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FARM FAMILY EFFECTS OF IMPROVED SORGHUM VARIETIES IN MALI: A MULTIVALUED TREATMENT APPROACH

By

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Institut d'Economie Rurale (IER). The IER was created on November 29, 1960, and serves as the main agricultural research institute in Mali with nearly 800 staff members, including 250 researchers in a variety of disciplines. It comprises six regional agronomic research centers, nine stations and 13 substations. Its scientific portfolio includes 17 programs.

Michigan State University (MSU). Established in 1855, MSU is the oldest of the U.S. Land Grant universities and has a long history of agricultural and food policy research in Africa, Asia and Latin America.

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Abstract

Uptake of improved sorghum varieties in Mali has been limited, despite the economic importance of the crop and long-term investments in sorghum improvement. One reason why is that attaining yield advantages that are substantial enough for farmers to discern in their own fields is difficult in a harsh, heterogeneous growing environment. Release of the first sorghum hybrids developed in Mali, which were developed primarily from the local Guinea race using a participatory approach, has the potential to change this situation. Here, we explore the adoption of improved sorghum seed with an ordered logit model, differentiating between improved varieties and hybrids. We then apply a multivalued treatment effects model to measure impacts on farm families. We utilize primary data collected from 628 farm family enterprises in the Sudanian Savanna region of Mali. Reflecting the fact that farm family enterprises both consume and sell their sorghum harvests, we consider effects on consumption outcomes as well as yield. We find that plot manager characteristics, in addition to household wealth and labor supply, are strongly and positively related to the improvement status of sorghum seed planted. The impact of hybrid use on yields is large and significant, positively affecting household dietary diversity and contributing to a greater share of the harvest sold. However, use of hybrids, as well as improved varieties, is associated with a shift toward consumption of other cereals. Findings support on-farm experimental evidence concerning yield advantages, and suggest that the use of well-adapted sorghum hybrids may contribute to crop commercialization by smallholders.

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I. Introduction

Globally, when combined with other farming practices, the diffusion of well-adapted, improved seed has enhanced the productivity of major food crops, including sorghum (Dalton and Zereyesus 2013; Evenson and Gollin, 2003). Since the devastating droughts of the 1970s-80s in the West African Sahel, national and international research institutes have invested to improve sorghum productivity in this region (Matlon 1985, 1990). Yet, in Mali, use of improved sorghum varieties has been limited; estimated adoption rates as a share of crop's area vary between 13% and 30%, depending on the measurement approach, geographical coverage, and time period (Kelly et al., 2015). From a policy perspective, numerous structural constraints have contributed to this situation, including a slow transition from an entirely state-managed supply channel (e.g., AGRA, 2010; Haggblade et al., 2015). From the perspective of a Malian farmer, on the other hand, one might argue that no seed value chain exists for sorghum (Eva Weltzien, pers. comm., April 16, 2016; see also Coulibaly et al.,2014).

In Mali, most smallholder farmers in the drylands have few resources other than seed, their labor, and their family lands to produce the cereal harvests they need to survive. Most of Mali's numerous sorghum growers remain largely outside the formal structures of "encadrement" (Thériault et al. 2015). By comparison, cash crops such as rice or cotton (and its primary rotation crop, maize) have vertically-integrated value chains that provide a range of services via registered cooperatives.

Sorghum is a traditional food staple in Mali and the West African Savanna is one of the centers of crop domestication. The fundamental role that sorghum seed plays in the well-being of smallholder farmers is reflected in rural cultural norms (Bazile 2006; Sperling et al. 2006). These include a customary reverence for the seed of local varieties, a perspective that all farmers have a right to seed, and a preference for giving or sharing seed rather than exchanging or purchasing seed with cash (Smale et al. 2010). The sorghum seed system has remained 'farmer-centered,' (Haggblade et al. 2015), with farmers themselves diffusing much of the local and improved seed plant each season through associations, social networks and other relationships based on trust.

Stimulating farmer demand for improved varieties has also been difficult because achieving significant yield advantages poses challenges in such a harsh, variable growing environment. Recently, the first sorghum hybrids developed from local Guinea landraces have been developed through farmer participatory testing. So far, data from on-farm, participatory trials demonstrate strong yield advantages associated with Guinea-race, sorghum hybrids across a range of conditions (Rattunde et al. 2013). There is also some evidence that preferences regarding seed acquisition may be evolving. For example, a census of sorghum varieties grown by over 2400 growers in the Sudan Savanna indicated that 38% of seed of improved varieties and 67% of seed of hybrids was initially obtained through a cash purchase as compared to gifts or exchanges.

In this paper, we examine adoption patterns and measure the impacts of improved sorghum varieties on Malian farm families at an initial point in the diffusion process for hybrids. We make several contributions to the literature on this topic. First, we include the first sorghum hybrids developed and released in Mali. Earlier, quantitative adoption studies generated from farm data in Mali focused on exotic, improved varieties and "purified" landraces (e.g. Yapi et al. 2000) on on a single variety (Sanogo and Teme 1996); other recent studies relied on key informants in the agricultural research system to estimate national diffusion rates (Ndjeunga et al. 2012). Detailed case studies of seed use have also been conducted in particular villages or village clusters, such as the studies by Siart (2008). We employ data generated by statistical sample drawn from 58 villages and differentiate hybrids from other improved varieties.

Second, we examine the impacts of each of these variety types on the well-being of farm families. To do so, we employ a less frequently used approach: multivalued treatment effects (Cattaneo 2010). Many treatment applications with observational data in agricultural development pertain to binary assignment, which is addressed instead with propensity score matching. We test three estimators: regression adjustment (RA), the augmented, inverse-probability weighted (AIPW) model, and the inverse-probability weighted, regression adjustment (IPWRA) model.

Finally, considering that Malian smallholders are farm families who both sell and consume their crop, our impact (outcome) indicators include plot yield as well as family dietary diversity and the share of sorghum in consumption and sales. Reflecting the social organization of production among sorghum growers, we include plot manager characteristics in addition to plot, household and market characteristics, among our control variables. Our study, a first glimpse of the impacts of newly released sorghum hybrids, draws on quantitative survey data collected from farm families.

