The Impact of Biofortified Iron Bean Adoption on Productivity, and Bean Consumption, Purchases and Sales

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I. Introduction

Much of the world's rural poor suffers from low crop yields and micronutrient malnutrition, two problems that reinforce one another and contribute to poverty: a household that achieves low yields may lack the resources to grow or buy nutritious food, while a lack of nutritious food can lead to poor health, fatigue, and low productivity (Alderman et al., 2006). For decades, policy makers have promoted improved crop varieties to address low crop productivity and fortified foods to address malnutrition. More recently, researchers have developed a technology called biofortification, which consists of breeding crops to be high-yielding and high in micronutrient content, to address both problems simultaneously (Bouis and Saltzman, 2017).

Biofortified crops have been released in 30 countries and are grown and consumed by over 20 million people around the globe (Bouis and Saltzman, 2017). Most of the literature on biofortified crops has focused on their nutritional benefits to consumers (Haas, 2014; Haas et al., 2016; Luna et al., 2015; Wenger et al., 2015). Randomized control trials in Mexico (Haas, 2014) and Rwanda (Haas et al., 2016) have proven that consumption of iron beans improves blood iron content after consumption for 3.5 and 4.5 months, respectively. A meta-analysis (Finkelstein et al., 2017) conducted on studies of iron biofortified beans (Haas et al., 2016), rice (Haas et al., 2005), and millet (Finkelstein et al., 2015) concluded that consumption of iron biofortified crops is effective at improving iron status. While the nutritional benefits of biofortified crops has been demonstrated in an experimental setting, less is known about the impacts of biofortified crops under farmer conditions or about their non-nutritional benefits, such as yield gains compared to traditional varieties. This paper helps close this gap by investigating the impact of iron bean adoption in Rwanda on yield and other indicators of bean consumption, sales and purchases.

Rwanda is a small, densely populated country in East Africa, where about 70% of the population lives in rural areas (The World Bank, 2015) and most depend on agriculture for their livelihood. Most of Rwanda has two growing seasons per year: Season A, which runs from September to February and Season B, which runs from March to June (NISR, 2015). Bean is a staple crop throughout the country and provides the average Rwanda diet with 32% of its calories and 65% of its protein (CIAT, 2004; Mulambu et al., 2017).

Four iron bean varieties were released in Rwanda in 2010 and six in 2012. Of the ten iron bean varieties released, two are bush varieties, which grow low to the ground, and eight are climbing varieties, which require the use of stakes to achieve their high yield potential. Formal delivery approaches began operation in 2012 and aimed to disseminate iron bean seeds to farmers throughout the country. The most widespread of these approaches is direct marketing, through which iron bean seeds are promoted and sold to farmers in local markets. Iron bean seed also spreads informally through social networks. About 41% and 33% of adopters got their first iron bean planting material from local markets and members of their social networks, respectively (Asare-Marfo et al., 2016a).

Released first in Rwanda due to its high levels of bean production and consumption (Asare-Marfo et al., 2013), iron beans contain about twice as much iron as non-biofortified beans (Boy et al., 2017) and offer higher yields than traditionally grown varieties. Nearly a third of Rwandan farmers has grown an iron bean variety (Asare-Marfo et al., 2016a), but the effects of adoption on household wellbeing have not been measured. We contribute to a vast literature documenting the benefits of improved crop adoption, including increased yields (Zeng et al., 2015), improvements to household income, reduced poverty (Becerril and Abdulai, 2010; Mendola, 2007; Zeng et al., 2015), and improved food security (Larochelle and Alwang, 2014; Shiferaw et al., 2014), by focusing on the effects of adoption of an improved biofortified crop.

The objectives of this paper are to estimate the impact of iron bean adoption on productivity, bean consumption of own-produced and purchased beans, bean sales, and the likelihood of being a net seller of beans. Because adoption may be endogenous to these outcomes, we use an instrumental variable (IV) method. Our IVs relate to iron bean dissemination, which has been found to correlate with adoption (Vaiknoras et al., 2017) but should not otherwise be correlated with our outcomes of interest.

Yield gain of biofortified varieties is expected to partially drive adoption. Thus, having an accurate estimate of these yield gains can help promotional efforts, in addition to strengthening the validity of findings related to the effects of adoption on higher-order outcomes, such as bean consumption, purchases, and sales. These higher-order effects of adoption are expected to be associated with enhanced household welfare such as improved nutrition, food security and higher incomes. Higher yield can increase consumption of beans, which is high in protein and micronutrients, and can also reduce the need to purchase beans for household consumption, freeing income to buy nutrient-dense foods such as animal products. Finally, greater productivity associated may allow households to sell beans in the market or increase quantity sold, boosting incomes.

