Food Policy 102 (2021) 102121

Contents lists available at ScienceDirect

Food Policy

journal homepage: www.elsevier.com/locate/foodpol

The unintended consequences of the fertilizer subsidy program on crop species diversity in Mali

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ARTICLE INFO

Keywords:
Fertilizer
Subsidy
Crop species diversity
Intensification
Mali

ABSTRACT

Over a decade ago, the Malian government launched a fertilizer subsidy program to expand fertilizer use, boost productivity, and ultimately, improve food and nutrition security. The program specifically targets key crops in the socio-economic development of Mali: rice, cotton, maize, millet, and sorghum. All farmers of target crops are eligible to obtain subsidized fertilizer at a quantity proportional to the number of hectares they expect to plant to those crops. Subsidy rates differ by crop. We hypothesize that the fertilizer subsidy in Mali changes the agricultural landscape by distorting the incentives to allocate land both among target crops and between target and non-target crops, with unintended consequences for crop diversification. We apply two econometric strategies to a farm household dataset collected in 2017/18 in the most productive agricultural zones of Mali and test the effects of the fertilizer subsidy program on indicators of crop species diversity. Findings from propensity score analysis and control function approaches reveal that the fertilizer subsidy program incites households to allocate more of their land to target crops, resulting in a greater concentration of area in target crops and reduced evenness of the area distribution among them. These findings raise concerns about how best to achieve food and nutrition security, when a costly program such as this favors a non-food crop (cotton) and starchy staples over other nutrient-dense or high value crops. The environmental sustainability of a program that reduces crop species diversity in an agricultural landscape is also questionable.

1. Introduction

Historically, Mali's agricultural growth has relied on extensification strategies, characterized by expansion of total cultivated land and minimal adoption of technologies such as improved seed, mineral fertilizer, and mechanical equipment. Harvested crop area has almost doubled since the early 2000s, reaching approximately 6 million hectares in the late 2010s (CountrySTAT 2020). Expansion into increasingly marginal lands, combined with aged, degrading soils, uncertain moisture, and weather variability have led to stagnating, low productivity. This is especially the case for the dryland cereals—sorghum and millet—that have long constituted the main staples of Mali's predominantly rural population.

With limited land available for farming, extensification is no longer a viable strategy to feed the growing Malian population. Intensification strategies to increase production and productivity while protecting natural resources have become central to achieving agricultural growth, food needs and nutrition security. With about four-fifths of the Malian population depending on agriculture as their main source of livelihood and one-fifth experiencing food insecurity (WFP (2020)), the Malian government has made it a top priority to increase agricultural intensification and diversification of farming systems (MDR (2015); CT-CSLP, 2016).

Over the last decade, numerous sub-Saharan African countries, including Mali, have established a new generation of agricultural input subsidies with the goal of expanding input use to smallholder farmers outside the reach of commercial suppliers to increase their productivity. Following the global food crisis of 2007/08, the Malian government launched a program called *Initiative Riz*, to boost rice production through subsidized fertilizer. Though the program had limited success (Smale et al. 2011), the government extended it first to cotton farmers. Long-standing, state-sponsored programs have favored cotton because of its role in the national economy (Kone et al., 2019b); after gold, cotton is the second source of export revenues in Mali (USDC (2019)). Maize,

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https://doi.org/10.1016/j.foodpol.2021.102121
Received 14 October 2020; Received in revised form 11 June 2021; Accepted 15 June 2021
Available online 26 June 2021
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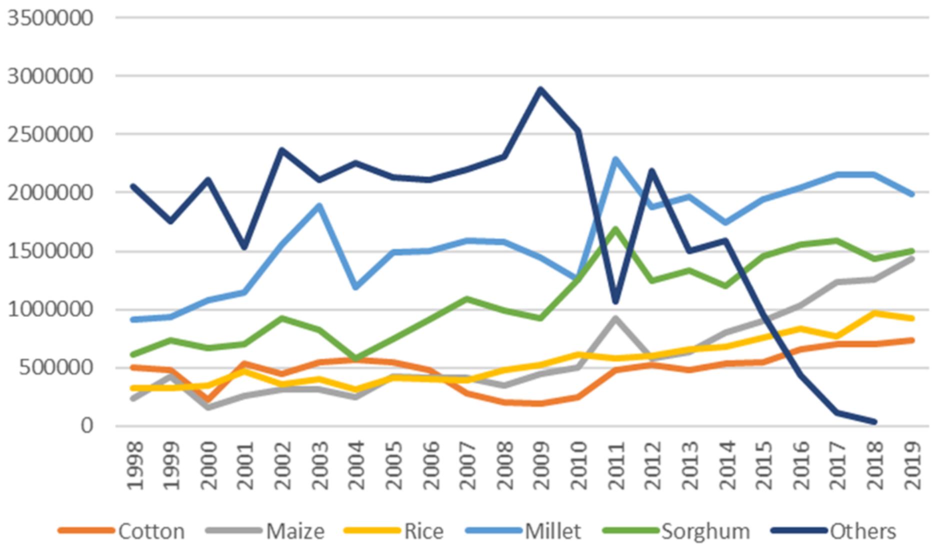

Fig. 1. Trends in cultivated area (hectares) planted to target and non-target crops. Source. FAOSTAT (2021).

originally promoted as a rotation crop with cotton in response to concerns for household food security (Theriault and Sterns 2012), was subsequently added. In recent years, maize has been gaining in popularity as a staple food and animal feed, but only grows in higher rainfall areas. Sorghum and millet, the principal starchy staples, were added to the list.[1] Only growers of target crops—rice, cotton, maize, millet, and sorghum—are eligible to benefit from subsidized fertilizer (DNA (2017)).

As currently designed, all Malian farmers of target crops are eligible to benefit from subsidized fertilizer at a quantity proportional to the number of hectares they state that they expect to plant. The quantity of subsidized fertilizer per hectare of rice, maize, and cotton is provided at rates per hectare as recommended by the national research institution, the Institut d'Economie Rurale (IER), whereas only 35% of the recommended rate is subsidized for millet and sorghum (AGRA 2018; Niangado 2020).

Although a substantial body of literature has analyzed the impacts of subsidized fertilizers on smallholder farmers in Eastern and Southern Africa (see reviews by Druilhe and Barreiro-Hurlé 2012; Wanzala-Mlobela et al. 2013; Kato and Greeley 2016; Jayne et al. 2018; Holden 2019), empirical evidence is relatively limited in West Africa, including in Mali. Farming contexts differ across regions of sub-Saharan Africa, as do program designs and implementation procedures (Smale and Theriault 2018). Most micro-economic studies have tested "first-order" effects on fertilizer use and crop yields, later including income and poverty outcomes. Area planted in the target crop is investigated in several studies, showing mixed results. However, we found only two studies that directly tested the impacts of the subsidy on the diversification of crop species, and these, conducted in Malawi, focused on the seed component of the input package (Chibwana et al. 2012; Snapp and Fisher 2015). In further analysis of Malawi's program, Asfaw et al. (2017) found that voucher recipients were among the less efficient producers; crop diversification, considered as a determinant rather than an outcome, was negatively associated with efficiency and counteracted with production variability.