Next, we present some contextual information on the sorghum economy and the history of sorghum improvement in Mali, highlighting the significance of recently released hybrids. Section III includes our methodology, including the data source, econometric strategy, and definitions of control and outcome variables. We then present results, include descriptive analyses, adoption regressions and treatment models. We draw conclusions and policy implications in the final sections.

II. Context

Sorghum is a “non-centric” crop with multiple centers of domestication and diversity in Sub-Saharan Africa (Harlan 1992). The West African Savanna, where the Guinea race originated and still dominates, produces most of the sorghum in Sub-Saharan Africa (Olsen 2012). Farmers in Sub-Saharan African grow four additional morphological forms or “races” of sorghum. These include caudatum sorghum (which originated in eastern Africa), durra (grown principally in the Horn of Africa), kafir (cultivated in eastern Africa), and sorghum bicolor, which is broadly distributed throughout the region.

Guinea-race sorghum is uniquely adapted to growing conditions in the West African Savanna. Photo-period sensitivity enables the plants of this race to adjust to the length of the growing seasons, which is important for farmers when rainfall is unpredictable. The lax panicles and open glumes of the Guinea-race reduces grain damage from insects and mold (Rattunde et al. 2013).

Most Malians farm and most Malian farmers cultivate drylands. Sorghum and millet continue to serve as the cereals base of the drylands economy—destined primarily for consumption by the farming families who grow them. Recognizing the importance of sorghum as a food staple, the government of Mali has long pursued a goal of raising sorghum productivity. During the Sahelian droughts of the 1970s-1980s, national and international research systems accelerated efforts to enhance sorghum yields, also introducing exotic germplasm from outside national borders.

Nonetheless, growth rates of national yields have not been as impressive as might be hoped. Yields reported by FAOSTAT (2016) show an average growth rate of 0.49% from 1961 to 2013. From 1980 to 2013, which corresponds to an active sorghum improvement program, the average growth rate in sorghum yields was 2.3%. This growth is quite modest, especially when compared with the 7.6% average growth rate in rice yields over the same time period. National average yields have rarely exceed 1 t per ha.

In Mali, sorghum is extensively cultivated on degraded soils with low fertility and little to no chemical fertilizer. Although not the only source of yield growth, use of well-adapted, improved seed can make important contributions. Estimates of adoption rates for improved sorghum differ markedly by source, measurement approach, and scale of analysis, although there is little doubt that a) these remain moderate and b) they continue to rise (Kelly et al. 2015). For example, Matlon's (1990) estimate for use of improved seed in the West African Sahel was a mere 5%. Diakité's (2009) analysis of farm surveys conducted in the areas around San and Sikasso showed that 20% of farmers grew improved sorghum seed. Based on key informant interviews, Ndjeunga et al. (2012) estimated that by 2010, 33% of national area was planted to sorghum varieties released since 1970, and 21% was planted to sorghum varieties released since 1990. These estimates include improved varieties for which farmers had not replaced seed of the same variety for a number of years, despite that breeders often recommend the seed replacement for the same improved variety every 3-4 years in order to maintain yield advantages.

In a detailed farm survey, Yapi et al. (2000) found that nearly 30% if sorghum area was planted to improved seed among farmers sampled in the major sorghum-producing zones of Segou, Mopti and Koulikoro. They differentiated between two breeding approaches pursued by the national sorghum improvement program: (1) selection and "purification" of superior landraces, and (2) crosses with exotic germplasm and pedigree selection. They found that despite the greater farm-level impacts of exotic germplasm in terms of yield advantages, farmers preferred the first group.

Subsequent research by scientists in the national sorghum improvement program also documented that although the cultivars based on exotic germplasm had yield potential, their grain quality was not well appreciated. Varieties in this group often lacked resistance to insects and mold. In general, achieving more than marginal yield changes has been difficult without hybrid vigor. The tremendous variation in climate, soils and farming systems means that the degree of plant stress is not only high, but also highly variable within and among fields in close proximity. Farmers need to be able to observe yield differences over seasons and across plots to recognize whether or not a new variety has advantages they can rely on.

Since 2000 Mali's sorghum breeding program has pursued two additional directions. The first is a participatory approach to sorghum improvement, based on a network of multi-locational, farmer-managed field trials. The second is the development of the first sorghum hybrids based primarily on Guinea-race germplasm. Summarizing the results of trials conducted by smallholder farmers in the Sudanian Savanna, Rattunde et al. (2013) reported yield advantages of individual hybrids of 17% to 47% over the local check, with the top three hybrids averaging 30%. Such yield advantages had not been previously achieved with improved varieties in this region; the mean advantage of the pure-line bred-cultivar check (Lata), a parent of the new sorghum hybrids, was only 6% above the landrace check (Tieble).

Trials analyzed by Rattunde et al. (2013) represented a broad range of growing conditions, with entries grown with and without fertilizer. As another point of comparison, the authors cite earlier work conducted by House et al. (1997) in Niger and Burkina Faso, who reported yield advantages of 49 to 185percent.

III. Methods

Data source

The sampling frame is a baseline census of all sorghum-growing households (2430) in 58 villages located in the Cercles of Kati, Dioila, and Koutiala, the purpose of which was to document use of sorghum varieties and measure adoption without sampling error. All variety names reported by farmers and improvement status of varieties (local, improved, hybrid) were identified with the assistance of field technicians and also verified by sorghum breeders working with the national program at the International Crops Research Institute of the Semi-Arid Tropics.

Kati, Dioila and Koutiala are located in the region of Koulikoro, and Koutiala is found in the region of Sikasso. Sikasso and Koulikoro regions have the largest proportions of agricultural land located in the Sudanian Savanna zone, and are the principal sorghum-producing regions in order of area cultivated and total production. As of the 2012-2013 season, the two regions represented more than 51% of total sorghum area planted in the country (Cellule de Planification Statistique du Secteur du Développement Rural (CPS-SDR)). Thus, they are priority target areas for sorghum breeding and especially for hybrid development in Mali. All villages are located within the isohyets corresponding to the broad Sudanian zone, near the center of that zone, just below or above the 800 mm isohyet.

