Zinder, and primarily purchased them in Nigeria. Overall, the results in Table 7 show a situation of sporadic supply of PICS on local markets, with regional variation mirroring the variation in farmers' WTP and demand. These results are qualitatively similar after conditioning on the traders' sales status (Table A3).

5.2. Traders' liquidity

Similar to farmers, liquidity constraints can play an important role in traders' willingness and ability to supply PICS bags, as over half of traders use cash in financing their PICS purchases (Table 7). This is confirmed by traders' themselves: When asked about the constraints to selling PICS bags, almost 10% of traders cited insufficient financing ("lack of money") (Table 7, Panel B), with important variation by region. Traders in Maradi and Zinder are less likely to be able to purchase on credit as compared with those in Dosso, with over 90% of traders in Zinder buying in cash. Beyond liquidity, 22% of traders cited that that purchase price of PICS bags was "too expensive", primarily driven by the Maradi and Zinder regions. Overall, this suggests that liquidity constraints – including access to cash and the option to pay via credit – could be a barrier to the supply of PICS bags, as well as traders' concerns about the potential profit margins. We address this in the next section.

5.3. Traders' beliefs about the PICS demand curve

Sustained supply of PICS bags will only emerge in areas where there is sufficient demand to warrant it. However, when traders and other input suppliers decide whether to stock PICS, they must do so based on their *perceptions* of demand, which may not match actual demand, particularly for a relatively new good. As we have shown, the supply of PICS bags on our sample markets was much lower than traders' adoption, especially in the Maradi and Zinder regions. In those regions, only 6% of all traders were selling PICS bags during the harvest period, reaching 12.5% of bag sellers (Table A3).

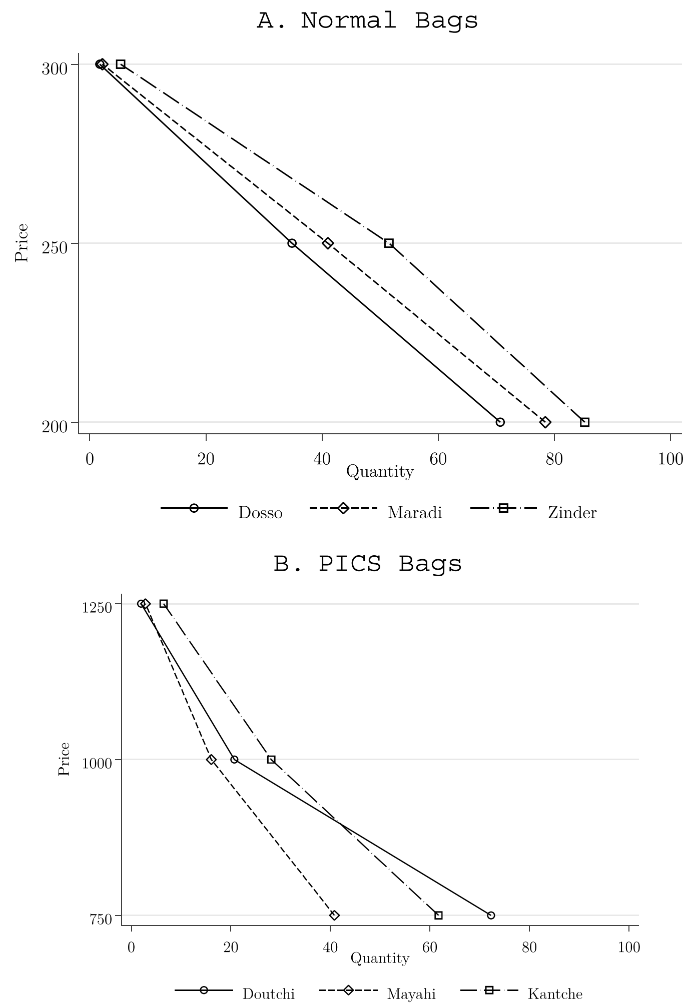
The results of the exercise on traders' beliefs about demand are presented in Fig. 6, with actual marketing behavior in Table 8. Several things are worth noting. First, the price options used to elicit trader beliefs about demand span the range of observed prices, and include at least one price weakly above or below the mean and median prices of each bag type in each region (Table 8, Panel B). Second, regional variation in perceived market size is apparent, with Zinder having the greatest demand for traditional bags and the lowest demand for PICS bags (Fig. 6). This ordering is largely reversed in Dosso. And third, while perceived demand for traditional bags in Maradi falls in-between the Dosso and Zinder perceived demand curves, traders in Maradi believe that demand is less elastic at high PICS prices (e.g., 1250 CFA) than traders in Dosso.

