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INTRAHOUSEHOLD EFFICIENCY OF FERTILIZER USE ON DRYLAND CEREALS IN MALI

By

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Food Security Policy *Research Papers*

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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

We examine fertilizer use among sorghum growers within Malian households in the Sudan Savanna. Dryland cereals in this region are typically produced by extended family members who are vertically (i.e., unmarried sons, married sons and their families) or horizontally (i.e., brothers; multiple wives) related to the head of the family farm enterprise. The head is usually an elder patriarch, or a work leader he designates. The head guides the organization of production on large plots labored collectively with the goal of meeting the staple food needs of the extended family. Custodian of the family's land use rights, he also allocates individual plots to household members who cultivate them privately to meet personal needs. We test intrahousehold differences in fertilizer adoption, efficiency and productivity by plot manager's gender and relationship to head. We apply a well-known econometric approach applied previously by researchers to data collected in Mali and Burkina Faso. In comparison with earlier research, we are able to control for unobserved variation in soil characteristics. We find that fertilizer application per ha on sorghum is on average higher among women than men. When we control for unobserved soil quality, we find little evidence that intrahousehold fertilizer allocation is inefficient, although productivity differentials persist. Further, differences in marginal products of nitrogen between female- and male-managed sorghum plots are not statistically significant. Findings have implications for design of programs to support cereals intensification in Mali.

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1. Introduction

A recent review of the structure and performance of the fertilizer value chain in Mali (Theriault et al. 2015) concludes that while total fertilizer use appears to have risen over the past decade, incentives for fertilizer use vary substantially among growers of the same crop. As in most other nations of Sub-Saharan Africa, Mali has blanket fertilizer use recommendations that too often fail to reflect the micro-variability of soil quality and differential benefits from use (Kaizzi et al. 2017; Kihara et al. 2016). Here, we examine the efficiency of fertilizer use and productivity among sorghum growers *within* Malian households in the Sudan Savanna region, which has the greatest agricultural potential in Mali (Dicko et al. 2017). We utilize data on soil nutrients measured by laboratory analysis of samples collected from plots managed by household members.

Dryland cereals in the Sudan Savanna are typically produced by extended family members who are vertically (i.e., unmarried sons, married sons and their families) or horizontally (i.e., brothers; multiple wives) related to the head of the family farm enterprise. The head is usually an elder patriarch who guides the organization of production on large plots labored collectively with the goal of meeting the staple food needs of the extended family. Custodian of the family's land use rights, he also allocates individual plots to household members who cultivate them privately to meet personal needs. If he is unable to supervise all production activities on collective fields, he designates a work leader.

In this patrilineal system, a large share of individual fields is operated by sons or brothers of the head, although according to social norms, women gain use rights to plots upon marriage. Traditionally, wives have grown the legumes they prepare in stews to accompany the family's starchy staple. They often use earnings from sales of produce on their individual plots to obtain supplementary food, pay for schooling or medical care of their children; any household member might use proceeds to purchase clothing, offer gifts, or contribute to ceremonies and festivals. Case studies conducted in the Sudan Savanna suggests that women increasingly grow cereals on these plots, in addition to legumes, in order to supplement food needs and ultimately, achieve food security (Van den Broek 2009; Donovan 2010).

Boosting cereals productivity through improved access to fertilizer is at the forefront of the Mali's agricultural policy (Theriault et al. 2015), but fertilizer is largely supplied via government programs rather than commercial markets, which remain underdeveloped. As the official household representative, the head is also the first point of entry of fertilizers received from registered cooperatives or formal programs. In the search for optimal resource allocation in this low-input, low-productivity farming system, land, labor, and other inputs like fertilizer are the objects of family negotiations. To depict decision-making in situations such as these, researchers have proposed collective (including cooperative) and non-cooperative models that emphasize the bargaining processes among household members rather than a single welfare function (e.g., Manser and Brown 1980; Chiappori 1992; Haddad et al. 1994; Smith and Chavas 1997).

Direct outcomes of intrahousehold bargaining include the allocation of modern inputs such as fertilizer, but intrahousehold models are largely absent from the literature on fertilizer adoption in Africa. In a seminal article, Udry (1996) tested a cooperative model of decision-making in Burkina Faso, where he found higher yields on plots managed by men compared with those managed by women, due to the fact that "virtually all fertilizer is concentrated on plots controlled by men" (1996: 1028). Analyzing data collected during the early 1980s, he was referring to use of manure rather than chemical fertilizer, and focused on gender comparisons without the ability to control for whether fields managed by men were collective or individual. More recently, Kazianga and Wahhaj (2013) applied a model similar to Udry's (1996) to data collected in Burkina Faso, concluding that labor intensity and productivity were higher on collective as compared to individual plots with similar characteristics. They attributed the difference to particular "social institution" of headship in this farming system. By contrast, Guirkinger et al. (2015) found greater productivity on individual than on collective plots when testing a comparable model with data collected in Mali. They ascribed their result to labor incentive problems.