The enumeration unit in the baseline census, and generally in Mali, is the Entreprise Agricole Familiale (EAF, or family farm enterprise). According to the national agricultural policy act (*Loi d'Orientation Agricole*), the EAF is a production unit composed of several members who are related and who use production factors collectively to generate resources under the supervision of one the members designated as head of household who can be a female or male member. The primary economic activity of the head is to encourage the optimal use of production factors as these are defined by the extended family. For the EAFs we study here, the first priority is universally food security. The head represents the EAF in all civil acts, including representation and participation in government programs. He or she may designate a team leader (*chef de travaux*) to supervise field work and manage the EAF on his/her behalf or to assist him/her when he/she has physical or other limitations.

The family farm enterprise is a complex organization that consists of numerous plots on which multiple crops are grown. Plots are managed collectively and individually by various members of the family. Members generally include the head, his wives and children, married sons and their wives and children, unmarried daughters and brothers of the head, and other relatives. Collective plots belonging to the whole EAF are managed by the household head or the team leader on behalf of the EAF. Individual plots belong to the EAF but are planted and managed by individual members, including both men and women. The production from these plots is not managed collectively. At each cropping season, the head distributes individual plots based on the needs of the family.

For more detailed analysis of adoption and effects of adoption on the well-being of farming households, a sample of EAFs was drawn with simple random sampling using the baseline adoption rate for improved varieties (22%) to calculate sample size. The sample was augmented by five percent to account for possible non-responses, and because of small numbers, all 45 hybrid-growing EAFs were included. The final sample size for adoption and impact analysis is 623 EAFs, with an overall sampling fraction of 25%. Enumerators inventoried all plots operated by each sampled EAF, grouping them by crop and plot management type. Considering sorghum and maize plots only (because of budget constraints), one plot was randomly sampled per management type per EAF. The total sample of sorghum plots analyzed here, including those collectively and individually-managed, is 734. In this analysis, plot is defined by variety; that is, only one sorghum variety is grown per plot.

The multi-visit analytic survey was conducted in four rounds from August 2014 through June 2015, with a combination of paper questionnaires and computer-assisted personal interviews, by a team of experienced enumerators employed by IER. Survey rounds covered: 1) inventories of plots, livestock, agricultural equipment and household assets; utilization of the harvest from the previous season; 2) input use and labor use on sorghum and maize plots; 3) measurement of area and production on sorghum and maize plots; 4) consumption expenditures and migration remittances.

Villages surveyed included all those listed as sites where the national research program (Institut d'Economie Rurale-IER) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have conducted testing activities via a network of farmer associations as early as 2000. Our findings are therefore representative of areas with at least some engagement by the national sorghum program. However, analysis of adoption rates in the baseline census shows variation from 0% to 80% and a distribution that does not differ significantly from normal—enabling us to treat villages as if they had been drawn at random rather than forming a separate control group. Some villages decided not to test varieties; in others, the sorghum program implemented only surveys to familiarize themselves with farmer priorities. Village adoption rates depend on the diffusion strategies pursued by farmer associations and other underlying social networks through which seed is exchanged among farmers, rather than on a formally-managed government program with specified selection criteria.

Econometric strategy

Our analysis has two components. First, we explore the determinants of plot-level variety choice. Estimation of two separate adoption equations (one for improved varieties and one for sorghum) is one feasible strategy, but this strategy would not account for interrelationships in either systematic or random components of the variety choice decision. Bivariate probit would be a modeling option that allows for correlations in the error structure. Conceptually, we prefer an ordered logit model, which enables us to differentiate between three ordered types of sorghum varieties: local (0), improved (1), and hybrid (2). The order, which is sometimes referred to as "improvement status," recognizes several potentially important differences between the three categories. Many improved varieties grown by farmers in this region are popular older releases, for which the seed may have been reused and shared among farmers. The hybrids have all been released since 2010 and introduced on a small-scale, pilot basis for testing by farmers. Moreover, although on-farm trial evidence demonstrates that these perform well with and without fertilizer (Rattunde et al. 2013), farmers and extension agents often portray that hybrids "require" fertilizer. In addition, it is recommended that farmers replace hybrid seed each year, while annual replacement is considered to be less important for improved sorghum varieties as long as good seed storage practices are followed. Evidence also suggests that most of the yields of second generation hybrids are still superior to local checks, which are typically among the most preferred local varieties (Eva Weltzien, pers. comm., April 22, 2016; Rattunde et al. 2014).

In the second component of our analysis, we estimate an impact model. The Randomized Controlled Trial (RCT) is often seen as the “gold standard” of evaluation approaches because it eliminates selection bias (Imbens and Wooldridge 2009). Bias due to nonrandom selection can occur because of program placement or participation criteria, or though processes of self-selection. In our context, adoption processes have occurred through naturally, with occasional programmatic interventions, over a period of years; treatment assignment is nonrandom because some farmers choose to adopt while others do not. Once introduced into a community by a development project or program, improved sorghum seed, like the seed of local sorghum varieties, has diffused from farmer to farmer based on relationships of trust, including kinship, social networks, formal and informal associations. Thus, we expect that adopters and non-adopters may be systematically different. Different methods have been used to address the question of establishing a counterfactual with non-experimental observations, including the class of treatment effect models, which we employ here. These models make treatment and outcome independent by conditioning on covariates or controls.

Let y_{1i} denote the potential outcome of individual i if he/she adopts an improved variety of sorghum and let y_{0i} if not. Let d_i denote adoption status by a dummy variable. For each individual, we observe $y_i = d_i\, y_{1i} + (1- d_i)\, y_{0i}$; that is, we observe y_{1i} for adopters and y_{0i} for non-adopters. The average treatment effect (ATE) and the average treatment effect on the treated (ATET) are given by: ATE=$E[y_{1i} - y_{0i}]$; ATET= $E[y_{1i} - y_{0i} \mid d_i =1]$. With observational data, we really observe only the outcome under one of the possible states. The outcome in all other cases is, in fact, potential (Rubin, 1974).

In the case of binary treatment, matching has become a popular approach (Imbens and Wooldridge, 2009), especially given the challenges of identifying appropriate instruments for two-stage least squares analysis. However, matching is based on Conditional Independence Assumption, which stipulates that the covariate vector is expected to contain all the pre-treatment variables that affect the treatment assignment. A major issue with matching methods consists in the possible presence of hidden biases caused by unobservable covariates, which is not testable.