Fertilizer subsidies on staple food crops could have a positive effect on crop diversification if adequate incentives exist to grow other crops. Norman Borlaug's "land-saving hypothesis" was that intensification of staple food crops can protect an agricultural landscape by enabling the production of the same (or more) amount of food on less (or same amount of) land—a notion that was adopted by resource conservationists during the 2000s (Ramankutty et al. 2018). Several studies have explicitly tested whether the Green Revolution spared land. Evenson and Gollin (2003) found that global crop areas of rice, wheat and maize would have been larger by 3–4% in 2000 without the Green Revolution. Considering ten crops, including these, Rudel et al. (2009) found that between 1970 and 2005, agricultural intensification was not accompanied by a decline or stasis in cropland area at a national scale, except among richer countries in temperate climates with grain imports and conservation set-aside programs. Yields generally increased but cultivated areas did not decline. Hertel et al. (2014) concluded that the Green Revolution not only spared land but also carbon dioxide, although the prognosis for sub-Saharan Africa would be similar only if global markets were segmented. Clearly, raising yields will not lead to cropland reduction without supportive policies.

Here, we test a version of the land-saving hypothesis. We ask whether the fertilizer subsidy in Mali changes the agricultural landscape by distorting the incentives to allocate land both among target crops and between target and non-target crops, with unintended consequences for the diversification of crop species across agricultural landscapes. Given that crop diversification is one of the major strategic axes of the Malian agricultural development plan (MDR (2015); CT-CSLP, 2016), we consider any reduction in crop species diversity that may result from the fertilizer subsidy program "unintended." We add to both the general literature on fertilizer subsidies in sub-Saharan Africa by highlighting the impacts of the subsidy on crop diversification and the literature on subsidy impacts in Mali by bringing quantitative evidence to bear on the national policy discussion.

We apply propensity score analysis to compare area shares and crop diversity indicators between beneficiaries and non-beneficiaries, followed by a control function approach to measure the marginal effects of the quantity of subsidized fertilizer applied, while controlling for endogeneity. We utilize a dataset collected from 2,400 farm households in the agro-ecological zones of the Niger Delta and Koutiala Plateau during the 2017/18 cropping season. Our crop diversity indicators are adapted to farm data on crop areas planted from ecological indexes of richness and proportional abundance.

2. Mali's fertilizer subsidy program

Fertilizer subsidy programs that do not target one group of farmers

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[1] Wheat growers also benefit from the subsidy, although area planted to this crop in Mali is negligible. Wheat is cultivated on less than 1,000 ha, or the equivalent of 0.16% of total harvested crop area (CountrySTAT 2020).

over another, such as female-headed households (as in Malawi and Tanzania) or small-scale farmers (as in Kenya and Zambia), have been referred to as universal (Wanzala and Groot 2013). Both men and women farmers as well as small-, medium-, and large-scale farmers are eligible to receive subsidized fertilizers in Mali. Yet, the program is not truly universal since it targets specific crops. Only farmers growing the target crops—rice, cotton, maize, millet, and sorghum—qualify for subsidized fertilizer. While 100% of the total recommended fertilizer application rates are subsidized for cotton, rice, and maize, only 35% of the total recommended fertilizer rate per hectare is subsidized for millet and sorghum (Niangado 2020). Sorghum and millet are less responsive to fertilizer than maize or rice (Haider et al. 2018).

Data compiled from FAOSTAT illustrate the trends in cultivated area (hectares) planted to target and non-target crops over the period that preceded and followed the beginning of the current subsidy program in Mali (Fig. 1). The number of cultivated hectares allocated to non-target crops has dropped precipitously since the *Initiative Riz* in 2008/09, except for a partial recovery around 2012. Less than 50,000 ha were allocated to non-target crops in 2018. On the other hand, the number of cultivated hectares devoted to target crops has increased.[2]

There are three channels through which farmers can access subsidized fertilizer: (1) the cotton parastatal company (Compagnie Malienne de Développement des Textiles, or CMDT); (2) the semi-autonomous governmental agency that manages the full-control irrigation system for rice (Office du Niger, or ON), and (3), the Regional Directorates of Agriculture (DRAs) that serve all other growers (Theriault et al. 2018a). The DRAs refer to Mali's regional extension centers. Given their limited financial and human capacities, services offered by the DRAs are sparse. In fact, farmers located in areas served only by the DRAs are referred to as "zones non-encadrées" (unsupervised zones). Regardless of the channels, all farmers must complete a voucher that states their production intentions in terms of crops and areas planted. The "paper" voucher remains the primary system for distributing subsidized fertilizer in Mali[3]. Farmers in the CMDT and ON zones are well-organized and benefit from the help of their cooperatives/organizations to ensure an early voucher submission. The quantity of subsidized fertilizer available in the DRA zones often fall short due to incomplete and late submission of vouchers.

There is no lower or upper limit to the quantity of subsidized fertilizer for which farmers can apply (DNA (2017)). Verification of landholdings claimed by farmers differs by zone (Smale et al., 2020a, 2020b). No official monitoring is conducted to ensure that actual planting patterns reflect the stated intentions in the ON zone. However, since the ON maintain records over the years, any large deviations could raise questions. Cotton farmers can obtain subsidized fertilizer on credit for both cotton and cereal crops through the CMDT on the promise of repayment at harvest via cotton sales. As such, the CMDT monitors closely the actual production of its members. Farmers who are neither members of the cotton cooperatives nor rice farmer organizations can only procure subsidized fertilizer from authorized private agro-dealers on their own initiative. Their claims are not consistently verified by DRA's agents. All farmers can also purchase unsubsidized fertilizer from private agro-dealers. Yet, the use of unsubsidized fertilizer remains rare in Mali. Survey data suggests that over 90% of total fertilizer applied is subsidized (Smale et al., 2020a, 2020b).

Fertilizer subsidies are one of the largest expense items in government spending on rural development in Mali. From 2008/09 to 2017/18, the quantity of subsidized fertilizer rose (from approximately 52,000 tons to 500,000 tons) as did the cost of the program (from approximately 11.6 billion CFA to 36.7 billion FCFA) (Kone et al., 2019b). During the same period, the share of the agricultural budget allocated to the fertilizer subsidy program expanded from 8.6% to 10.5% (Ibid). Increases were mostly due to the growing number of beneficiaries as new target crops were added. There were 210,160 beneficiaries in 2008/09 (under the *Initiative Riz*) compared to 819,230 beneficiaries in 2017/18 (AGRA 2018). Fertilizers are subsidized at 50% of their market price (Ibid). One subsidized bag of 50 kgs of NPK costs approximately 11,000 FCFA, not considering transaction costs. In Mali, as in many other sub-Saharan African countries, subsidized fertilizers are sometimes sold at higher prices than authorized (Liverpool-Tasie 2014; Theriault et al. 2018a; Theriault et al. 2018b).