In her critical review of the early literature on gender differentials in farm productivity, Quisumbing (1996) concluded that lower yields on farms managed by women resulted from lower amounts of inputs and resources used, rather than from any intrinsic differences. Recently, estimating a restricted profit function to test the relatively efficiency of men and women maize farmers in Western Kenya, Alene et al. (2008) found no evidence of gender-related differentials in either technical or allocative efficiency. In Ghana, Goldstein and Udry (2008) found that women achieved lower outputs and profits on their cassava/maize plots than did their husbands—although this outcome was related to less secure tenure rights.

Here, we contribute to the literature on gender and adoption by testing the intrahousehold efficiency of fertilizer use, building particularly on the work of Udry (1996), Kazianga and Wahhaj (2013) and Guirkinger et al. (2015). We invoke the standard econometric model applied by these authors, but focus on inorganic fertilizer, highlighting differences by gender of the plot manager and also his/her relationship to the head. In addition, we apply a yield response framework to test the differences in marginal products of fertilizer applied on male-managed and female-managed plots. Compared with the research conducted by these authors, we are able to control for soil nutrient content as measured by laboratory tests conducted on soil samples, or unobserved variation. “Unobserved variation in plot characteristics” could explain apparently inefficient allocation of resources (Udry 1996: 1029).

Understanding adoption patterns, efficiency and productivity differentials within as well as among households can contribute to the design of programs to raise productivity and support the future of farming in Mali. While findings have particular relevance to the process of agricultural intensification in the West African Sahel, they also complement gender analyses of technology adoption that have been recently conducted in other regions of the African continent (e.g., Theriault, Smale, and Haider 2017; Wainana, Tongruksawatta and Qaim 2016; Ndiritu et al. 2014; Lambrecht, Vanlauwe and Merckx 2014).

2. Methods

2.1. Estimation strategy

Our underlying perspective is that of a complex, family farm enterprise that maximizes utility over the consumption of leisure, farm-produced and purchased goods. Farm production occurs over multiple plots managed by various family members. Virtually all production depends on family labor and there is no discernible market for land (as confirmed in our data). The senior decision-maker (head, or designated work leader) is vested with authority to allocate pooled land and fertilizer inputs among plots depending on the family status of members and crop. Individuals can negotiate, but social norms encourage certain principles of allocation, including, for example, rights of access to land by all able-bodied male descendants of the head and above a certain age and their wives. In any single season, we view the land allocation as already predetermined when fertilizer decisions are made (Guirkinger and Platteau, 2014; Authors’ interviews). A priori, we know little about how fertilizer allocations are decided, although we have reason to believe, based on previous research in the region (Udry 1996; Kazianga and Wahhaj 2014; Guirkinger and Platteau 2014), that this is the outcome of a household bargaining process in which the welfare of individuals and the family as a whole are interwoven.

The null hypothesis we test in this paper is that fertilizer is allocated efficiently among household members, considering the gender of the plot manager and his/her relationship to the head.

Intrahousehold allocative efficiency is a necessary condition for Pareto efficiency. Consistent with Udry (1996), and subsequent work by Kazianga and Wahhaj (2013) and Guirkinger et al. (2015), we begin by testing a model that controls for crop-year-household fixed effects and plot characteristics.

Udry's (1996) approach enables us to restrict attention to variation in the intensity of fertilizer applied by members of the same household. Compared to the period during which he conducted his analysis, although labor and land markets remain virtually nonexistent in our study area, markets for fertilizer are nascent. However, his approach also controls for household-crop-specific transactions costs related to obtaining inputs.

Following Udry (1996), we specify the empirical model as

$$Z_{icj}{*}= \mathbf{X}_{icj}\boldsymbol{\beta} + \mathbf{G}_{icj}\boldsymbol{\gamma} + \lambda_{cj} + \boldsymbol{\varepsilon}_{icj}, \qquad (1)$$

where $Z_{icj}{*}$ is the observed amount of fertilizer applied per hectare to a plot i planted with crop c cultivated by a household j in the survey year. The vector **X** includes plot characteristics. λ_{cj} are crop-household fixed effects. We have only a single year of survey data, although this does not detract from our identification strategy since the Udry model also considers variation among plots and households one year at a time. **G** designates, in our case, not only gender of the plot manager but also his/her relationship to the head. If the elements of $\boldsymbol{\gamma}$, the vector of coefficients on the binary variables in **G**, are not statistically different from zero, ceteris paribus, we fail to reject the null hypothesis of Pareto efficiency in fertilizer allocation.

Udry's (1996) model, which is the basis of all three studies on which we build, assumes that any member of the household has access to the same technology for producing a given crop. By controlling for crop-year-household fixed effects and plot characteristics, he accounted for factors that might generate differences in marginal productivity among plots. In each of the three studies, data permitted researchers to control for soil characteristics associated with the location of the plot in the toposequence (lowland, plain, slope) and farmer-recognized soil type.

Here, we are able to include not only the location of the plot in the toposequence (lowland, plain, slope) but soil nutrients (soil organic matter, nitrogen, phosphorus, potassium, sand, silt and clay content) as measured in laboratory analysis of soils samples collected from plots. Such infrequently measured, unobserved soils characteristics or "land quality" are often invoked as an explanation for apparently "inefficient" (unequal) allocation of inputs. We compare regression results based on estimating the model with these soils characteristics and farmer-recognized soil types.