Cattaneo (2010) proposes an alternative approach that can be used with multivalued treatment and differs in the way that treatment enters the analysis and how the ATE is estimated. This approach is of particular interest because it addresses the potential existence of selection bias and results are robust. Following this approach, we model the potential-outcome as

$$y_i = \sum_{t=0}^{2} d_i(t) y_i(t)) \ , \qquad (1)$$

where i is an index for observations (i=1, 2, …, N); y_i is the observed outcome of interest; $d_i(t)$ is an indicator that equals 1 if treatment type is t and 0 otherwise; and $y_i(t)$ is the outcome when treatment type is t; t is an index for treatment type (t = 0 if local variety (treatment control), 1 if improved variety, and 2 if hybrid variety).

We estimate three multivalued treatment models to estimate the ATE and ATE as a percent of the control value. The base model is the regression adjustment (RA) model. As a robustness check, we also present average treatment effects using augmented, inverse-probability weighted (AIPW) and inverse-probability weighted, regression adjusted

(IPWRA), or "doubly robust" models. Augmented, inverse-probability weighted (AIPW) and inverse-probability weighted, regression adjustment (IPWRA) estimators model both the outcome and the treatment probability. These enable consistent estimation of treatment parameters when at least one of the outcome model or treatment model is correctly specified. For this reason, these models are known as having the "doubly robust property." Unlike AIPW and IPWRA approaches, RA estimators model the outcome without any assumptions about the treatment model. Therefore, AIPW and IPWRA estimators can be more efficient than RA (Cattaneo 2010).

Variables

The conceptual basis of our variety choice model is the non-separable model of the agricultural household (Singh, Squire and Strauss 1986), reflecting production by a farm family enterprise (EAF) that primarily deploys its own labor supply and land to address staple food requirements. In our survey data, we find virtually no evidence of land or labor markets; farm families consume, sell, and give their harvests to others.

According to this conceptual basis, we expect household capital endowments (wealth, education, labor supply) and proximity to market infrastructure to affect transactions costs and thus the likelihood of acquiring inputs in sorghum production. Although we would argue that typically, sorghum seed is not viewed as a purchased input in the same way as fertilizer or herbicides, endowments also affect access to information and knowledge about new seed types. The market network extends to weekly fairs conducted in villages. We include a dummy variable for the presence of a weekly fair in the village of the EAF.

In Mali, access to formalized extension structures ("encadrement") substitutes to some extent for commercial markets, influencing farmer access to inputs and services of various kinds, including subsidized fertilizer. To express "encadrement," we include a variable measuring the share of all plot managers in the village who are members of a registered farmer cooperative.

Finally, as described above, we recognize the social organization of production in this region of Mali, and add the characteristics of the plot manager (education of the manager, whether the plot is managed by an individual other than the head; whether the manager is the wife or son of the head) among our explanatory variables. Table 1 shows the definitions and means of our independent variables in the ordered logit model, grouped in terms of plot manager, plot, household and market factors (Table 1).

The objective of the impact model is to quantify the potential outcomes that express changes in the supply of sorghum to the EAF and the EAF's consumption patterns that are associated with these changes. For yield, we specify the fixed effects model:

$$yield=\alpha+\beta t' outcomecovar+ \Theta t' treatmentcovar +\mu, \qquad (2)$$

where yield is sorghum yield in kg/ha, and *outcomecovar* is a vector of agricultural inputs applied on sorghum plots. Corresponding to a notional yield response function, we include input quantities per ha (seed, adult male labor, adult female labor, children's labor, fertilizers), as well as plot characteristics (time in minutes to travel from homestead to the plot; whether any structure has been built on the plot to offset soil and water erosion). *Treatmentcovar* is a vector of the same plot manager covariates that are included in the adoption analysis (with the exception of individual management; regressions did not converge with this covariate). Impact model control variables are shown in Table 2.

For consumption outcomes, following the conceptual basis of the agricultural household, we consider that relevant factors include both the supply side and those that affect outcomes via a constraint on expenditures. We specify a fixed effects model that includes the production function aspects of the yield model (the supply outcome), and add the covariates that are likely to condition consumption, given the amount produced. These include household size, transfer receipts from absent household members (exogenous income), as well as household wealth in assets and the presence of a weekly market fair in the village, which affect transactions costs of purchasing consumption goods. Consumption outcomes are defined as dietary diversity, the share of sorghum in household cereal consumption, and the share of harvested sorghum sold.

Outcome variable definitions are shown in Table 3. Of particular interest is the calculation of the Household Dietary Diversity Score (HDDS), which represents a count of the different food groups consumed during the 7 days preceding the survey (Swindale and Bilinsky 2005). The EAF receives a score of 1 for each food group consumed at least once, 0 otherwise. The HDDS is the sum across scores. With ten groups, the hypothetical range of this indicator is 1-10. The HDDS including frequency of consumption augments the score to better capture the number of times a food group is consumed (Arimond and Ruel 2002a,b). For each food group, the EAF receives a score of 0 for frequencies fewer than four times per week, a score of unity for frequencies from four to six (inclusive) times per week, and a score of 2 for frequencies of seven or more. With ten groups, the hypothetical range of the sum is 1-20.

Table 3 also shows the differences in the means of each outcome variable by treatment. Without controlling for other factors, yields and dietary diversity appear to increase with the improvement status of sorghum varieties. Given the same caveats, the share of sorghum in cereal consumption appears to decline with adoption of improved varieties and hybrids, while the share sold increases. These are the hypotheses we carry to the estimation.

In the next section, we begin with some descriptive statistics on our covariates, followed by the presentation and interpretation of regression results.

IV. Findings

Descriptive statistics

Comparisons of adoption percentages for improved and hybrid seed by type of plot management characteristics are shown in Tables 4 and 5. Based only on bivariate statistics, adoption rates differ weakly (at about 10%) by gender of plot manager, with slightly higher rates visible among women (45% v. 39%). The same pattern is reproduced when comparing all collectively-managed to all individually-managed sorghum plots, since most collective sorghum plots are managed by heads or designates (of which there are only two women), and most individual plots are managed by women. Not shown here, but visible in the underlying data, patterns of use are nearly identical between the plots managed collectively by the head or designate, with slightly under 40% of these plots planted to an improved variety or sorghum hybrid in the 2014 main growing season.