3. Crop diversification matters

Over the longer-term, the diversification of crop species on farms has implications for soil nutrient balances, plant pests and diseases as well as income and diets of farming households (Bellon et al. 2020; Jarvis et al. 2015; Kontoleon and Pascual, 2009). Spatial diversification of crop species can support agroecosystem resilience by enabling the suppression of pest and pathogen transmission, lowering dependence on insecticides through biological control (Redlich, Martin and Steffan-Dewenter 2018), and buffering crop production against climate variability and extreme events (Gaudin et al. 2015; Lin 2011). Crop diversity is economically valuable. Analysis over five decades of data and 176 crops in 91 nations demonstrates that greater crop diversity at the national scale is associated with greater temporal stability in national food production (Renard and Tilman 2019).

Recent studies document the role of crop diversification in enabling farmers to manage income risk and adapt to climate anomalies in sub-Saharan Africa (Asfaw et al. 2018; Bozzola and Smale 2020). Michler and Josephson (2017) concluded that crop diversity reduced poverty among Ethiopian farmers. Noack and Quaas (2021) calculated that a 10 percent increase in crop species diversity on farms in Uganda raised revenues by 3 percent.

4. Data

We utilize a detailed farm household survey dataset collected by the Institut d'Economie Rurale and Michigan State University in two major agro-ecological zones during the 2017–2018 cropping season. The sampling frame was drawn from the latest General Census of the Population and Housing, stratified by 1) agro-ecological zone (Niger Delta and Koutiala Plateau); 2) extension services operating zone (ON, CMDT, and DRA only); and 3) fertilizer subsidy delivery system (paper voucher and e-voucher). The Niger Delta and Koutiala Plateau were selected as the sampling universe because of their importance to agricultural production in Mali and geographical overlap with Feed the Future priority regions. In the Niger Delta, major crops are irrigated rice, millet, and sorghum (in the drylands), compared with cotton, lowland rice, maize, and sorghum in the Koutiala Plateau. Known as the grain baskets of Mali, these two agro-ecologies contribute more to total agricultural production in Mali due to great availability of arable land, higher rainfall, or large-scale gravity irrigation system (ON), and less political insecurity. (See Haggblade et al. 2019 for detailed information on the survey, including its sampling design.)

Rural standard enumeration areas (SEs) were randomly selected within each of the eight strata, with probability proportional to size of population. In total, 60 standard enumerations (SEs) were selected per agro-ecological zone, for a total of 120 SEs. In each SE, 20 farm households were randomly selected for a total of 2,400 farm households. Out of 2,400 households included in the original sampling strategy and household listing, 2,331 farm households participated in all stages of the multi-visit survey. Villages and households became inaccessible during

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[2] To our knowledge, no significant diversion of fertilizer from target to non-target crops has been reported. Fertilizer diversion from cotton to cereal fields was previously a major concern (Theriault and Serra 2014) but receded with the expansion of the subsidy program to cereal crops.

[3] As discussed by Kone et al. (2019a), the number of farmers who received the subsidized fertilizer solely through the e-voucher system remains negligible (less than0.15% in 2017/18).

later visits due to political insecurity. Detailed information on fertilizer subsidy and input use for plots of target crops was collected along with information on household and household members. The survey was specifically designed to assess the impacts of Mali's fertilizer subsidy program.

5. Methodological approach

5.1. Framework

Our empirical model is based on the underlying approach of the agricultural household model as developed by Singh et al. (1986), extended with emphasis on incomplete markets by de Janvry, Fafchamps and Sadoulet (1991) and Key et al. (2000), and adapted by Van Dusen and Taylor (2005) to the analysis of crop species diversity as an outcome of crop choices. Decreasing returns to scale in any given crop motivate the decision to grow multiple crops. These can result from soil heterogeneity that requires matching crops to soil conditions, incomplete markets for a crop that a household prefers to consume, or a factor such as fertilizer to which crops respond differentially and that may be rationed through a program (Van Dusen and Taylor 2005).

Van Dusen and Taylor (2005) articulated the "diversity outcome" as the farm household's derived demand for multiple crops. In reduced form, the diversity outcome is a function of the household, farm, and market characteristics on which farm household decisions are conditioned. Farm characteristics include factors such as the heterogeneity of soil types, topology, dispersion in the landscape (distance to plots), and operational scale (farm size). Other farm determinants include use of manure, which serves as either a substitute or a complement to inorganic fertilizer, and the average age of the farm household plots, which is likely to be related to soil quality.

Key household characteristics include the physical labor endowments that affect capacity to grow multiple crops and apply fertilizer, and the human capital (education) that enable access to markets and related information—and in our case, the fertilizer subsidy. Labor markets remain largely absent in our data; farm labor is supplied almost exclusively by unpaid male and female household members. The capacity of a farm household to participate in the fertilizer subsidy program is likely to depend on the education of the household head, number of years that the household head has been a member of any farm organization/cooperative, as well as household labor availability and wealth, proxied by the number of adults and farm size. Non-farm income received before planting could relieve cash constraints on the farm.

A major motivation for the fertilizer subsidy has been to compensate for incomplete commercial markets by driving the factor price downward. We use average distances to the nearest retail store and the capital city, Bamako, as market characteristics. Other influences include whether the farm household is in a zone "encadrée" by the CMDT or ON.

We test hypotheses concerning the effect of household participation in the fertilizer subsidy program on land allocation among crops (diversity outcomes) while controlling for these factors. By reducing the cost of fertilizer on target crops, the subsidy provides incentives that favor land allocation to these crops. At the same time, according to the land-saving hypothesis, higher productivity in target crops could enable households to re-allocate land toward non-target crops.

In Mali, as in other sub-Saharan African countries, participation in the fertilizer subsidy program is non-random. Participating farm households may have different (un)observable characteristics that influence their decisions. For instance, participating farm households may be more likely to belong to a farmer organization/cooperative than non-participating farm households and in turn, membership in a farmer organization/cooperative affects land allocation. Identifying causal effects requires correcting for potential selection bias emerging from (un) observable characteristics. We can observe the outcomes for farmers who participated in the program and those who did not, but we cannot observe outcomes for participating farmers had they not participated. We are faced with the fundamental problem of causal inference, which is our inability to observe the counterfactual. To estimate causal effects without randomization, we employ two econometric strategies: propensity score analysis (PSA) and control function approach (CFA).

5.2. Propensity score analysis (PSA)

PSA has been extensively used to control for potential selection bias in analysis of the impacts of program participation, including in fertilizer subsidy programs (Chirwa 2010; Liverpool-Tasie 2014; Snapp and Fisher 2015; Mason et al. 2016; Wossen et al. 2017; Theriault et al. 2018a). PSA allows us to compare the outcome of participating farm households with those of non-participating farm households that have similar observed, causally relevant characteristics, other than their participation in the fertilizer subsidy program.