It is important to gain an understanding of the harvest usage of biofortified varieties (i.e. whether they are consumed or sold) since it dictates who benefits from biofortification efforts. Moreover, household decisions regarding harvest usage of biofortified crops might differ from those of non-biofortified improved varieties due their nutritional value. These aspects matters greatly for biofortification since it is a nutrition intervention that targets vulnerable rural populations. Knowledge gains from this study will inform the development and promotion of future biofortification and help policy makers allocate resources most efficiently.

The next section explains the theoretical framework while section three describes our data. An explanation of our empirical model and estimation is next, followed by results and conclusions.

II. Theoretical Framework

We assume that households are utility-maximizing and will grow a particular bean variety when the utility they obtain from growing that variety is higher than from other varieties. Adoption thus depends on factors that influence the utility households obtain from each bean type (T_{ij}) (i.e. local, iron, or other improved). These include their land and inputs (I_{ij}), market conditions (M_i), household characteristics (H_i), and ease of access to iron bean varieties (E_i), which depends in part on their proximity to direct marketing delivery approaches and the availability of iron beans within their social network.

$$T_{ij} = F\left(I_{ij}, M_i, H_i, E_i\right) \quad (1)$$

Because bean varieties have different traits, including yield potential, the choice of variety is a factor that influences yield. The yield of bean variety *j* grown by household *i* depends on the bean variety (T_{ij}), production inputs and characteristics of the land on which it is grown (I_{ij}), and household (H_i) characteristics.

$$Y_{ij} = F(T_{ij}, I_{ij}, H_i) \quad (2)$$

We hypothesize that households achieve higher yield when cultivating iron bean varieties than local bean varieties. Adopting households subsequently choose how to use this additional bean production. Households may choose to consume all or part of it, increasing total consumption from own-production (C_i) and/or reducing bean purchases for consumption (P_i). Households may also choose to sell part of the additional harvest (S_i). By altering purchase and sales behavior, adoption could change the market position of the household; households could shift from being net buyers to autarky, or self-sufficiency, or from autarky to being a net seller, depending on their initial market position. Households that are already net sellers could also increase their quantity sold.

We thus hypothesize that adoption will increase household consumption from own-production, reduce purchases, increase sales, and increase the probability of being a net seller of beans (N_i). These outcomes are also likely to be affected by market characteristics faced by the household (M_i) such as ease and profitability of participating in the market, and household characteristics (H_i) that relate to household preferences and constraints, including bean production capability in relation to consumption needs.

$$C_i, P_i, S_i, N_i = F(T_{ij}, M_i, H_i) \tag{3}$$

Because the adoption decision is based on many of the same factors that dictate yield, consumption, purchases, and sales, including some factors that may be unobserved, the adoption decision could be endogenous. In order to determine the impacts of adoption, this endogeneity must be addressed. Factors that relate to the access of iron beans (E_i), which affect adoption but not the outcomes of interest, are natural candidates for IVs that can allow impacts to be determined despite endogeneity.

Increases in consumption from own-production and reductions in purchases will improve nutrition and food security of households, who will be less dependent on the market for its bean consumption. Increases in sales will improve incomes, and an increase in the likelihood of being a net seller of beans will further improve the economic and food security of households. It is through these pathways that iron beans can improve the wellbeing of adopting households.

III. Data

This study uses nationally representative data of bean producers in Rwanda collected in two stages in 2015. The first stage occurred in May and June 2015 during season 2015B; 120 villages were randomly selected and each household in these villages was interviewed regarding their iron bean adoption histories from 2010-2015B in a listing exercise. A subset of interviewed households was selected to be interviewed again in September 2015, just after 2015B, in the main household survey.

In the listing exercise, enumerators collected iron bean adoption histories from 19,575 households. Enumerators showed each household samples of iron bean seeds, one by one, and asked if the household had ever heard of the variety and had ever grown the variety. If they had, enumerators asked when they first grew the variety and if they grew it in each subsequent season. Further questions were asked to verify that the household was identifying the correct variety, including the color and type of the variety.

A subsample of 12 households per village was interviewed again for the main household survey. When possible, six iron bean adopters and six non-adopters were selected randomly from each village using an equal probability approach; otherwise, all village adopters were interviewed and up to 12 non-adopters were randomly sampled. Enumerators collected more detailed information about iron bean adoption, household composition, bean farming decision making, and household assets. They asked households to list every variety they grew in 2015B and on which plot(s) each was grown. For each plot under cultivation, households reported plot characteristics such as inputs and the household member who worked on it the most. Finally, they asked households about their bean consumption from own-production and purchases, and bean sales from the previous 12 months, which covered seasons 2015A and 2015B.