Further, in this analysis, we also estimate separate yield response functions plots managed by men and women in order to compare marginal products of nitrogen. All plots managed by men are collective, while all those managed by women are individual. Since women grow only sorghum in our sample, we restrict these models to sorghum plots. Major differences in the magnitude of the coefficient of nitrogen nutrient in kgs per hectare would suggest differences in marginal productivity based on gender of plot manager. To estimate the yield response functions, we add a vector of other production inputs **Y** to model (1), include measured soil characteristics, and separate the sample into plots managed by males and females. Subsample sizes are not large enough to estimate separate regressions reliably by relationship to head. Yield response functions are estimated with ordinary least squares and robust standard errors (clustered by household).

2.2. Data

Before sampling, a baseline census was conducted of all sorghum-growing households in 58 villages located in the Sudanian Savanna within the 800 mm isohyet. 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 since 2009. Our findings are therefore representative of areas with at least some engagement by the national research program. Only villages with fewer than 1000 persons were included. The survey was conducted in four visits from August 2014 through June 2015, using a combination of paper questionnaires and computer-assisted personal interviews by a team of experienced enumerators.

The enumeration unit in the survey is the *Entreprise Agricole Familiale* (EAF), which is the base unit most frequently used to analyze farm production systems in Mali. 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 collectively use production factors to generate resources under the supervision of one the members designated as head of the household, who is generally male. The head is the guardian of the household's productive resources and he also represents the EAF in all civil acts, including representation and participation in government programs.

As explained above, collective plots belonging to the whole EAF are managed by the household head or a designated team leader on behalf of the EAF. Individual plots belong to the EAF but are planted and managed by male or female family members for their own account. At the outset of each cropping season, the head distributes these plots based on the needs of the family.

The sample of EAFs was drawn with simple random sampling from the census of all sorghum-growing households in the 58 villages. The sample was augmented by five percent to account for possible non-responses, leading to a total of 623 EAFs and an overall sampling fraction of 25%. Enumerators interviewed heads to list all plots operated by each sampled EAF, selecting sorghum and maize plots and grouping these by plot management type (collectively- or individually-managed by men or women who are not heads). Questions regarding household characteristics were also addressed to the head.

One plot was then randomly sampled in each group (two crops by three management types) per EAF. The number of plots per household in the dataset depends on the type of plots found in the EAF. The full plot inventory (4617 plots) showed that sorghum and maize represented 75% of all cereals plots, excluding millet, which was not fertilized, and a few plots of rice and fonio. The inventory also demonstrated that 15% of listed plots were managed by men who were not household heads, and most of these were designated team leaders who have the same status as the household head or who managed plots planted to other crops, such as cotton or groundnuts. In our sampling from the plot inventories of each EAF, we identified only 16 usable records on individual plots managed by other male household members who planted either sorghum or maize. Women managed 205 individual sorghum plots in our sample, and none of the individual maize plots (in the full plot inventory they managed only 5 out of 753). The total analytical sample we employ here is 1,106 plots, including 674 sorghum plots and 432 maize plots. We include all collective plots managed by men and all individual plots managed by women, but for statistical reasons, we exclude the few individual plots managed by men, and observations with outliers in key variables. Plot managers were interviewed concerning fertilizer use, use of other inputs, and other plot characteristics.

2.3. Variables

Definitions, means and standard deviations of dependent and explanatory variables are shown in Table 1. For ease of interpretation, in the descriptive statistics, fertilizer is measured as total kgs of fertilizer applied per ha as wells as total nitrogen (N) nutrient kgs per ha. In the regression models, fertilizer use $Z_{icj}*$ is measured as total nitrogen (N) nutrient kgs per ha. N nutrient kgs per ha is calculated by taking the percentage of nitrogen in each fertilizer type and multiplying by total kgs applied. Yield is measured by farmer recall of quantities harvested, converted to kgs, and divided by the plot area as calculated with GPS units.

In the Udry-type model, plot characteristics (vector **X**) comprise the size of the plot (measured by GPS), a binary variable marking the presences of a legume intercrop, and binary variables for location of the plot in the toposequence (plain, lowland, and slope, as the omitted category). Farmer-recognized, or observed soil classes include sandy, silty, and clayey, with gravelly as the omitted category. These soil classes are also recognized by extension services, although a single plot may contain a combination or gradient of types. **G** is a vector of binary variables that refer to a) gender of the plot manager and b) to his/her relationship to the household head. Other plot manager categories include daughters-in-law of the head and sons of the head (the omitted category includes brothers).

In the yield response function, we estimate separate regressions to test for differences in the marginal products of nitrogen by gender. To the covariates noted above, we add conventional production inputs. These consist of adult labor days per ha, and equipment hours per ha.

In both approaches, we include soil nutrient indicators measured in laboratory tests conducted on soil samples by the *Institut d'Economie Rurale*, Sotuba, Mali. Soil samples were obtained by following a standard protocol with 8 sub-samples per plot collected in a zig-zag pattern (details available on request). We include percentage content of soil organic matter (C), sand, silt and clay, the percentage nitrogen content (N), assimilable phosphorus (P) and potassium (K). Soil samples count not be collected from all plots due to budget constraints.