Building on Rosenbaum and Rubin (1983), we specify an empirical model that estimates the differences between outcomes of those participating in the fertilizer subsidy program and the outcomes that they would have achieved had they not participated. Since we can only observe the outcomes from one regime at one point in time, we estimate the propensity score with a probit model in order to find comparable participating and non-participating farm households based on a set of causally relevant characteristics. The propensity score is defined as the conditional probability that a farm household is assigned to a particular participation regime given a vector of observed, causally relevant characteristics.

We first create two comparable groups: the participant group (treated) and the non-participant group (control). We then estimate the average causal effect from the observed outcomes in each group. The model relies on two key assumptions. The overlap assumption posits that each farm household has a positive probability of participating or not in the fertilizer subsidy program. The unconfoundedness assumption stipulates that outcomes are independent of the participation regime conditional on the set of covariates. Assuming that the assumptions are satisfied, we can impute the outcomes of the non-participating farm households that have similar characteristics as if it were the counterfactual outcomes of the participating farm households.

We assess the quality of matching by conducting the balancing property test and analyzing the variance ratios as well as the Rubin's B and Rubin's R. We look at the distribution of the propensity scores and probability scores to ensure a strong common support across groups. "If the groups show good balancing properties on observables, then it is reasonable to assume that there is no imbalance on unobservables" (Binci et al. 2018:9). Since matching methods are not insensitive to "hidden bias" that can arise from unobservables, we compute the Rosenbaum bounds to check the sensitivity of the estimated results. The Rosenbaum bounds do not test the unconfoundedness assumption itself, but rather test the robustness of the estimated results to potential bias from unobservables.

We employ several methods to estimate the conditional probability of participating in the fertilizer subsidy program based on observable covariates. Since no single method is optimal, we seek robustness across different matching (first and three nearest neighbor, Mahalanobis distance), weighting (inverse-probability weights (IPW)) and combined (inverse-probability weighted regression adjustment (IPW-RA) propensity score methods. Matching techniques can be computationally intensive and vary in terms of their exactness and completeness to match (Guo et al. 2020). Matching can be done on a set of covariates or estimated propensity scores. The (three) nearest neighbor matches each participant household to one (or three) non-participant household based on estimated propensity score. The Mahalanobis distance method matches participants to non-participants on a set of covariates based on the minimum Mahalanobis distance. Although the neighbor matching methods achieve a lesser degree of balance on covariates, these drop fewer observations than the Mahalanobis distance method (Guo et al. 2020).

Table 1
Spatial indices of crop diversity adapted from the ecological literature.

Diversity Index (D)	Concept	Construction	Definition in this study
Count	richness	$D = S$	S = number of crops,
Target count	richness	$D = S$	S = number of target crops
Menhinick	richness	$D=(S)/\text{sqrt}\ (A_i)$	A_i = total area planted on farm
Herfindahl	evenness	$D = -\Sigma\alpha_i{}^2\ D \geq 0$	α_i = area share in target crops

Source: Magurran (2004), Smale (2006).

We also use propensity score weighting methods, such as the inverse-probability weights (IPW) and a combination of propensity score and regression-based methods via the inverse-probability weighted regression adjustment (IPW-RA). The IPW estimator uses the predicted treatment probabilities to weight the observed outcomes. This estimator is not sensitive to whether some observations are unlikely to be treated but is highly sensitive to extreme values of the propensity score. As recommended, we trimmed the observations with a weighted propensity score of less than 5% and greater than 90%. The IPW-RA uses the IPW weights to estimate corrected regression coefficients to calculate predicted outcomes. The IPW-RA has the double-robust property of accounting for the nonrandom treatment assignment in both treatment and outcome models. For more details on the different propensity score methods, we refer the readers to Wooldridge (2010) and Guo and Fraser (2015).

5.3. *Control function approach*

We employ a control function approach (CFA) to examine the marginal effect of the total amount of subsidized fertilizer applied on cropping patterns, test, and control for potential endogeneity. Compared to PSM, CFA allows us to examine the effect of a continuous variable, test, and potentially control for endogeneity of fertilizer in the outcome variables. The total amount of subsidized fertilizer applied by the farm household has a large concentration of zero values. In the presence of this non-linearity, CFA is preferred to two-stage least squares (Smith and Blundell 1986; Vella 1993; Wooldridge 2015). In the first stage regression, the quantity of applied subsidized fertilizer is regressed on the instrumental variables and other covariates using Tobit. Endogeneity in subsidized fertilizer arises when the error term in the first stage is correlated with the outcome variable in the second stage.

To be valid, the instruments must be highly correlated with subsidized fertilizer (inclusion restriction) in the first stage regression but uncorrelated with the error term in the second stage regression (exclusion restriction). The F-statistic of the regression and significance of the instrument coefficients, individually and jointly, inform us whether the inclusion restriction is met (diagnostic for the presence of weak instruments). There is no formal test of the exclusion restriction and it is typically addressed through logical argument.

We tested multiple instruments. Like Bezu et al. (2014) and Mason and Smale (2013), we tested access to social capital at the household and village levels (including the number of members who have a leadership role in farmer organizations within a household and village). Following Asfaw et al. (2017), we examined the average distance to the fertilizer subsidy outlet. We also explored whether the farm household is in the pilot zone of the electronic voucher and the number of years that the farm households have benefited from any agricultural subsidies, including not only fertilizer, but also improved seeds and farming equipment, prior to the survey season. We tested access to information (Di Falco et al. 2011; Shiferaw et al. 2014; Coromaldi et al. 2015), measured as the number of household members within a village who received extension services during the year preceding the survey. Receiving extension services is correlated with participation in the subsidy program through better access to information but is unlikely to directly affect the cross-crop diversity metrics. Finally, we tested a unique binary variable that takes a value of one if the households experienced sickness as a major shock in the last three years as instrument. Past sickness reduces farm household labor supply, potentially reducing farm and non-farm income and the capacity to purchase costly inputs such as fertilizer—creating incentives to seek subsidized fertilizer but not necessarily affecting crop species diversity in the current year. Overall, our results remain robust to the choice of instruments. Among the statistically significant instruments, past sickness and access to information were the strongest. We report results for regressions that include these instruments.

In the second stage regression, we use several estimators (e.g., Tobit, OLS, Poisson) to accommodate for the different forms of the outcome variables (see Section 6 below for a detailed description of each outcome variable). When the quantity of subsidized fertilizer applied by the farm household is endogenous in the diversity outcome, the estimated coefficient of generalized residuals is statistically different from zero. Bootstrapped standard errors are computed to account for the inclusion of generalized residuals from the first-stage regression into the second stage. All standard errors are computed using the Delta method in the case of corner solution variables and are robust for OLS regressions. Regressions were estimated in STATA 15.

6. Variables

6.1. *Crop diversity outcomes*

As outcome variables of interest, we begin with the farm area share planted to target crops (maize, millet, sorghum, rice, cotton) and key target crops (rice, maize, and cotton). We then employ spatial diversity indicators that are adapted primarily from the ecological literature on measuring biological diversity (Magurran 2004).