Several considerations may explain these somewhat surprising findings. In our sampling strategy, we selected households that had adopted hybrids in 2013 in order to re-interview them in 2014 because they were "rare" during this pilot phase of hybrid seed development and dissemination. We purposively selected sorghum plots managed by women, although seed choice was not a sampling criterion at the plot level and thus does not in itself explain the result. As part of the current outreach strategy of the national sorghum improvement program, women farmers, in addition to men in the household, have been targeted in recognition of their roles in sorghum production. Still, the result that use of improved seed is at least as high (if not slightly higher) on individual fields, and particularly those managed by women, suggest that improved seed is clearly distributed among plot managers in a fairly equitable way. This is not surprising, since availability of sorghum seed is not generally a constraint for the EAFs studied here unless the seed is purchased or newly introduced. Relatively speaking, seed is a highly divisible input with relatively low cost and easy to transport, unlike fertilizer. Culturally, the right to seed is still an important social norm. In addition, sorghum is a food staple. Qualitative work in this region has underscored the fact that women are increasingly planting sorghum on their individual fields, often grown as an intercrop with other crops they grew previously (such as legumes), in order to supplement the family food supply. In some areas, women's groups grow the crop to generate additional income outside the EAF (Eva Weltzien, pers.comm, April 10, 2016).

Similarly, the data in Table 5 do indicate that the wife of the head is slightly more likely to grow improved materials than other family members who manage sorghum plots (p-value 7%; the son of the head is no different in this respect). Recalling our description of the EAF organization, this finding merely suggests that the immediate family of the head, as compared to other extended family members, is more likely to obtain seed from the head first or to be targeted by program or project representatives. Consulting the data, the wife who plants improved seed is more likely to be the first, senior wife of the head. Thus, in our adoption model, we use "wife" and "son" of the household head as determinants of adoption and impact, rather than gender of the plot manager.

As expected, primary education of the plot manager plays a strong role in hybrid seed adoption, as shown in Table 6. Despite that variety information is transmitted by word of mouth, in general, primary education broadens interest in and access to information and services, supporting innovation. The improvement status of the sorghum variety grown on the plot increases with the likelihood that the plot manager attained a primary school education. We expect the ability to read and write strongly affects receptiveness and access to new information, techniques, or technologies. Plot managers reported that on average, they had grown the local varieties planted in their plot for 11 years, as compared to 9 years for improved varieties and 3 for hybrids. The difference between the longevity of local and improved varieties is not particularly meaningful, which confirms that the seed of these two types of varieties is diffused largely from farmer to farmer after initial introductions have been made.

All sorghum plots were rainfed. Virtually all were cultivated in the previous season (overall, 97%), and this did not vary by variety grown. More than half (53%) of those cultivated in the previous year were planted to sorghum highlighting the fact that sorghum has been continuously cropped. About one-quarter of plots were intercropped, and when sorghum was the principal crop, the most common intercrop on plots managed by either men or women was cowpea. Among women plot managers overall, sorghum is most often intercropped with groundnuts as the primary crop.

Mean distances to the plot from the household appear to differ significantly by sorghum variety type. Although soil types reported by farmers did not appear to differ by variety type, and although improvement status of seed was negatively correlated with the presence of soil and water conservation structures in the plot, when improved varieties and hybrids are combined, differences are not significant by variety type (Table 7). Presence of anti-erosion structures on plots typically reflects the slope of the land and dissemination efforts by formal cooperative structures more than variety type (Eva Weltzien, pers. comm. April 10, 2016).

In Table 8, we present the household characteristics that we expect to be strongly related to the adoption of new techniques, technologies, and seed varieties. Despite the small numbers of hybrid growers in 2013 (45 EAFs), we see plainly that they are wealthier in terms of total value of assets and enjoy a larger number of economically active adults per household (2 more adults). Thus, they are relatively advantaged in terms of financial and human capital endowments. These findings are commonly reported in the broad literature on the adoption of agricultural technologies (Feder, Just and Zilberman 1985; Feder and Umali 1993: Foster and Rosensweig 2010). With respect to credit and other services, "encadrement" of the plot manager's village (membership in an organized farming cooperative structure) is greater among plot managers who grow sorghum hybrids, but the opposite is true for those who grow other improved varieties. This result suggests diffusion of older improved varieties from farmer to farmer beyond initial points of introduction by government programs. The national sorghum program began disseminating improved varieties in study villages as early as 2001, and these still dominated dissemination until 2015. On the other hand, there is no clear relationship evident between whether or not the village hosts a weekly market fair and seed use by plot managers in the same village.

Ordered logit regression

The ordered logit regression model explaining the adoption of sorghum varieties by improvement status is shown in Table 9. Marginal effects are presented in Annex. Multivariate results are broadly consistent with bivariate findings.

Plot manager characteristics, which reflect the social organization of farming in this region of Mali, are key determinants of variety adoption in sorghum production. These features are not often included in adoption studies, which usually focus on household characteristics. Individual management of a plot, compared to collective management of a plot, reduces the likelihood that improved varieties of sorghum are grown. Controlling for this factor, management by the wife of the head increases the chances that improved varieties, and especially hybrids, are grown in the plot; the effect of management by the son is also significant but weaker in magnitude and significance. Attainment of primary education by the plot manager is strongly significant for adoption of improved varieties, and even more so for sorghum hybrids. While plot location does not appear to play much of a role, erosion control structures on the plot (stone contour walls, contour bunds, living fences) are negatively associated with improvement status. Hybrids have been more recently introduced; the average time since initial construction of stone bunds on sorghum plots in the sample is 10 years. Furthermore, while women managers in our sample grow hybrids, they are less likely to have anti-erosion structures on their smaller plots. As in the broad adoption literature, capital endowments (household wealth and household labor supply) are strongly significant in predicting the use of improved sorghum varieties.

On the other hand, neither the extent of membership of village plot managers in a registered cooperative nor the presence of a weekly market fair in the village appears to influence the likelihood that improved varieties of sorghum are planted on a plot. The explanation for the first result is that registered cooperatives are primarily conduits for inputs and services related to cotton production, which also includes maize seed but not sorghum seed. Fertilizer subsidies, while facilitated by cooperatives, have also been facilitated by other associations and are in principle available to sorghum growers, though at a lower rate (Thériault et al. 2015). Improved sorghum seed has been introduced occasionally by external organizations and programs, but directly and indirectly via farmers' associations. However, diffusion has occurred primarily from farmer to farmer, among those who are members of farmers' associations, but not exclusively. Concerning the local market, it is still the case that little of the sorghum seed planted by farmers in this region passes through commercial markets or agrodealers, despite efforts by donors to stimulate the development of seed markets (Haggblade et al. 2015).