We also use data collected from a community survey conducted at the same time as the main household survey, in which village leaders were interviewed regarding village characteristics, iron bean delivery approaches in the village, market access, crop prices and extension services within the village. Finally, we use data collected by the HarvestPlus marketing team located in Rwanda. This includes the number of direct marketing approaches in each administrative sector in each season.

After dropping observations with missing data, outlier values, and likely misclassified bean varieties, our sample includes 1,383 households who grew 2,227 bean varieties in 2015B.

III.a. Variables

We first explain the outcomes of interest, followed by our measures of iron bean adoption and other explanatory variabels. Our IVs are discussed in section IV.b (see table 1 for a description of all variables).

Table 1: Variables in yield (Y), consumption (C), purchases (P), and sales (S) models

Variable	Variable Description	Models
Dependent		
Multiplication ratio	Quantity harvested/quantity planted	Y
Consumption	Consumption of own-produced beans in the last 12 months, in kg per adult equivalent[a]	C
Purchased beans	The household purchased beans for consumption in the last 12 months	P
Purchases	Quantity of beans purchases for consumption in the last 12 months, in kg per adult equivalent	P
Sold beans	The household sold beans in the last 12 months	S
Sales	Quantity of beans sold in the last 12 months, in kg per adult equivalent	S
Net seller	The household sold a greater quantity of beans than in purchased in the last 12 months	N
Adoption measure		
Bean type	0 = local variety; 1 = improved (non-iron) variety; 2 = iron variety	Y
Adoption 2015	0 = did not grow an iron bean in 2015; 1 = grew an iron bean in 2015A; 2 = grew an iron bean in 2015B; 3 = grew an iron bean in 2015A and 2015B	CPSN
Input		
Recycled	Planting material came from household's last season harvest	Y
Stake Type	0 = none; 1 = trees, maize stalks, napier grass; 2 = poles, sticks	Y (climbing)
Slope	0 = flat; 1 = gentle slope; 3 = moderate slope; 4 = steep slope	Y
Intercrop	Bean and some other type of crop were grown on plot	Y
Only bean	Only one variety of bean was grown on the plot	Y
Walk time	Walking time from the house to the plot	Y
Labor	Household hired labor to work on the plot	Y
Organic fertilizer	Compost or manure was used on plot	Y
Chemical fertilizer	Chemical fertilizer was used on plot	Y
Market		
Price of bean	Price of a kg of beans in time of high availability 2015B	CPSN
Price of maize	Price of a kg of maize in time of high availability 2015B	CPSN
Price of SP	Price of a kg of sweet potatoes in time of high availability 2015B	CPSN
Local market	% of village households who sell beans at the local market	CPSN
Distance to road	Distance to nearest road, in km	CPSN
Distance to city	Distance to nearest city of at least 50,000 people, in km	CPSN
Household		
Elevation	Elevation, in m	All
Household size	Number of people in the household	All
Sex	1= main decision maker (CPS) or plot worker (M.R.) is female	All
Education	Education level of the main bean decision maker (CPS) or plot	All

	worker (M.R.): 0 = no schooling; 1 = some primary education; 2 = some secondary education or more	
Age	Age of main bean decision maker, in years	CPSN
Experience	Bean farming experience of plot worker, in years	Y
Land size	Land cultivated 2015B for all crops, in ha	All
Wealth quintile	Wealth index created using polychoric components analysis (pca) expressed in quintile. It includes housing characteristics, access to water, and household assets.	All
Equipment	Number of pieces of agricultural equipment owned	All
Livestock	Livestock ownership measure, expressed in tropical livestock unit[b]	All
Extension	% of households in the village who obtain information from agricultural extension agents	All
IV		
Direct markets 2015A	Number of direct marketing approaches in the household's sector in 2015A	All
Direct markets 2015B	Number of direct marketing approaches in the household's sector in 2015B	All
Village adoption rate 2014B	Percentage of households in the village that grew an iron bean in 2014B	All

[a] Calculated based on a scale obtained by USAID (Dary and Hainsworth, 2008).
[b] 1 cow = .5; 1 sheep = .1; 1 goat = .1; 1 pig = .2; 1 chicken = .01; 1 rabbit = .02.