These findings indicate that regional variation in PICS demand is not driven by trader mis-reading of the market. It is not surprising that PICS are more readily available at markets in Dosso than elsewhere, as that is where demand is greatest. While these findings do not explain why this regional pattern in PICS demand emerged, they suggest that there is no obvious mismatch between supply and demand across space.

5.4. PICS market structure

A final potential explanation for the regional heterogeneity in demand is the initial market structure associated with the importation, financing and distribution of PICS bags. At the time of their introduction into Niger, PICS bags could only be imported by one distributor, based in Dosso. This exclusive import relationship lasted for ten years (Moussa et al., 2014; Coulibaly et al., 2012). During this time, the sole importer developed a network of wholesalers, semi-wholesalers and retailers, with the thickest network in Dosso (with 3 wholesalers and 25 semi-wholesalers) and the thinnest network in Maradi and Zinder (with 1 wholesaler and 10 semi-wholesalers each) (Coulibaly et al., 2012). While PICS bags were initially sold on credit, the sole distributor shifted primarily to a "cash and carry" system as of 2010, with the credit option remaining for "trusted" vendors (Coulibaly et al., 2012).

Our survey data suggest that this initial market structure has led to persistent differences in the supply of PICS bags in Niger. This is evident in regional supply patterns: There are relatively fewer PICS sellers in Maradi and Zinder as compared to Dosso, ranging from 0.47 to 2.5 on a given market (Table 7, Panel A). Traders in Maradi and Zinder purchase PICS primarily in cash, are less likely to know PICS suppliers, experience longer delays between order and delivery and are less likely to import directly from Nigeria as compared to their Dosso counterparts (Table 7, Panel A). All of this suggests that traders in Dosso, who had a preferential relationship with the sole importer for ten years, were



Notes: These figures show traders' beliefs about the quantities of each product that they could sell on a given day for given price points.

Fig. 6. Traders' Perceptions of Farmers' Demand Curves
Notes: These figures show traders' beliefs about the quantities of each product that they could sell on a given day for given price points.

Table 8
Beliefs about demand.

	All Mean (s.d.)	Dosso Mean (s.d.)	Maradi & Zinder Mean (s.d.)	N
Panel A: Farmers' Revealed Preferences for PICS				
Purchase price (CFA) of traditional bag	219 (83)	278 (106)	201 (66)	275
Purchase price (CFA) of PICS bag	1053 (230)	1073 (224)	978 (239)	222
Panel B: Traders' Sales of Storage Bags				
Purchase price (CFA) of traditional bag	233 (119)	228 (25)	234 (130)	155
Purchase price (CFA) of PICS bag	986 (99)	962 (87)	1043 (103)	78
Traders' Sales price (CFA) of PICS bag	1006 (88)	979 (66)	1058 (106)	36
Lowest price on market for PICS	929 (99)	924 (67)	938 (133)	154
Highest price on market for PICS	1066 (129)	1049 (92)	1092 (169)	154

Column 1 shows the mean and s.d. of the full sample, whereas Columns 2–4 show the means and s.d. for each region. Panel A show data from the farmer sample, Panel B for the trader sample.

incentivized to promote PICS adoption.

A striking aspect of this finding is that it suggests that segmentation at higher levels of supply chains can have long-lasting effects on technology adoption downstream. Monopoly theory suggests that the importer would restrict supply in order to drive up the price (Krugman 1979). While the price in Dosso is not higher than elsewhere, if PICS markets were in spatial equilibrium across-regions, then the sales price could be above its competitive level, and the importer would earn monopoly rents. In such a case, with a monopoly quantity restriction, it would be natural to favor one's longstanding network when rationing supply. This is especially the case in contexts where trade is characterized by relational contracts, repeated interactions and creditor relationships that rely on trust (Coulibaly et al., 2012).