Table 1 shows the spatial indices of crop diversity we apply, by concept and construction. Simply stated, richness refers to the number of different types of individuals regardless of their frequencies in the population of a given “space” or area (Jarvis et al. 2008). By contrast, evenness takes account of the similarity among the frequencies of the different types. Low evenness implies dominance by one or a few types. In the richness index, units are distinct but equal in importance. Evenness indices consider the relative abundance or distribution of individual units.

Richness is generally measured with a count of species encountered per unit of geographically defined area, such as a farm or village. Thus, one of our indicators is a simple count of all crops inventoried during the first survey visit to the farm household. A second is the count only of crops grown that are targeted by the subsidy program. Magurran (2004) mentioned two simple indicators of richness that normalize the simple count by total population size: the Margalef and the Menhinick indexes. The first divides the count by the logarithm of the population size and the second divides by its square root. We prefer the second because it is strictly positive.

The basis of the ecological indexes is the plant or animal population encountered in a circumscribed area of a natural landscape. In an agricultural landscape, we use area planted as a proxy for population size. Crop area shares have been utilized in the adoption literature in applied economics and can be interpreted as a measure of on-farm, constrained demand for the crop as derived from market incentives. Richness and evenness indices based on area shares have been applied in the analysis of crop diversity on farms in previous empirical analyses (see examples in Smale 2006).

The Herfindahl index, which is a commonly used measure of market concentration in the economics literature, can be adapted to measure concentration of crops targeted by the subsidy program. We employ it here as an evenness indicator. A high value of the Herfindahl index implies high concentration of area share in target crops and low evenness.

Taking into consideration the form of the dependent variable, we use

Table 2
Summary statistics for variables, by treatment.

	All (N = 2,331)	Treated (N = 1,997)	Untreated (N = 334)
Dependent Variables			
Target Crop Share	0.936 (0.103)	0.942*** (0.093)	0.898 (0.142)
Key Target Crop Share	0.622 (0.341)	0.672*** (0.303)	0.324 (0.400)
Herfindahl Index	0.903 (0.133)	0.910*** (0.126)	0.857 (0.166)
Menhinick Index	1.65 (0.66)	1.66** (0.67)	1.58 (0.66)
Crop Count	4.38 (2.03)	4.49*** (2.09)	3.76 (1.58)
Target Crop Count	2.51 (1.38)	2.66*** (1.40)	1.82 (0.86)
Treatment			
Participation in the subsidy program	0.856 (0.350)	——	—
Endogenous variable			
Quantity of subsidized fertilizer (ln kgs)	13.40 (10.14)	——	—
Covariates			
Adults (# of person)	8.31 (5.11)	8.48*** (5.07)	7.26 (4.61)
Education of the household head (years)	1.86 (3.27)	1.97*** (3.38)	1.18 (2.42)
Membership (years)	10.88 (10.94)	11.37*** (11.03)	7.91 (9.89)
Non-farm income (ln 000 FCFA)	6.42 (6.11)	6.47 (6.11)	6.12 (6.11)
Use of manure (yes = 1, No = 0)	0.657 (0.474)	0.636*** (0.480)	0.727 (0.445)
Average age of all household plots (years)	18.29 (11.85)	18.40 (11.78)	17.60 (12.26)
Total landholding (ha)	9.43 (7.55)	9.66*** (7.68)	8.06 (6.57)
CMDT zone	0.330 (0.470)	0.376*** (0.484)	0.057 (0.232)
ON zone	0.331 (0.470)	0.324* (0.468)	0.375 (0.484)
Soil types (n)	1.13 (0.59)	—	—
Topology types (n)	0.858 (0.439)	—	—
Time to plots (minutes)	19.00 (14.07)	—	—
Distance to nearest store (km)	2.75 (13.62)	—	—
Distance to Bamako (km)	385.02 (84.72)	—	—
Instruments			
Sickness (Yes = 1, No = 0)	0.350 (0.477)	—	—
Access to information (# of person within a village)	3.94 (2.21)	—	—

Source: Authors, from data collected by IER/MSU in 2017–18.
Notes: *, **, and *** denote a statistically significant difference between the treated and untreated groups before matching at 10%, 5%, and 1%, respectively. Standard deviations in parentheses.

a Tobit model for the area shares and Herfindahl index, OLS is employed for the Menhinick index, and a Poisson model is applied for crop and target crop counts.

6.2. *Explanatory variables*

Summary statistics for the covariates described above are shown in Table 2 for the full sample and per treatment group. There are statistically significant differences in the means of most covariates between the participant (treated) and non-participant (untreated) groups in the fertilizer subsidy program before matching. Hence, the importance of controlling for differences in observable causally relevant characteristics. As further explained in Section 7.1, several tests are conducted to ensure that the covariates are balanced after matching.

7. Results and discussion

7.1. *The effect of participation in the subsidy program on crop diversity outcomes*

The test of the balancing property of the property score indicates that balancing is satisfied. We fail to reject the null hypothesis of the overidentification test for covariates (Prob > chi2 = 0.666), meaning that covariates are balanced. After matching, the covariates are balanced, with standardized difference near zero and variance ratio close to one. The Rubin's B (17.6) is less than 25 and Rubin's R (1.11) is between 0.5 and 2 for the sample, indicating sufficient balance (Binci et al. 2018; Leuven and Sianesi 2020). As seen in Figs. A1 and A2 (appendices A-B), there is strong common support in the distributions of the propensity score and the probability score across treatment and control groups. We also fail to reject the null hypothesis that treatment and outcome unobservables are uncorrelated, leading us to conclude that treatment assignment is not correlated with potential outcomes (no endogeneity). Results from the probit model are presented in appendix C (Table A1).

Table 3 reports the average treatment effect on the treated for the diversity outcome variables using five different treatment effect estimators: 1) nearest neighbor matching, 2) three nearest neighbors matching, 3) Mahalanobis distance matching, 4) inverse-probability weights (IPW), and 5) inverse-probability weighted regression adjustment (IPW-RA). All the estimators, which are all subject to the two key assumptions, produce similar results. On average, households participating in the subsidy program devote nearly 6% more land to all targeted crops than non-participating households. The ATET is much larger on key target crops only. Participant households allocate, on average, over 30% more land to cotton, maize, and rice than non-participant households.

The Herfindahl index, which provides a measure of concentration of land allocated to target crops, increases by 7% with the subsidy. The effect of participation in the subsidy program on the Menhinick index, as

Table 3
Average treatment effect on the treated (ATET).

Methods	**Target Crop Share**	**Key Target Crop Share**	**Herfindahl Index**	**Menhinick Index**	**Crop Count**	**Target Crop Count**
Nearest neighbor	0.057*** (0.015)	0.365*** (0.028)	0.070*** (0.020)	0.114** (0.053)	0.405** (0.191)	0.581*** (0.140)
Three nearest neighbors	0.058*** (0.014)	0.361*** (0.027)	0.074*** (0.018)	0.086* (0.047)	0.336** (0.146)	0.561*** (0.099)
Mahalanobis distance	0.086*** (0.015)	0.338*** (0.023)	0.105*** (0.017)	0.018 (0.055)	0.245* (0.141)	0.633*** (0.092)
IPW	0.041*** (0.099)	0.290*** (0.042)	0.052*** (0.013)	0.050 (0.072)	0.223 (0.184)	0.437*** (0.129)
IPWRA	0.039*** (0.009)	0.280*** (0.040)	0.050*** (0.013)	0.035 (0.069)	0.272 (0.171)	0.461*** (0.123)

Source: Authors, from data collected by IER/MSU in 2017–18.
Notes: *, **, and *** denote statistically significant at 10%, 5%, and 1% using AI robust standard errors for matching and village cluster standard errors for inverse probability weight estimators.