Multivalued treatment effects models

Estimates of Average Treatment Effects, expressed as means and percentages, are shown for all outcomes and the three modelling approaches in Table 10. In terms of significant effects, results are generally, but not always consistent across models. Of the three models, the AIPW and IPWRA is expected to be "doubly robust" and more efficient.

Signs and significance differ by outcome, and by improvement status of the sorghum variety. Yield effects are strongly significant and of a large relative magnitude for sorghum hybrids, but not for improved varieties, relative to local varieties. Yield advantages are between 479 and 1055 kg/ha, depending on the model, which represents 79% to 180% of the mean of the local varieties grown by farmers (Table 10). This result confirms findings reported by Rattunde et al. (2013), which were generated by on-farm trials. The fact that yield advantages of 34-35% for improved varieties are not statistically significant probably reflects the underlying variability of yields under farmers' conditions for this heterogeneous category or older and more recent introductions.

The ATE on Household Dietary Diversity (HDDS) is not statistically significant in any of the three models, indicating that higher sorghum yields do not translate into a broader range of food groups consumed when measured as a simple count. Yet, when the frequency of consumption is taken into account, there is an impact on dietary diversity that is meaningful and significant for hybrid growers (and increase in the score of 7-8% in the AIPW and IPWRA models).

The impact of growing improved varieties or sorghum hybrids on the share of sorghum in cereals consumed is negative, by either measure (week prior to survey or harvest). Higher yields lead to the capacity to release land for other cereals or utilize earnings from sales to purchase them or other food items. In these villages, maize is both grown and consumed more than in the past. Consistent with these points, the impact of growing improved varieties is positive on the share of other cereals consumed. The effect was not apparent for hybrids, but small areas were planted and these are more recently adopted. At the same time, the share of the sorghum harvest sold rose by 10 to 14% depending on the models. Growing improved sorghum varieties or hybrids thus contributes to commercializing a food crop for which no formally developed market channel has been developed. Assuming a consumer price of 150 FCFA in the hungry season, and 90 FCFA as the sales price just after harvest, improved varieties and hybrids (combined) give the farmers the potential to increase their sales revenue by between 4644-7740 FCFA and 6500-10836 FCFA depending on model.

V. Conclusions

In this analysis, we have contributed to a sparse literature on the adoption and impacts of improved sorghum varieties in Mali, also including the first sorghum hybrids released by the national program, which are based on Guinea-race germplasm and developed with participatory, on-farm trials. First, we used ordered logit model to identify determinants of adoption, which enabled us to differentiate between three ordered types of sorghum varieties: local (0), improved (1), and hybrid (2). Reflecting the social organization of sorghum production in the Sudanian Savanna of Mali, we tested the significance of plot manager characteristics, as well as plot, household and market characteristics in our regressions. Then, we applied a multivalued treatment effect approach to evaluate the impact of adoption of sorghum varieties and sorghum hybrids on farm families. In terms of outcomes, we evaluated both supply outcomes (yield) and consumption outcomes (dietary diversity, share of sorghum in consumption and sales). For robustness, we applied three statistical models.

Our data also shows that adoption varies between collectively-managed plots and individually managed plots. Most of the individual sorghum plots in our dataset are managed by women who planted sorghum in association with groundnuts or cowpea; male managers of individual plots tended to grow cash crops such as cotton or maize, which are not analyzed here. There is continuous use of land under sorghum for over half of plots studied. The cultivation of hybrid varieties is negatively correlated with soils and water conservation techniques, perhaps because these techniques are more likely on older, collectively-managed fields that have been continuously cropped for a longer period of time and addressed by previous cooperative programs. Sorghum plots managed by women, which are smaller and often intercropped with legumes, are also unlikely to have soil and water conservation (SWC) structures (1%). Lower likelihood of SWC practices on cereals plots managed by women was also reported by Thériault et al. (2016) based on analysis of data from Burkina Faso. Consistent with a large literature on the topic, early adopters of new techniques (in our case, sorghum hybrids) are wealthier in terms of assets and human capital (household labor supply, education of the plot manager).

Bivariate results were generally borne out in the ordered logit regression model. Attainment of primary education by the plot manager was a significant factor, as were household capital endowments and the absence of anti-erosion structures on the plot. Our analysis found also that being a member of a cooperative or the presence of a weekly market fair in the village has no effect on adoption of improved sorghum varieties because cooperatives facilitate mainly access to fertilizer and other credits to members; while seeds are mostly not traded in the market but passes form farmer to farmer. Management of the plot by individuals other than the head, and especially the senior wife, is positively associated with hybrid use. This finding may simply reflect our sample design and recent recognition by the sorghum program of the evolving role of women in sorghum production. It is also consistent with the notion that innovations are generally introduced into these extended families via the household head, subsequently diffusing to other members.

The multivalued treatment effects model shows that yield effects are strongly significant and of a large relative magnitude for sorghum hybrids, but not for improved varieties, relative to local varieties. Yield advantages are between 479 and 1055 kg/ha, depending on the model, which represents 79% to 180% of the mean of the local varieties grown by farmers. When the frequency of consumption is taken into account, growing hybrids has a meaningful and significant effect on Household Dietary Diversity (HDDS) and there is an impact on dietary diversity that is meaningful and significant for hybrid growers (and increase in the score of 7-

8% in the AIPW and IPWRA models). The impact of growing improved varieties or sorghum hybrids on the share of sorghum in cereals consumed is negative, by either measure (week prior to survey or harvest). The impact of growing either improved varieties or hybrids is positive on the share of other cereals consumed. At the same time, the share of the sorghum harvest sold rose by 10 to 14% depending on the model.