6. Conclusion

Using farmer and trader survey data, we document the rates of adoption, usage and demand for an improved storage technology in Niger. We find that farmers and traders use a variety of storage technologies, including traditional bags, plastic jugs and PICS. These technologies are largely effective in reducing storage losses, with losses estimated at 7%. We find that PICS bags are largely profitable for small-scale farmers as compared to traditional storage technologies, even in the short-term.

Despite the effectiveness of PICS in reducing storage losses, as well as its potential profitability, a majority of farmers and traders do not store in PICS bags, with farmers' adoption ranging from 4% to 49% across regions. This geographical variation in adoption is also mirrored in WTP: average WTP is approximately 50% of the market price for PICS bags, with significant geographic heterogeneity by region. This heterogeneity persists after controlling for a number of covariates and using for bias-adjusted coefficients, although is smaller in magnitude. We show that regional differences in PICS adoption cannot be explained by regional variation in beliefs about their effectiveness nor in the profitability of switching from traditional technologies to PICS.

We provide evidence that regional differences in PICS adoption may be driven in part by behavioral barriers to adoption, rooted in the salience (or lack thereof) of current storage outlays. But biases in financial accounting cannot fully explain the regional patterns: our intervention to address salience is effective in the highest adoption region, but not effective at all in the lowest adoption region. Instead, we posit that the main explanation for these distinct equilibria is variation in supply, driven by a market structure introduced over a decade ago that created thicker distribution networks in one region. This is consistent with other recent research in this area: Omotilewa et al. (2019) find that a one-time subsidy can crowd in commercial purchases for the technology, and perhaps encourage greater future supply, while Dar et al. (2021) find that interventions targeted to suppliers increased farmer demand by over 50 percentage points.

Given that the emergence of a new market is a dynamic process, we cannot be certain that the PICS markets in our sample regions have settled into their long-run equilibria. Recent surveys in Niger in 2020 suggest that PICS adoption in Maradi and Zinder remain at 10% (authors' calculations). Overall, this suggests that initial supply chain dynamics can have important consequences for the longer-term. Given that the PICS market was liberalized in Niger in 2017, this may provide some opportunity to implement either supply or demand-side interventions in the market to crowd in commercial demand, thereby increasing incentives to supply. This is the subject of future work.

Table A1
Correlates Between WTP and Usage

	(1) Still have PICS Bag (=1) Coeff (s.e)	(2) Still have PICS Bag (=1) Coeff (s.e)
Bid price (CFA)	.00012 (.0001)	
Randomly drawn price (CFA)		.000077 (.00009)
Maradi (=1)	.11 (.091)	.086 (.079)
Zinder (=1)	−.051 (.099)	−.076 (.095)
Female (=1)	−.075 (.051)	−.098* (.049)
No. of Observations	170	169
R squared	0.04	0.04

Column 1 shows the results of a regression of whether the farmer still used the bag on the bid price from the BDM game in 2016, plus region fixed effects. Column 2 shows the results of a regression of whether the farmer still used the bag on the farmers' randomly drawn price from the BDM game in 2016, plus region fixed effects. Data are from the 2017 farmer survey across 30 villages. S.e. are clustered at the village level and corrected for heteroskedasticity.* ** and *** are statistically significant at the 10, 5 and 1 percent levels, respectively.

Table A.2
Correlates Between Winning PICS Games and Storage

	(1) Quantity of cowpeas (kg) stored in 2016/17 Coeff (s.e.)	(2) Quantity of cowpeas (kg) stored in 2016/17 Coeff (s.e.)	(3) Quantity of cowpeas (kg) stored in 2016/17 Coeff (s.e.)	(4) Duration of storage across seasons Coeff (s.e.)
Respondent won WTP game	21* (11)	15* (9)	13 (12)	.055* (.028)
Bid price (CFA)			.0066 (.018)	.000029 (.000054)
Maradi (=1)	−90*** (23)	−82*** (22)	−81*** (23)	−.13** (.048)
Zinder (=1)	−94*** (23)	−66*** (20)	−65*** (21)	−.13** (.055)
Female (=1)	−46*** (16)	−28* (15)	−27* (16)	.0056 (.045)
Respondent owns a mobile phone (=1)		18 (13)	17 (14)	.018 (.047)
Quantity of cowpea harvested (kg) in 2015–2016, unconditional		−.033 (.049)	−.033 (.048)	−.00002 (.00015)
Cowpea storage in 100-kg units, 2015/2016		32** (15)	32** (15)	.013 (.015)
No. of Observations	386	371	366	394
R squared	0.13	0.20	0.20	0.06

Column 1 shows the results of a regression of the amount stored in 2016/2017 on whether the farmer won the PICS bag from the prior year, plus region fixed effects. Column 2 adds in additional controls. Column 3 also controls the respondent's bid price in 2016 during the BDM game. Column 4 regresses these on the duration of storage acros seasons. Data are from the 2017 farmer survey across 30 villages. S.e. are clustered at the village level and corrected for heteroskedasticity.* ** and *** are statistically significant at the 10, 5 and 1 percent levels, respectively.