3. Results

3.1. Descriptives

We begin by comparing mean fertilizer use rates between plots managed by males and females in Table 2. Average rates of fertilizer application, measured in terms of total kgs per ha, differ significantly between the two groups (88 compared to 38 kgs per ha, for males and females). The same is true when expressed in terms of N nutrient content (22 v. 9 kgs per ha, for males and females). However, controlling for crop reveals that N application rates are actually higher on female-managed plots (9 v. 6 kgs per ha). The large difference overall, favoring plots managed by males, is explained by application rates on maize. Mean rates of N nutrients applied to maize plots, all of which are male-managed, are 40 kg per ha, which is a different order of magnitude than that applied to sorghum.

Maize responds better to fertilizer and is also a rotation crop with cotton. There is ample evidence that the institutional and technical relationship of maize to cotton has contributed to a surge in both the scale of maize area and maize productivity—at the expense of sorghum, in particular. From the mid-1970s to mid-1980s, the state-owned cotton ginnery, CMDT (Malian Company for Textile Development), engaged in the promotion of maize production to help support household food security among cotton growers (Theriault and Sterns, 2012). CMDT still allocates a part of its budget to fertilizers offered to farmers (more than 90 percent in the cotton zone), boosting maize production (Tefft 2010). Koulibaly et al. (2011) report that the CMDT recently began to provide input loans for fertilizer and herbicides for maize as a diversification strategy and to prevent the continued decline in cotton yields. With falling cotton prices, farmers decided to re-allocate fertilizers destined for cotton to maize, resulting in maize intensification of maize and hefty yield gains (Laris et al.2015; Foltz et al. 2012).

The allocation of fertilizer across sorghum and maize plots managed by household members is shown in Table 3. Again, looking at the first set of columns that represents use of fertilizer on all plots combined, application rates per ha appear markedly higher on plots managed by the head, brother, or son, compared to those managed by the first or second wife or daughters-in-law. In fact, controlling for crop, use rates are lowest among sons managing either sorghum or maize plots (middle and right-hand set of columns), and highest among wives of the head.

As discussed above, compared to Udry (1996) and Kazianga and Wahhaj (2013), we are able to control not only for observable but for unobservable characteristics of soils. Unobservable soil characteristics could be a source of endogeneity in fertilizer use, and may also explain apparent inefficiencies in resource use once we have controlled for household, crop, and survey season. Table 4 presents summary statistics on farmer-recognized and tested soil types, by plot management type.

In general, apparent differences in farmer-recognized soil types are not matched by differences in soil test results. According to farmers, plots managed by male family members are far more likely to be clayey in soil type (31% as compared to 12%), and clay soils are considered to be the most fertile. Female-managed plots are more likely to be silty, but particularly to be sandy (48% as compared to 36%). According to farmer-recognized soils types, there is no difference in the likelihoods of gravelly plots between male- and female-managed plots. Gravelly soils are the least productive.

Turning first to these indicators among the soil test results, we see significantly higher mean percentages of clay in plots managed by females as compared to those managed by males. Silt content is statistically higher on female-managed plots, although the magnitude of the difference is very small (roughly 2 percentage points). Contrary to perceptions, sand content appears significantly lower on female-managed than on male-managed plots. Differences between the soil classification of plots by farmers and the measurements on these same elements may reflect either measurement errors or misperceptions.

The difference in mean C is weakly significant (10%), but not appreciable in size, and there are no statistically significant differences in mean N, P or K content. All three of these elements reflect both underlying nutrient content and quantities applied, since they were measured on samples taken late in the survey season. The fact that these are not significantly different at the mean gives us a preliminary suggestion that plot managers have a good sense of nutrient content and apply fertilizers adaptively in ways that do not differ by gender.

The descriptive statistics shown here provide no immediate evidence that plots managed by women are any less fertile than those managed by men. The underlying data also demonstrate that plots managed by female household members have very small sizes—on average, 0.85 ha as compared to 1.59 ha for plots managed by male household members in our analytical sample. They are also situated further from the homestead (a mean of 22 minutes compared to 15), suggesting that their fields were cleared later and may not have been cultivated continuously for as long as the collective plots of the extended family. Nearly 70% of female-managed plots are intercropped with legumes, while none of the male managers of collective plots of maize or sorghum reported intercropping.

3.2. Econometric findings

In this section, we first present the results of a Udry-type model to test the null hypothesis that fertilized is allocated efficiently within households (Tables 5, 6). Household-crop fixed effects are not reported. Second, we show yield response functions estimated separately by gender of plot manager (Table 7). In the first of these approaches, we compare results obtained when controlling for farmer-recognized soil types, as did Udry (1996), Kazianga and Wahhaj (2013), and Guirkinger et al. (2015). In the yield response framework, instead, we use information from soils tests on samples collected from plots.

The most striking result shown in Table 5 is that whether we control for observed or unobserved soil quality changes the significance of the gender differential. This holds when we control for plot characteristics and crop-household fixed effects in a single year of data, focusing on variation by plot management. The gender differential is significant when we include observed soil quality, and insignificant when we include measured, unobserved soil quality. Similarly, differentials for first and second wives, as well as daughters-in-law appear significant when we control for soil quality with farmer-recognized classes, but only that of the second wife is significant in the regression with soil quality as measured in the laboratory. Thus, in the Udry-type model as it was estimated in previous research we reject the null hypothesis that fertilizer allocation within households is efficient, while we fail to reject it in the same model when we control for unobserved soil quality. Udry offered this possibility in his 1996 article.