VI. Implications for policy and future research

The analyses presented here permit us to draw several implications of relevance to national policy in Mali. First, we find that adoption of improved varieties of sorghum improved variety adoption is slightly higher on plots managed by individuals than on collectively managed plots (45% vs. 39%, respective), although the effect is statistically weak. In our study area, many women are increasingly growing sorghum on the individual plots they manage to address the nutritional needs of their children and meet the costs of clothing, school, and health care. Any policy aiming to promote the development and diffusion of improved varieties of sorghum (especially hybrids) should now recognize the potential role of women members of the farm family enterprise in planting and producing sorghum. This pattern is clearly a change in cultural norms; the conventional wisdom has been that women were not involved in sorghum production outside the collective fields of the family.

Second, generally speaking, the characteristics of the plot manager, in addition to the plot and household characteristics, are strong determinants of variety and hybrid adoption in sorghum production. To encourage higher adoption rates, our results indicate that channels of introduction for seed and complementary inputs such as fertilizer should incorporate not only the household head but also all economically active members of the EAF. The role of senior women in the EAF is seen to be strong in our sample, which reflects a combination of factors, including that the sorghum program made an effort to ensure that women contribute and benefit from variety testing programs and related activities.

Market access and access to cooperative structures do not yet seem to be as important, although this may change as sorghum production commercializes. Morever, these channels need to be better structured and well supported by informational services. Major improvements still need to be made to facilitate the production and dissemination of improved sorghum to widely dispersed smallholders. Policy makers must be realistic in their expectations of the extent and form of private sector interest in supply sorghum seed to farmers; parapublic models, and decentralized means of seed supply to more remote areas through farmer seed producer associations appear to be a workable model in regions where the formal cooperative structures are inactive (Koulibaly et al. 2014; Haggblade et al. 2015).

Third, the impact analysis confirms the major yield impacts of hybrid seed on yields, as reported in previously published results based on data from on-farm trials. We also observe an impact on household dietary diversity when the frequency of consumption is considered. We see that the share of the harvest sold increases when hybrids are grown, suggesting that households have the choice of expanding their consumption purchases. When yields rise, land may be released for the production of other crops (although we cannot confirm this pattern in one survey season). In this way, hybrid production could contribute to a more commercial orientation of production for some growers. In order to facilitate the expansion of yield and revenue benefits more widely among smallholder sorghum growers in Mali, the constraints to hybrid seed multiplication, production and distribution should be addressed. At the time these data were collected and analyzed, sorghum hybrids had been introduced only on a pilot basis in the Sudan Savanna.

In terms of technical aspects of future research, further calibration of these results with detailed soils data in the yield outcome model and enhanced measures of dietary diversity in the consumption model may prove informative. Some sensitivity analysis on model results might shed light on the high-end values we obtain in some of the yield models. As another robustness check, it may be helpful to test binary impacts with improvement categories taken two at a time.

More importantly, concerning substantive issues, testing impacts findings in other regions of Mali and in other crops will be important for national policy. Should the findings concerning the gender of the plot manager be borne out in other studies, it would underscore the need to reconsider the design of conventional extension approaches.

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Table 1. Adoption model explanatory variables, definitions and means

Explanatory variable	Definition
plot manager characteristics	
individually-managed	plot managed individually by male or female who is not the EAF head or designate=1, else 0
education	plot manager attended primary school=1, 0 else
wife	plot manager is wife of the head of EAF =1 , 0 else
son	plot manager is son of the head of EAF =1, 0 else
plot characteristics	
location	time in minutes to travel from home to the plot
erosion control	any anti-erosion structure built on plot=1, 0 else
household characteristics	
assets	total value of household assets, excluding livestock (ln FCFA)
labor supply	number of adults in EAF between 12 and 55 years of age (inclusive)/total area operated by EAF
market characteristics	
cooperative	share of plot managers in village who are coop members
market	weekly market fair in village=1, 0 else

Source: Authors.

Table 2. Impact model control variables, definitions and means

Control variable	Definition
production inputs	
seed	quantity of seed used
fertilizer	total kgs of fertilizer applied
male labor	number of adult male person-days (14 years and above)
female labor	number of adults female person-days (14 years and above)
child labor	number of children person-days (under 14 years)
plot characteristics	
location	time in minutes to travel from home to the plot
erosion control	any anti-erosion structure built on plot=1, 0 else
plot manager characteristics	
education	plot manager attended primary school=1, 0 else
wife	plot manager is wife of the head of EAF =1 , 0 else
son	plot manager is son of the head of EAF =1, 0 else
consumption factors	
market	weekly market fair in village=1, 0 else
household size	number of EAF members
transfers	income from absent household members in previous 12 months
assets	total value of household assets, excluding livestock (ln FCFA)

Source: Authors

Table 3. Impact model outcome variables, definitions and means, by treatment

Outcome	Definition	Local variety	Improved variety	Hybrid variety
yield	sorghum kgs harvested/ha (GPS)	782.4	873.9	994.6
hdds	Household Dietary Diversity Score (HDDS); see text	7.44	7.47	7.78
freqhdds	Household Dietary Diversity Score (HDDS) with frequency of consumption; see text	11.8	11.8	12.7
sorghum share	value share of sorghum in consumption expenditures during 7 days before survey	0.075	0.0841	0.00536
sorghum share1	quantity share of sorghum in cereals consumed during crop season	0.38	0.322	0.364
partcereal	value share of other cereals in consumption expenditures during 7 days before survey	0.266	0.285	0.39
sharesold	share of sorghum harvest sold	0.0591	0.113	0.179

Source: Authors. N=730 plots, 623 EAFs.

Table 4. Sorghum variety adoption by plot management

		Sorghum variety			
		Local	Improved	Hybrid	All varieties
Gender of plot manager					
	Male	328	174	36	538
		60.97	32.34	6.69	100
	Female	106	78	9	193
		54.92	40.41	4.66	100
Management type					
	Collective plot	322	171	36	529
		60.87	32.33	6.81	100
	Individual plot	112	81	9	202
		55.45	40.1	4.46	100

Source: Authors. Pearson chi2(2) = 4.5083 Pr = 0.105; 4.5982 Pr = 0.100

Table 5. Sorghum variety adoption, by relationship of plot manager to head

	Sorghum variety			
	Local	Improved	Hybrid	All varieties
Other family members	352	186	36	574
	61.32	32.4	6.27	100
Wife of head	82	66	9	157
	52.23	42.04	5.73	100
Total	434	252	45	731
	59.37	34.47	6.16	100
	Pearson chi2(2) = 5.0949 Pr = 0.078			
	Locale	Ameliore	Hybride	Total
Other family members	395	217	39	651
	60.68	33.33	5.99	100
Son of head	39	35	6	80
	48.75	43.75	7.5	100
Total	434	252	45	731
	59.37	34.47	6.16	100
	Pearson chi2(2) = 4.2128 Pr = 0.122			

Source: Authors.