Table 4
Second-stage regressions predicting effects of subsidized fertilizer on outcomes.

Variables	Target Crop Share	Key Target Crop Share	Herfindahl Index	Menhinick Index	Crop Count	Target Crop Count
	APEs (SE^{1})	**APEs (SE^{2})**	**APEs (SE ^{1})**	**Coef. (SE^{3})**	**APEs (SE ^{1})**	**APEs (SE^{1})**
First-stage residual	NS	0.0003*** (0.0001)	NS	NS	NS	NS
Subsidized Fertilizer	0.0020*** (0.0004)	0.012*** (0.001)	0.0023*** (0.0005)	−0.004** (0.002)	0.006 (0.007)	0.016*** (0.005)
Adults	−0.0001 (0.0004)	0.008*** (0.002)	−0.0002 (0.0006)	−0.007** (0.003)	−0.007 (0.008)	−0.007 (0.005)
Education	0.0002 (0.0007)	0.011*** (0.002)	0.0002 (0.0010)	−0.005 (0.005)	−0.028* (0.015)	−0.028*** (0.009)
Membership	−0.0001 (0.0002)	0.0002 (0.0008)	−0.0002 (0.0003)	0.001 (0.001)	0.004 (0.004)	0.003 (0.003)
Non-farm income	−0.0010*** (0.0003)	0.002* (0.001)	−0.0014*** (0.0005)	0.005** (0.002)	0.008 (0.006)	−0.001 (0.003)
Use of manure	−0.017*** (0.006)	−0.221*** (0.022)	−0.024*** (0.008)	0.140*** (0.037)	0.712*** (0.128)	0.478*** (0.088)
Age of plots	−0.0001 (0.0002)	−0.001 (0.001)	−0.0002 (0.0003)	−0.003** (0.001)	−0.003 (0.004)	−0.003 (0.002)
Landholding	−0.0012*** (0.0004)	−0.018*** (0.001)	−0.0018*** (0.0005)	−0.046*** (0.003)	0.056*** (0.009)	0.029*** (0.006)
CMDT zone	−0.016 (0.011)	0.134*** (0.016)	−0.021 (0.015)	0.179*** (0.067)	0.395** (0.188)	0.281** (0.121)
ON zone	0.079*** (0.010)	0.473*** (0.024)	0.114*** (0.015)	−0.501*** (0.070)	−2.20*** (0.278)	−1.43*** (0.197)
Soil types	0.0007 (0.005)	0.024 (0.017)	−0.003 (0.007)	0.127*** (0.037)	0.314*** (0.100)	0.322*** (0.060)
Topology	−0.004 (0.008)	−0.074*** (0.026)	−0.006 (0.011)	−0.077* (0.047)	0.117 (0.150)	−0.020 (0.104)
Time to plots	−0.00001 (0.00017)	0.0015*** (0.0006)	0.00001 (0.00024)	0.001 (0.001)	−0.002 (0.003)	−0.003* (0.001)
Distance to store	0.0005*** (0.0001)	0.0004 (0.0004)	0.0007*** (0.0002)	−0.005*** (0.001)	−0.011*** (0.003)	−0.005*** (0.001)
Distance to BKO	0.00013*** (0.00004)	0.0003*** (0.0001)	0.0002*** (0.0001)	0.0076*** (0.0002)	0.002*** (0.001)	0.003*** (0.001)
	Prob > F = 0.0000	Prob > F = 0.0000	Prob > F = 0.0000	Prob > F = 0.0000	Prob > LR = 0.000	Prob > LR = 0.000

Source: Authors, from data collected by IER/MSU in 2017–18.
Note: APEs denote average marginal effects. 1. Standard errors computed by the Delta method. 2. Bootstrap standard errors. 3. Standard errors clustered by village. The dependent variable is logged. *, **, and *** denote statistically significant at 10%, 5%, and 1%.

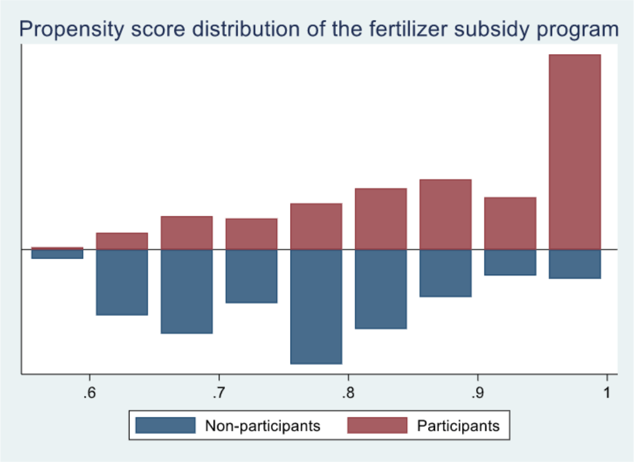

Fig. A1. Propensity score distribution in the fertilizer subsidy program. Source: Authors, from data collected by IER/MSU in 2017–18.

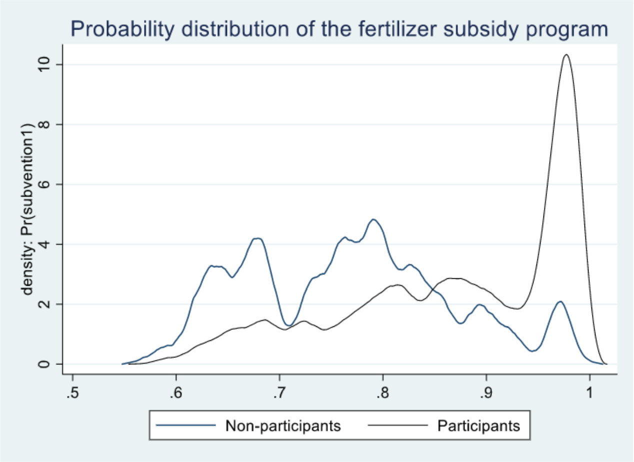

Fig. A2. Probability score distribution in the fertilizer subsidy program. Source: Authors, from data collected by IER/MSU in 2017–18.

well as on the crop count, is statistically positive when using neighborhood matching. Participating households plant more crops than non-participating households, even accounting for total farmed area. Yet, this finding does not necessarily translate into more crop diversity, since those crops are more likely to be those targeted by the subsidy program, as evidenced by the statistically positive ATET for target crop count.