Outcomes of interest

We use the multiplication ratio as a proxy for yield because it is less likely to suffer from measurement error associated with inaccurate estimation of land size, which is accentuated with small plot size like in Rwanda. The multiplication ratio is measured at the variety level; it is the quantity harvested of each variety divided by the quantity of seed planted of that variety.

Bean consumption, purchases and sales are measured at the household level for the last 12 months prior to September, 2015, which correspond to seasons 2015A and 2015B. Quantity of beans consumed from own-production over that period is divided by the number of adult-equivalents in the household (Dary and Hainsworth, 2008). Two variables are used to represent household bean purchase (sale) decisions: the first variable indicates whether the household purchased (sold) beans, and the second reports the quantity of beans purchased (sold) per adult equivalent. We divide consumption and purchases by adult equivalents to capture meaningful impacts on household outcomes, as the consumption needs of certain household members is predictably higher than those of others depending on age and gender. We do the same for sales so that we can easily compare changes across outcomes. Finally, the variable indicating whether the household was a net seller of beans over the 12 months prior the study is equal to one if the household sold a greater quantity of beans than it purchased during this period.

Adoption measures

When estimating the impact of iron bean adoption on yield, adoption is measured at the variety level using a categorical variable for local varieties, iron varieties, and other improved varieties. Since bean consumption, purchase and sale decisions are measured at the household-level, adoption is defined at the household level in these models. We consider the intensity of adoption by defining adoption over the two seasons considered. A categorical variable is used to differentiate between households who: i) did not adopt, ii) adopted only in 2015A, iii) adopted only in 2015B and, iv) adopted in both 2015A and 2015B.

Explanatory variables

Plot and input variables are measured at the plot level, and can vary within households. These enter the multiplication ratio models. All market variables, which enter consumption, purchase, sales, and net seller models, are measured at the household level except for the crop price variables, which are measured at the village level to avoid endogeneity. Household characteristics are measured at the household level except for the characteristics of the household member who worked the bean plot the most, which are measured at the plot level, and access to extension, which is measured at the village level to avoid endogeneity. Household characteristics enter all models, although they vary between the multiplication ratio models and remaining models.

III.b. Descriptive Statistics

Outcome variables

The average multiplication ratio is 8.11 for bush iron bean varieties, 8.15 for other improved bush bean varieties, and 6.62 for local bush beans (figure 1). The respective values for climbing varieties are 8.95, 8.68, and 7.55. The average multiplication ratio of iron beans is higher than that of local varieties at a 5% significance level for both bush and climbing varieties.

While nearly all households consumed beans from their own-production, 75% purchased beans and 40% sold beans. Households on average consumed 30 kg from own-production, purchased 12 kg, and sold 11 kg of beans in the 12 months prior to data collection, and 37% of households were net sellers of beans. Adopting households (defined in this section as those that grew an iron bean in season 2015A or 2015B, or both seasons) consumed and sold a greater quantity of beans than non-adopting households and purchased a smaller quantity of beans (figure 2). They were also less likely to purchase beans, and more likely to sell beans and to be net sellers of beans. These differences are statistically significant at a 5% level.