The results shown in Table 6 indicate that grain output per ha is significantly lower on female-managed as compared to male-managed plots, regardless of whether we include observed or unobserved indicators of soil quality. In the third column of results, we see that the yield differential appears for each category of female plot manager (first wife, second wife, daughter-in-law), in order of worsening magnitude. In the fourth column, where we control for unobserved soil quality, gender differentials in productivity are robust for wives of the head, although they are considerably smaller in magnitude. As in Table 5, where we explore fertilizer use intensity, there are no significant coefficients on the binary variables for son of the head, as compared to the brother of the head, in any of the regressions.

Lower yields on the plots managed by wives of the head are consistent with Udry's (1996) results in Burkina Faso, which he attributed to a concentration of fertilizer use (primarily manure) on plots managed by male household members. As noted in Table 2 and 3, we find that concentration only on maize fields, and in our sample, all female plot managers grew sorghum on their individual plots. We attribute lower yields to other factors. First, GPS area measurements are prone to error with very small plot sizes, like those found on female-managed plots in our analytical sample, but not on male-managed plots, all of which are collective and "large" (the term used is often grands champs). Second, we note the high rate of intercropping on female-managed plots of sorghum, which leads to measurement errors by construction, because the denominator in the yield variable is overstated relative to the actual area in the primary crop. The negative coefficient on this variable in Table 6 supports this notion. The importance of the legume intercrop, which is often groundnuts, may lead to higher rates of nitrogen use per ha, which we observe in the significant positive effect in Table 5, fourth results column. Groundnuts are a remunerative cash crop. Unfortunately, our data do not permit us to correct for this type of measurement error because we have neither estimates of the plot share intercropped nor of output from the secondary crop.

The gender differential in productivity remains, however, when we control for whether or not the plot is intercropped. Abstracting from measurement error, case studies in the region have also suggested that non-divisible inputs, such as farm equipment, are allocated first to collective plots (Some 2011). As is well known, female family members allocate labor between essential household work and agricultural activities and are likely to be labor-constrained.

Turning to other covariates of interest in the productivity equation, the negative sign on the intercrop dummy confirms the measurement problem. Production on larger plots is generally more difficult to manage, and associated with lower yields. P and K seem to constrain production, since they are highly significant and their effects are positive in sign. The "silence" of variables representing the location in the toposequence and farmer-recognized soil types is not surprising in the Udry-type model. Udry (1996) noted the "strong correlation both the location and the soil type of a plot and the crop planted on that plot," so that much of the effect of these characteristics is picked up by the household-crop fixed effect (p. 1025).

Also in Burkina Faso, Kazianga and Wahhaj (2013) found a large, positive, statistically significant effect of the dummy for household head on plot yield, but no significant effect of the dummy for junior male relative to female status. In Mali, Guirkinger et al. (2015) found significantly larger yields on individual plots managed by male family members on individual fields relative to those obtained by heads for "care-intensive crops" (including maize) or cash crops.

In Table 6 we present the coefficients of yield response functions estimated separately for male and female plot managers. Sample sizes are too small to estimate regressions reliably by each relationship to the head, and these are not reported here. However, they are consistent with Table 6 in terms of the parameter of primary interest—the marginal physical product of fertilizer (and are available on request).

Table 6 shows the marginal product of fertilizer, measured as the change in grain yield per hectare for an additional 1 kg of N nutrient per hectare, by plot manager, when accounting for soil nutrient content as tested in the laboratory (C, N, P, K, Sand, Silt, Clay), other production inputs (labor, equipment), intercropping, and plot size. The binary variable representing the presence of a legume intercrop drops out of the regression for male plot managers, since none reported this practice. Subsample sizes are quite small when the crop has been restricted to sorghum and only plots on which soil samples were collected are included, contributing to high standard errors.

The estimated marginal product of N nutrients on plots is statistically insignificant in both regressions, although the magnitude is greater on female-managed plots. The two coefficients lie within the same confidence interval given the large standard errors. Thus, despite the differences in magnitude of the coefficient, we are unable to reject the hypothesis that the marginal product of N is the same on sorghum plots managed by male and female household members.

Sorghum yields on plots managed by male household members drop by 275 kg/ha when intercropped with legumes, reflecting measurement difficulties. The marginal product of labor is nearly twice as high on plots managed by female household members and this coefficient is significant at 10% despite the small subsample sizes—suggesting, as noted above, that labor is a binding constraint in either case but particularly for female plot managers. Use of equipment enhances productivity and is significant only in the regression for plots managed by male household members. Larger plot size contributes positively and insignificantly to yields on plots managed by women, but relates negatively and significantly to yields on plots managed by men.

Regarding soil nutrients, the productivity effect of N is negative but not significant on plots managed by either men or women, perhaps because it is in competition and offset by N nutrient application during the cropping season. The sign on C is negative, and its magnitude is large, on male-managed plots. Clay has the largest positive effect on sorghum yield relative to silt and sand content. Even though P (phosphorus) is often combined with N (in NPK formulation), the positive and significant effect of P suggests that this nutrient constrains yields.