Taken together, these results reveal a strong bias toward target crops. We performed the Rosenbaum bounds test to assess the robustness of those results to potential bias from the presence of unobserved heterogeneity and these findings are considered robust to unobservable characteristics (See Table A2 in appendix). As additional robustness check, we re-run the propensity score matching based on the first (third) nearest neighbor and Mahalanobis distance matching after dropping observations that have a greater than 90% probabilities of being treated.

Table A1
Probit results for propensity score matching.

Covariates	
Constant	0.592*** (0.112)
Adults (# of person)	0.028*** (0.008)
Education of the household head (years)	0.057*** (0.012)
Membership (years)	0.010*** (0.003)
Non-farm income (ln FCFA)	−0.001 (0.005)
Use of manure (yes = 1, No = 0)	−0.432*** (0.084)
Average age of all household plots (years)	0.002 (0.003)
Total landholding	0.002 (0.006)
CMDT zone	1.24*** (0.11)
ON zone	0.106 (0.082)
Pseudo- R2	0.1353
Prob > chi2	0.0000
Common support	[0.590 0.998]

Source: Authors, from data collected by IER/MSU in 2017–18.
Notes: *, **, and *** denote statistically significant at 10%, 5%, and 1%. Standard errors in parentheses.

The results remain robust (See Table A3 in appendix).

7.2. *The effect of total subsidized fertilizer applied on crop diversity.*

Next, we employ a CFA to examine the marginal effect of quantity of applied subsidized fertilizer on the agricultural landscape. The coefficient estimates from the first-stage Tobit regression are reported in the appendix (Table A4). The F-statistic of the first-stage regression is highly significant (F-statistic = 33.92; Prob > F = 0.000). Both instrumental variables are individually and jointly strongly correlated with the potentially endogenous variable, quantity of applied subsidized fertilizer (F-statistics > 10 and Prob > F = 0.001). The coefficient estimates for both instruments are positive and statistically significant at the 1% level.

Second-stage regressions are shown in Table 4. Target crop share, key target crop share and the Herfindahl index are regressed using Tobit. The OLS estimator is employed to estimate the Menhinick index. Both crop count outcomes are estimated using Poisson. The quantity of subsidized fertilizer applied by farm households has a strong effect on all diversity outcomes, except for crop count—as we found in our results of PSM estimation. As a robustness check, we also ran OLS, fractional probit, and negative binomial regressions, depending on the form of the dependent variables.

The more farmers benefit from the subsidy, the greater the area shares they allocate to target crops. An additional 1% of subsidized fertilizer leads, on average, to 0.2% in land allocated to all target crops. This result is mostly driven by the key target crops (i.e., maize, rice, and cotton) as indicated by the large and highly significant elasticity coefficient (1.2%) on subsidized fertilizer in the key target crop share regression. The amount of subsidized fertilizer applied has a strong positive effect on the Herfindahl index, contributing to the dominance of target crops on farms and reducing evenness. The amount of subsidized fertilizer applied by the farm household has no effect on overall crop count but exerts a negative influence on the Menhinick richness index, which normalizes by farm size. Again, we find a positive marginal effect on the count of target crops. As currently designed, the fertilizer subsidy program in Mali incites households to cultivate more target crops to the detriment of non-target crops, such as cowpea, peanut, and fonio.

Other covariates are statistically significant across the different diversity regressions. Use of manure is negatively associated with both target crop share indicators and Herfindahl index. Farm households with greater share of land allocated to target crops, such as maize, rice, and cotton, are eligible to receive greater quantity of subsidized fertilizer, since there is no limit per se. However, use of manure is positively associated with crop count measures, some of which are not eligible to subsidized fertilizer. These results suggest a substitute relationship between manure and inorganic fertilizer.

Landholding has a strong effect on all diversity outcomes. As it is expected in Mali's extensive, primarily rainfed farming systems, larger landholding is associated with less concentration in target crops and a greater richness of crops overall. Location in the Office du Niger has a positive effect on the share and concentration of land allocated to target crops but a negative effect on crop counts. These findings reflect that the survey was conducted during the primary farming season, which is the rainy season and coincides with rice production. Results might have been different if the survey would have been implemented during the off-season, which is more conductive to production of horticultural crops. Location in a CMDT zone is associated with more land allocated to

Table A2
Results from the Rosenbaum bounds test.

	All Target Crop Share		Key Target Crop Share		Herfindahl Index		Menhinick Index		Crop Count		Target Crop Count	
Gamma	Sig+/Sig-	CI + CI-	Sig+/Sig-	CI + CI-	Sig+/Sig-	CI + CI-	Sig+/Sig-	CI + CI-	Sig+/ Sig-	CI + CI-	Sig +/ Sig-	CI + CI-
1	0/0	0.954 0.962	0/0	0.612 0.647	0/0	0.917 0.931	0/0	1.58 1.64	0/0	4 4.5	0/0	2.5 2.5
2	0/0	0.921 0.985	0/0	0.5 0.764	0/0	0.866 0.972	0/0	1.39 1.85	0/0	3.5 5	0/0	2 3
3	0/0	0.9 1	0/0	0.447 0.821	0/0	0.836 1	0/0	1.29 1.98	0/0	3.5 5.5	0/0	1.5 3

Source: Authors, from data collected by IER/MSU in 2017–18.
Note: sig + and sig - denote the upper and lower significance level. CI + and CI- denote the upper and lower bound confidence interval at 0.95.

Table A3
Average treatment effect on the treated (ATET).

Methods	Target Crop Share	Key Target Crop Share	Herfindahl Index	Menhinick Index	Crop Count	Target Crop Count
Nearest neighbor	0.047*** (0.011)	0.291*** (0.030)	0.060*** (0.012)	0.062 (0.049)	0.197* (0.109)	0.434*** (0.066)
Three nearest neighbors	0.046*** (0.009)	0.298*** (0.025)	0.059*** (0.011)	0.057 (0.041)	0.230** (0.091)	0.421*** (0.061)
Mahalanobis Distance	0.051*** (0.009)	0.327*** (0.032)	0.068*** (0.012)	−0.012 (0.055)	0.111 (0.113)	0.388*** (0.063)

Note: Observations with estimated propensity score above 90% were trimmed.

Table A4
First-stage Tobit regression – Applied subsidized fertilizer (ln kgs).

Variables	APEs (S.E)
Sickness	1.36*** (0.48)
Access to information	2.75*** (0.26)
Adults	0.026 (0.063)
Education	0.228*** (0.061)
Membership	0.023 (0.020)
Non-farm income	−0.063* (0.036)
Use of manure	−3.49*** (0.66)
Age of plots	0.067*** (0.024)
Landholding	0.064 (0.048)
CMDT zone	4.97*** (1.05)
ON zone	3.20** (1.59)
Soil types	0.396 (0.571)
Typology	0.137 (0.943)
Time to plots	−0.037** (0.015)
Distance to store	−0.122*** (0.034)
Distance to BKO	0.024*** (0.008)
F (16, 2188) = 33.92 Prob > F = 0.0000	

Source: Authors, from data collected by IER/MSU in 2017–18. Standard errors computed by the Delta method.
Note: APEs denote average marginal effects. Errors clustered by village. The dependent variable is logged. *, **, and *** denote statistically significant at 10%, 5%, and 1%.

key target crops (i.e., cotton), but also to more crops grown. These results reflect that the CMDT has been historically involved in promoting an integrating farming system, encouraging the production of cotton in rotation with maize, millet, and sorghum (Theriault and Sterns 2012). Distances to the nearest store and the capital city, Bamako, have significant effects on all crop diversity indicators. The number of soils and topologies are also predictors of crop diversity. Literature about crop diversity on farms has repeatedly demonstrated that agroecological features (including soils and topology) and location (including market access) are major determinants of crop diversity on farms (Bellon and Taylor 1993; Benin et al. 2004; studies included in Smale 2006; Snapp and Fisher 2015).