Table 6. Sorghum variety adoption, by education of plot manager

	Attained a primary education		All
	No	Yes	
Local variety	388	46	434
	89.4	10.6	100
Improved variety	195	57	252
	77.38	22.62	100
Hybrid variety	34	11	45
	75.56	24.44	100
Total	617	114	731
	84.4	15.6	100

Pearson chi2(2) = 20.3520 Pr = 0.000

Table 7. Soil erosion structure on plot?

	No	Yes	Total
Local	346	88	434
	79.72	20.28	100
Improved	216	36	252
	85.71	14.29	100
Hybrid	42	3	45
	93.33	6.67	100
All sorghum varieties	604	127	731
	82.63	17.37	100

Source: Authors. Pearson chi2(2) = 6.5960 Pr = 0.037

Table 8. Sorghum variety adoption, by household and village market characteristics

	Grow sorghum hybrids			Grow improved varieties		
	No	Yes	p-value	No	Yes	p-value
Total value of EAF assets (ln)	13.9	14.3	0.0437	13.9	14.1	0.0221
Number of EAF active adults (12 to 55 years)	8.80	10.5	0.0418	8.35	9.56	0.0032
Proportion of plot managers in village who belong to a cooperative	37.5	45.2	0.0428	40.1	32.9	0.0002
Presence of market fair in village						
No market	541	37	578	373	205	578
	93.6	6.4	100	64.53	35.47	100
Market	145	8	153	106	47	153
	94.77	5.23	100	69.28	30.72	100
	Pearson chi2(1) = 0.2880 Pr = 0.592			Pearson chi2(1) = 1.2074 Pr = 0.272		

Source: Authors. Note that comparison group for hybrid growers in this table includes both improved and local varieties.

Table 9. Ordered logit model explaining sorghum variety adoption

	Improvement status
individually-managed	-0.573*
	(0.327)
wife	0.882**
	(0.344)
son	0.407*
	(0.240)
education	0.878***
	(0.204)
location	0.00207
	(0.00363)
erosion control	-0.475**
	(0.204)
assets	0.206***
	(0.0785)
labor supply	0.191**
	(0.0826)
cooperative	-0.0147
	(0.353)
market	-0.154
	(0.197)
Constant cut1	3.605***
	(1.143)
Constant cut2	6.049***
	(1.148)
Observations	728

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1
Improvement status: 0=local variety; 1=improved variety; 2=hybrid variety

Table 10. Average treatment effects, by outcome and model

		RA	AIPW MNL	IPWRA MNL
		coef	coef	coef
yield	ATE			
	improved	203.8	173.0	204.3
	Hybrid	478.5**	779.4**	1054.8***
	ATE %			
	improved	.3357052	.2275826	.3486967
	hybrid	.7880124**	1.025119**	1.8005***
hdds	ATE			
	improved	0.278	-0.0680	-0.0548
	Hybrid	0.418	0.255	0.243
	ATE %			
	improved	.0423875	-.0091213	-.0073566
	hybrid	.0637822	.0341591	.032652
freqhdds	ATE			
	improved	0.388	-0.0915	-0.0873
	Hybrid	1.207	0.841**	0.903**
	ATE %			
	improved	.0369894	-.0077307	-.0073753
	hybrid	.1150511	.0710718**	.0762431**
sorghum share	ATE			
	improved	0.000373	-0.00828	-0.00725
	Hybrid	-0.0679***	-0.0694**	-0.0699***
	ATE %			
	improved	.0053511	-.1082744	-.0946649
	hybrid	-.9744761***	-.9076069**	-.9125638***
sorghum share1	ATE			
	improved	-0.0363	-0.0734**	-0.0720**
	Hybrid	0.0120	-0.00288	-0.00522
	ATE %			
	improved	-.1126063	-.1902753**	-.1867071**
	hybrid	.0373155	-.0074596	-.0135241
partcereal	ATE			
	improved	0.0456*	0.0646*	0.0592*
	Hybrid	0.0202	0.0542	0.0625
	ATE %			
	improved	.1835128*	.2393542*	.2194374*
	hybrid	.0811734	.2009184	.2316561
sharesold	ATE			
	improved	0.0522**	0.0811**	0.0760**
	Hybrid	0.142***	0.104**	0.105**
	ATE %			
	improved	.937192**	1.242769**	1.166684**
	hybrid	2.556126***	1.601737**	1.614431**

* p<0.10, ** p<0.05, *** <0.001

Annex Table 1. Predicted marginal effects, ordered logit model

	dy/dx	Delta-method Std. Err.	z	P>z
Individually-managed plot				
local variety	0.13004	0.073798	1.76	0.078
improved variety	-0.09757	0.055008	-1.77	0.076
hybrid variety	-0.03247	0.019407	-1.67	0.094
Wife				
local variety	-0.20016	0.077019	-2.6	0.009
improved variety	0.150182	0.057427	2.62	0.009
hybrid variety	0.049976	0.020973	2.38	0.017
Son				
local variety	-0.09246	0.05413	-1.71	0.088
improved variety	0.069376	0.040743	1.7	0.089
hybrid variety	0.023087	0.013827	1.67	0.095
Education				
local variety	-0.19928	0.044414	-4.49	0.000
improved variety	0.149523	0.033556	4.46	0.000
hybrid variety	0.049757	0.013174	3.78	0.000
Anti-erosion				
local variety	0.107774	0.045797	2.35	0.019
improved variety	-0.08086	0.033982	-2.38	0.017
hybrid variety	-0.02691	0.012477	-2.16	0.031
Assets				
local variety	-0.04677	0.017592	-2.66	0.008
improved variety	0.035094	0.013091	2.68	0.007
hybrid variety	0.011678	0.004828	2.42	0.016
Labor supply				
local variety	-0.04325	0.018644	-2.32	0.02
improved variety	0.032448	0.014146	2.29	0.022
hybrid variety	0.010798	0.004777	2.26	0.024

* only statistically significant variables are included
n=728