Estimates of sorghum yield response to fertilizer, though low and statistically insignificant, are within the range cited in the literature. Analysis of trial data by Institut de Recherches Agronomiques Tropicales (IRAT) from 1978-82 in Burkina Faso showed experimental responses of

10.3 kg grain of sorghum per N nutrient kg, with much lower figures measured in farmers' fields (Matlon 1983). In an early review of literature on this topic, Yanggen et al. (1998) found that the marginal physical product of nitrogen nutrients in sorghum production was similar in Sub-Saharan Africa to other regions of the sorghum-producing world such as India, but were lower in West Africa, were most reported rates were in the 4-5 range. In a recent analysis conducted in Nigeria, Omonona et al. (2016) found response rates of only around 1 kg of sorghum in cereal root crop and agro-pastoralist farming systems. Kihara et al. (2016) found P to be a more limiting factor than N in sorghum trials conducted in Mali.

4. Conclusions

Stagnating yields of dryland cereal crops in Mali are often attributed to limited use of fertilizer on aging, degraded soils. In Mali, as elsewhere in the West African Sahel, dryland cereals are typically grown on fields managed by extended families that are headed by a male elder. The elder, or his designate, manages large plots that are farmed collectively with the primary aim of meeting staple food needs; he also allocates individual plots to household members as an incentive to provide labor to the group and as a means for them to meet some of their private needs. In recent years, researchers have observed women's production of sorghum on their plots—often alongside legumes—which is a departure from historical norms and described as a means of ensuring food security.

As land quality declines and populations rise in Mali, the evolving roles of women and other members of the household have implications for the uptake of modern inputs such as fertilizer. However, a sizable literature on adoption of agricultural innovations in developing agriculture rarely considers intrahousehold dimensions or the household status of who manage plots within hierarchical households such as these. Similarly, although fertilizer use is an outcome of intrahousehold bargaining, neither the literature on intrahousehold bargaining nor previous studies on the efficiency of resource use by households in this region has directly addressed intensity of fertilizer use by different members, other than the seminal article by Udry (1996), whose data permitted only the examination of manure use.

Here, we began by testing whether intensity of fertilizer use differ by gender of the plot manager and his/her relationship to the head. We then tested the allocative efficiency of fertilizer use on plots managed by male and female household members (by gender, and then by relationship to head) with the modeling approach developed by Udry (1996), and later applied to data collected in this region by Kazianga and Wahhaj (2013) in Burkina Faso and Guirkinger et al. (2015) in Mali. The Udry model (1996) assumes that by controlling plot characteristics and household-crop-year fixed effects in a decision-making context where all household members have access to the same production technology, marginal products are equalized so that a difference in the coefficients on the gender or generation variable implies Pareto-inefficiency. In this article, we also applied a yield response framework to test the differences in marginal products of fertilizer applied on male- and female-managed plots. In the first modeling approach, as in the work by previous authors, we control for farmer-recognized soils classes and then substitute these with unobserved soils characteristics. In the yield response functions, we control for unobserved soil nutrients as measured by laboratory tests with soil samples.

Comparing use rates at the mean, use rates per ha in total kgs are many times higher on male-managed plots (all of which are collective plots in our sample) than those found on female-managed plots (all of which are individual plots). However, when we look more closely at sorghum plots alone, rates of nitrogen nutrients applied are higher on female-managed plots. Thus, crop largely explains differential intensity of fertilizer use between male-and female-managed plots. None of the women in our sample managed maize plots, though this may not hold true in other areas of Mali. The history of the maize as a crop introduced into the cotton farming system leads us to expect that women's maize plots remain rare, despite the growing importance of maize as a food crop on farms. The differences between use rates on sorghum and maize is a consequence not only of its higher yield response of maize but of its privileged status due to its relationship with the cotton program.

The principal result of this paper is that when we control for unobserved variation in soil quality, as compared to farmer-recognized soils classes, the Udry-type model shows little evidence of inefficiencies in intrahousehold allocation of fertilizer. Authors applying the same model in earlier studies conducted in the region (Kazianga and Wahhaj 2013; Guirkinger et al. 2015) were able to account only for farmer-recognized soils classes. However, controlling for household fixed effects, plot characteristics and unobserved variation in soil quality, yields remain lower on female-managed plots in our analysis. The differential remains when we control for intercropping, which contributes to underestimation of sorghum yields. Consistent with the results on fertilizer use, yield response functions estimated separately for plots managed by male and female household members demonstrate no statistical differences in marginal products of nitrogen. The limitations of our sample underscore the need to test the efficiency hypothesis with a larger sample size—but if it holds true, the result concerning fertilizer use stands in contrast to earlier research.

Results, combined with other features of the production system as represented in our data, suggest that differing strategies for managing production and soil fertility could explain productivity differentials. On average, we find no strong statistical differences in tested soils characteristics between plots managed by heads and their wives other than organic matter. However, the distribution of farmer-recognized soil classes is not the same for the two groups—and is more likely to be identified as clayey, and less likely to be classified as sandy, for plots managed by men—suggesting greater fertility. On the contrary, soil samples suggest higher clay content and lower percentages of sand in plots managed by women. Farmers manage fields according to their perceptions. Further, women's plots are on average small, a large share of them are intercropped with groundnuts or cowpea, and these are reported to serve as "food reserves" for the extended family in case harvests on the large collective fields are insufficient.