8. Conclusions and policy implications

Over the last decade, Mali has established a new generation of agricultural input subsidies with the goal of raising productivity and ultimately, achieving food and nutrition security. Fertilizer subsidies are now one of the largest expense items in government spending on rural development in Mali (Kone et al., 2019b). Initially targeting only rice, the subsidy program expanded to include cotton, maize, millet, and sorghum. As currently designed, all Malian growers of target crops are eligible to obtain subsidized fertilizer at a quantity proportional to the number of hectares they expect to plant. The program clearly distorts incentives for farmers to grow target crops compared to non-target crops, with implications for crop diversification across the farming landscape.

Utilizing a household dataset collected in the major agroecological zones of Mali, we brought empirical evidence to bear concerning the effects of the fertilizer subsidy on cropland allocation. We employed the propensity score analysis and control function approach to estimate the average and marginal effects of fertilizer subsidies on indicators of crop species diversity. Specifically, we examined the effect of the subsidy program on the share of land allocated to target crops (all five and the three key crops), the concentration of land allocated to target crops (adapted Herfindahl index), to richness measured as crop counts (target and non-target crops and target crops only) and normalized by total areas planted (adapted Menhinick index).

Findings demonstrated that in the Niger Delta and the Koutiala Plateau, both the participation in the subsidy program and quantity of subsidized fertilizer applied by farming families had strong and significant effects on the diversity of crops they grow. Controlling for other factors, on average, farm households participating in the fertilizer subsidy program allocated a larger share of land to target crops, and particularly to the key crops of cotton, maize and/or rice. Their farm area was more uneven due to its heavier concentration in target crops. Participation in the subsidy program was associated with growing more crops, but especially more crops targeted by the subsidy program. Marginal effects estimated with the control function approach were similar in sign to average effects estimated with propensity score matching, with one exception. The greater the amount of subsidized fertilizer applied by the farm household; the lower was crop richness when normalized by total farm area.

Taken together, our results confirm a strong bias in the fertilizer subsidy program. As currently designed, the fertilizer subsidy program induces farm households to grow more target crops, and in particular maize, rice, and cotton, and allocate more land to them and away from non-target crops. The program unintentionally contributes to reducing crop diversification on farms, which is a key objective of the Malian agricultural development plan (MDR (2015); CT-CSLP, 2016).

Non-target crops and crop species diversity likely contribute to both the nutritional needs of farming households and to the health of the farming environment. When a program with high fiscal costs such as the fertilizer subsidy favors a non-food crop (cotton) and starchy staples (rice and maize) over other nutrient-dense or cash crops (cowpea, peanut, fonio, horticultural crops), food and nutrition security can be adversely affected either through less diverse food produced on the farm or through less diverse food purchased on markets. Caloric sufficiency is not enough. The human costs of undernutrition in Mali are of pressing concern, given evidence that less than half of rural women of reproductive age consume food sources that meet the minimum adequate dietary diversity during the cropping season (Adubra et al. 2019; Smale et al., 2020a, 2020b). The environmental sustainability of a program that reduces crop diversity across an agricultural landscape is also questionable.

Due to data limitation, we were unable to further explore the causal relationship between crop diversity, income, and nutritional outcomes. Future work should investigate whether crop diversification has a positive impact on diet quality and if so, whether it is through consumption of home-produced crops and/or through purchase of more nutritious and diversified food on the markets with income generated by crop sales. Another avenue for future research is to develop estimates comparing the costs and benefits of crop specialization induced by the subsidy.

Findings also suggest the need for policy stakeholders to revisit the current design of the subsidy program and consider ways to enhance its contribution to the goals of sustainable farming systems and nutrition security. If the fertilizer subsidy program continues, we recommend that the subsidization rates for target crops be reconsidered, especially for sorghum and millet. Otherwise, millet and sorghum crops will likely continue to lose area in favor of cotton, maize, and rice.

Ideally, further development of the program will be based on well-defined objectives. At present, Mali's fertilizer subsidy program appears to mix the objectives of attaining resilience among smallholder farmers and encouraging commercialization. If the program is to be targeted, the first step is a clearly articulated targeting goal. Depending on the goal, targeting farmer types might be more effective that targeting crops. Removing the crop criteria will provide more flexibility for farmers to allocate their land across crops. If increasing resilience is the main objective, then farmers who can afford fertilizer the least should be targeted. If promoting commercialization is the main objective, then farmers who are market-oriented should be targeted. Lists of farm households classified by typology already exists in the CMDT zone. This typology could be extended, and adapted, if need be, to the ON and DRA zones.

Moreover, if the subsidy program is to be continued, then it should not only cover fertilizer but also seeds for emerging, nutrient-dense crops, such as legumes and moisture-conserving technologies. The program should promote sustainable agricultural intensification. Although less crop diversification (more specialization) at the farm household level may be expected with the process of agricultural commercialization, it is critical that policies and programs, such as fertilizer subsidies, protect the agricultural landscape across all agro-ecologies if food and nutrition security is to be achieved.

CRediT authorship contribution statement

Veronique Theriault: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Melinda Smale:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing.

Acknowledgements

This work was supported by the United States Agency for International Development (USAID)'s Innovation Laboratory for Food Security Policy [AID-OAA-L-13-00001] and the United States Agency for International Development (USAID) Bureau for Food Security under Agreement #7200AA18LE00003 as part of Feed the Future Innovation Lab for Legume Systems Research. We also thank Yénizié Kone and Alpha Kergna for their insights regarding the fertilizer subsidy program in Mali. Any opinions, findings, conclusions, or recommendations expressed here are those of the authors alone.

Funding sources

This work was supported by the United States Agency for International Development (USAID)'s Innovation Laboratory for Food Security Policy [AID-OAA-L-13-00001] and the United States Agency for International Development (USAID) Bureau for Food Security under Agreement #7200AA18LE00003 as part of Feed the Future Innovation Lab for Legume Systems Research. Any opinions, findings, conclusions, or recommendations expressed here are those of the authors alone.

Declarations of interest

None.

Appendix A

(See Fig. A1)

Appendix B

(See Fig. A2)

Appendix C

(See Table A1)

Appendix D

(See Table A2)

Appendix E

(See Table A3)

Appendix F

(See Table A4)

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