Table A.3
Supply of PICS Bags (Conditional on Selling Storage Inputs)

	All Mean (s.d.)	Dosso Mean (s.d.)	Maradi Mean (s.d.)	Zinder Mean (s.d.)	N
Panel A: PICS Sales					
Trader sold PICS last year	.43 (.5)	.74 (.45)	.23 (.42)	.36 (.48)	138
Trader sells PICS today	.26 (.44)	.57 (.5)	.05 (.22)	.18 (.39)	138
Price for PICS bag today	1006 (88)	979 (66)	1125 (177)	1045 (96)	36
Sale of PICS bag in other markets now	.78 (.42)	.71 (.46)	1 (0)	.9 (.32)	36
Panel B: Reasons for Lack of Sales					
Do not know PICS	.11 (.32)	0 (0)	.074 (.27)	.18 (.39)	72
Do not know suppliers	.25 (.44)	.27 (.47)	.37 (.49)	.15 (.36)	72
Not enough money	.11 (.32)	.18 (.4)	.074 (.27)	.12 (.33)	72
Insufficient demand for PICS	.31 (.46)	.18 (.4)	.26 (.45)	.38 (.49)	72
Too many sellers	.028 (.17)	.091 (.3)	.037 (.19)	0 (0)	72
Too expensive	.38 (.49)	.18 (.4)	.52 (.51)	.32 (.47)	72

Column 1 shows the mean and s.d. of the full sample, whereas Columns 2–4 show the means and s.d. for each region.

Data availability

Data will be made available on request.

Appendix A1. Methodology for Assessing the Profitability of PICS versus Other Storage Technologies

This appendix outlines a semi-parametric approach to compare expected storage costs using traditional technologies (normal bags and plastic jugs) with the counterfactual cost of switching to PICS. All of these analyses are conducted separately (e.g., PICS versus normal bags + pesticides, as well as PICS versus plastic jugs). To simulate storage costs using current technologies, we first assign farmers using traditional technologies to one of eight groups, defined by gender and cowpea output quartile. We then randomly draw cowpea output quantities over three hypothetical seasons from a Normal distribution, parameterized with the within-group mean and standard deviation of cowpea output. We then estimate the share of output stored using the results of a linear regression of the observed stored share on total output for those using traditional technologies, and add a stochastic term drawn from $\sim N(0,s)$, where s is the standard deviation of the residuals from that regression. This avoids having deterministic storage shares. We then estimate storage costs conditional on stored quantity using the results of a regression of total storage expenditures on stored quantity, again only for those using the traditional technology and again adding a stochastic term based on the residuals. We then value crop loss using the mean depreciation rate for those using traditional technologies and the mean per kg price of cowpeas (219 CFA). This approach simulates "business-as-usual" storage costs over three seasons, allowing for group-specific output distributions and heterogeneity in both the share of output stored and the cost of storing a particular quantity.

To simulate the cost of switching to PICS, we assume (conservatively) that farmers must switch at once, and that they must buy a 100 kg PICS bag as soon as the quantity stored reaches the 100-kg threshold (e.g., they must buy three 100 kg PICS bags to store 201 kg of cowpea). We then take the simulated storage quantities described in the prior paragraph and calculate the direct cost of buying sufficient PICS bags to store, as well as the expected value of crop loss during storage, which is based on the observed deprecation rate of stored crops among those currently using PICS and the market price of cowpeas (219 CFA). Finally, we calculate the difference in total cost of storage between traditional bags (jugs) and PICS over one, two, and three seasons, allowing farmers to reuse PICS bags for up to three years (our costing approach for the business-as-usual cases is based on the observed distribution of storage expenditures, and hence already builds in the possibility of reusing traditional storage goods).

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