GPS measurement errors on small-sized fields managed by women could also contribute to the differentials we observe. So too could differential allocation of other resources such as equipment, and labor constraints, which are confirmed to be greater for women than for men in the yield response regressions.

There is a nagging concern that, despite these findings, fertilizer may not be cooperatively allocated within households in Mali because it remains a scarce input whose use is largely governed by programs. How agricultural policies and programs are designed and implemented greatly influences fertilizer use. Given that fertilizers are provided by official programs to the head of the extended family only and that all area planted to maize is eligible, but not all area planted to sorghum, the existing fertilizer program tends to bypass women, younger household members, and less commercialized food crops (Thériault et al. 2015). As it is, the allocation of any fertilizers received through official programs depends entirely on intrahousehold negotiations between the head and other household members. An area of further research would be to explicitly analyze the process of intrahousehold decision-making over fertilizers received through government programs and those purchased commercially.

Findings raise general questions concerning food security policy. Understanding adoption and intensification of food crop production within and among households is important for the future of farming in Mali. By what mechanism should the engagement of women and junior household members (sons, daughters-in law) be expanded as part of existing programs geared to raising productivity and farm income? For instance, increasing the participation of female plot managers in formal farmer cooperatives, while respecting family structures, could facilitate their access to credit and information services. In the short-run, improving involvement of female farmers in input programs may be helpful, but input programs in and of themselves are not a viable means of raising overall fertilizer use over the longer-term. Agricultural policies should focus on removing constraints that prevent all farmers, including women. Gender differentials in productivity between male and female farmers are a persistent policy concern given their private and social costs.

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Annex: Tables and Figures

Table 1. Definition of variables

Variable	Definition
Productivity	kg grain harvested/ha measured by GPS
Fertilizer	kg of fertilizer applied/ha measured by GPS
N nutrient	N nutrient kg of fertilizer applied/ha measured by GPS
Female	plot manager is female=1, 0 else
First wife	plot manager is first wife of head=1, 0 else
Second wife	plot manager is second wife of head=1, 0 else
Daughter-in-law	plot manager is daughter-in-law of head=1, 0 else
Son	plot manager is son of head=1, 0 else
Legume intercrop	plot planted to sorghum=1, 0 else
Plain	Plot located on the plaine=1, 0 else
Lowland	Plot located on lowland (*bas-fonds*)=1, 0 else
Sandy	Farmer-recognized soil type of plot is sandy=1, 0 else
Silty	Farmer-recognized soil type of plot is silty=1, 0 else
Clayey	Farmer-recognized soil type of plot is clayey=1, 0 else\
N	Log of N nutrient (%) content of plot soils
C	Soil organic matter (%) of plot soils
P	Log of Phosphorus (assimilable) content of plot soils
K	Log of Potassium (exchangeable) content of plot soils
Sand	Sand (%) of plot soils
Silt	Silt (%) of plot soils
Clay	Clay (%) of plot soils
Labor	Total person-days of labor/ha measured by GPS
Equipment	Total hours of equipment used/ha measured by GPS

Source: Authors.

Table 2. Fertilizer use by gender of plot manager

	Male	Female	p-value difference of mean test
	(mean)		
total fertilizer, kgs/ha	87.9	38.2	0.000
N nutrients, kgs/ha	21.9	8.66	0.000
N nutrients, kgs/ha, sorghum plots	5.62	8.66	0.000
N nutrients, kgs/ha, maize plots	40.3	--	--

Source: Authors. N=1,106. Female plot managers grew only sorghum.

Table 3. Fertilizer use on sorghum plots, by relationship of plot manager to head

	All plots			Sorghum			Maize		
Relationship to head	total fertilizer (kg/ha)	N nutrient (kg/ha	n	total fertilizer (kg/ha)	N nutrient (kg/ha	n	total fertilizer (kg/ha)	N nutrient (kg/ha	n
	(mean)			(mean)			(mean)		
Head	87.5	21.65	663	24.6	5.64	354	159.6	40.0	309
First wife	39.5	9.69	108	39.5	9.69	108	42.2		
Second wife	43.9	8.05	43	43.9	8.05	43	56.3		
Son	72.5	18.10	119	15.4	3.92	65	141.3	35.2	54
Brother	101.9	26.14	140	29.2	7.02	71	176.8	45.8	69
Daughter-in-law	27.6	6.36	33	27.6	6.36	33			
Total	79.6	19.68	1106	93.3	6.45	674	160.0	40.3	432

Source: Authors. N=1,106. Female plot managers in sample grew only sorghum.

Table 4. Farmer-recognized soil types and soil test results on male- and female-managed plots

	Male	Female	p-value	n
Farmer-recognized (%)				
Sandy	35.8	48.1	0.002	1106
Silty	19.1	25.9	0.035	1106
Clayey	30.9	12.3	0.000	1106
Gravelly	14.8	13.5	0.659	1106
Soil sample tests (mean)				
C (%)	0.510	0.563	0.074	686
N (%)	0.027	0.027	0.082	636
P assimilable ppm P	1.26	1.35	0.734	707
K exchangeable meq/100g	0.252	0.234	0.339	707
Sand % > 0.05mm	60.2	57.5	0.017	707
Silt % 0.05-0.002 mm	35.7	37.9	0.040	707
Clay % < 0.002mm	4.15	4.61	0.069	707

Source: Authors based on survey and test results.

Notes: test on percentages is Pearson chi, others are difference of means, ttests.

Table 5. Intensity of Fertilize Use by Gender and Relation to Head

	Gender		Relation to head	
	observed soil	measured soil	observed soil	measured soil
Female plot manager	-14.72***	-6.918		
	(4.688)	(4.991)		
First wife			-12.02**	-4.104
			(5.001)	(5.415)
Second wife			-22.08***	-16.61**
			(7.625)	(8.166)
Daughterinlaw			-21.12***	-11.13
			(7.534)	(8.266)
Son			5.088	4.270
			(6.652)	(8.193)
Plot size	-4.799***	-3.360**	-4.896***	-3.524**
	(1.195)	(1.647)	(1.199)	(1.657)
Legume intercrop	4.365	7.590	7.375	11.08*
	(5.687)	(6.107)	(5.958)	(6.478)
Plain	-0.709	-4.405	-0.744	-4.494
	(6.201)	(9.034)	(6.200)	(9.037)
Lowland	-16.74	-37.48	-19.60	-43.30*
	(15.85)	(23.01)	(15.98)	(23.49)
Sandy	6.482		6.069	
	(5.243)		(5.252)	
Silty	3.723		3.991	
	(6.335)		(6.362)	
Clayey	2.157		2.105	
	(5.746)		(5.786)	
C		-3.098		-2.081
		(6.975)		(7.005)
N		2.349		1.528
		(4.451)		(4.467)
P		18.30***		18.21***
		(4.628)		(4.643)
K		-0.216		1.028
		(4.864)		(4.916)
Sand		4.130		3.684
		(3.441)		(3.472)
Silt		4.045		3.604
		(3.448)		(3.477)
Clay		4.560		3.991
		(3.422)		(3.465)
Constant	29.31	-351.7	29.90	-307.8
	(27.94)	(344.7)	(27.94)	(347.7)
Observations	1,106	629	1,106	629
R-squared	0.450	0.586	0.454	0.592

OLS model with household-crop fixed effects. Standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table 6. Productivity by Gender and Relation to Head

	Gender		Relationship to head	
	observed soil	measured soil	observed soil	measured soil
Female plot manager	-558.6***	-317.3**		
	(130.1)	(140.2)		
First wife			-513.4***	-285.0*
			(139.1)	(152.8)
Second wife			-742.3***	-506.0**
			(212.0)	(230.4)
Daughterinlaw			-617.8***	-341.5
			(209.5)	(233.3)
Son			29.86	-68.63
			(185.0)	(231.2)
Plot size	-464.3***	-326.7*	-412.3**	-282.2
	(157.8)	(171.5)	(165.7)	(182.8)
Legume intercrop	-183.4***	-58.03	-184.6***	-58.87
	(33.17)	(46.25)	(33.33)	(46.77)
Plain	-206.2	-294.5	-204.8	-291.5
	(172.0)	(253.8)	(172.4)	(255.0)
Lowland	-285.7	-1,217*	-337.8	-1,279*
	(439.8)	(646.3)	(444.3)	(662.9)
Sandy	129.1		121.3	
	(145.5)		(146.0)	
Silty	171.4		168.8	
	(175.8)		(176.9)	
Clayey	154.3		149.5	
	(159.4)		(160.9)	
C		67.19		87.42
		(195.9)		(197.7)
N		-29.12		-42.99
		(125.0)		(126.1)
P		542.4***		549.2***
		(130.0)		(131.0)
K		312.1**		326.4**
		(136.6)		(138.7)
Sand		57.80		44.75
		(96.66)		(97.98)
Silt		32.81		19.78
		(96.85)		(98.13)
Clay		67.53		52.65
		(96.11)		(97.78)
Constant	1,771**	-2,153	1,779**	-870.5
	(775.3)	(9,683)	(776.8)	(9,812)
Observations	1,106	629	1,106	629
R-squared	0.652	0.768	0.652	0.769

OLS model with household-crop fixed effects. Standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

Table 7. Sorghum yield response functions, by gender of plot manager

	Male Plot Manager	Female Plot Manager
N nutrients	-0.634	3.008
	(3.647)	(2.187)
Labor	0.830	2.950*
	(0.777)	(1.676)
Equipment	0.603***	0.114
	(0.0586)	(0.171)
Legume intercrop+	-	-274.7***
		(74.04)
plotsize	-56.28*	166.0
	(30.89)	(100.7)
C	-300.3***	88.66
	(109.6)	(73.04)
N	-95.40	-29.80
	(61.78)	(44.50)
P	158.6***	46.21
	(45.22)	(44.74)
K	-45.01	-75.18
	(60.51)	(69.81)
Sand	16.68*	143.0
	(9.531)	(142.4)
Silt	21.43**	144.7
	(10.12)	(142.0)
Clay	40.58**	168.0
	(15.85)	(148.7)
Constant	-1,755*	-14,556
	(936.6)	(14,218)
Observations	319	157
R-squared	0.379	0.502

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

+ No intercropping reported on collective fields managed by men.