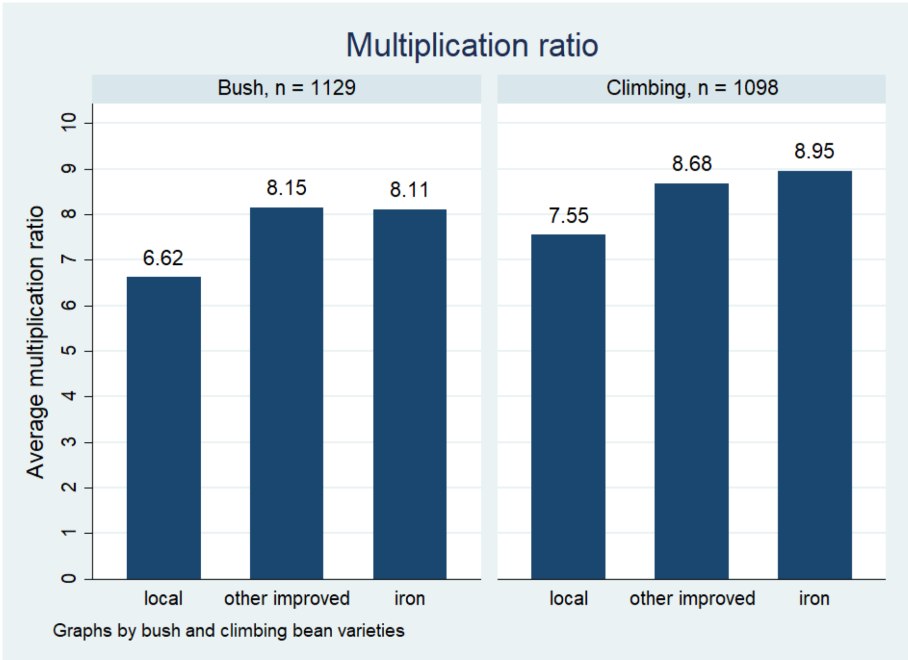

Figure 1: Average multiplication ratio of bush and climbing bean varieties

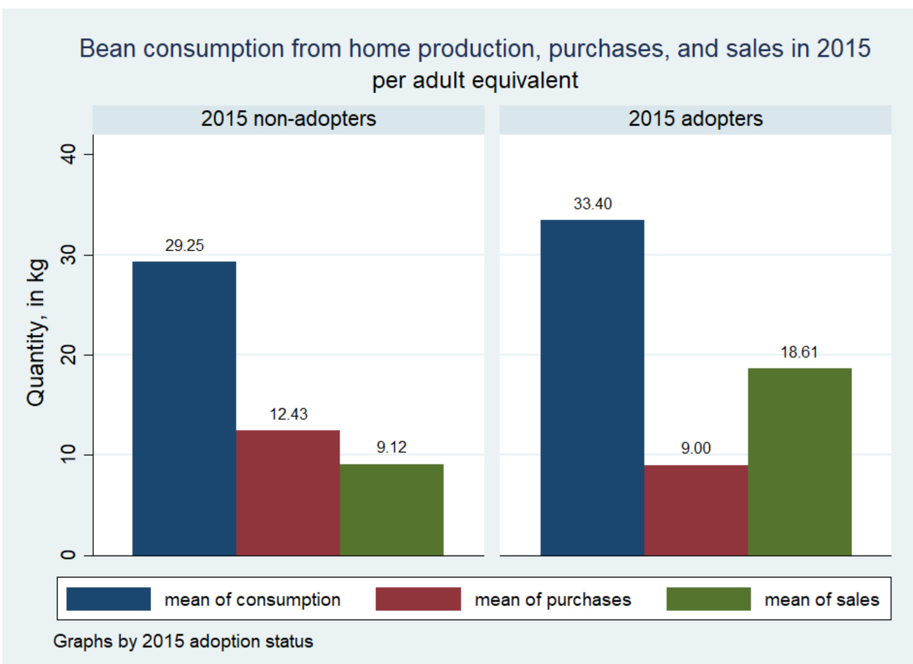

Figure 2: Average consumption from own-production, purchases, and sales of adopters and non-adopters in the last 12 months

Adoption measures

About 13% of bush beans and 11% of climbing bean varieties cultivated during 2015B were iron bean varieties; local varieties represent about two-third of bush and climbing bean varieties, and the remaining varieties were other improved varieties (figure 3). About 4% and 10% of households grew an iron bean in 2015A only and 2015B only respectively, while 7% of bean growers in Rwanda grew an iron bean varieties in both seasons (figure 4), corresponding to an average household adoption rate of about 21% for 2015.

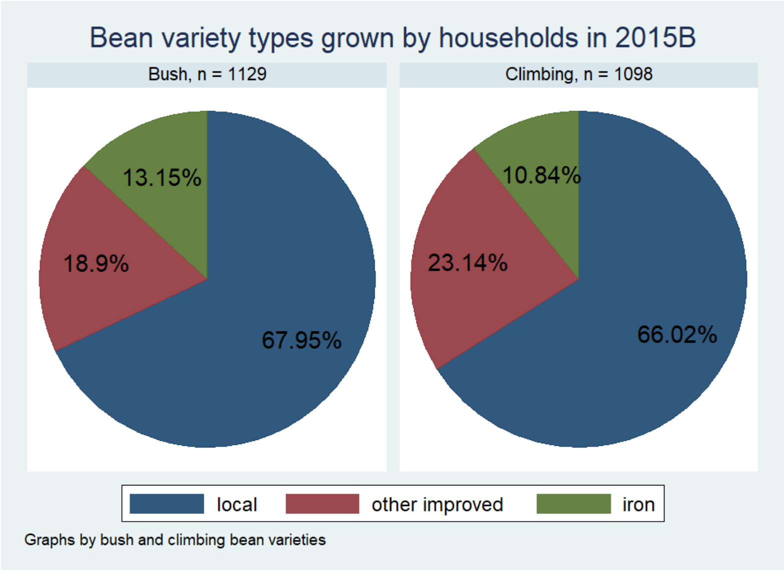

Figure 3: Iron bean adoption by variety in 2015B

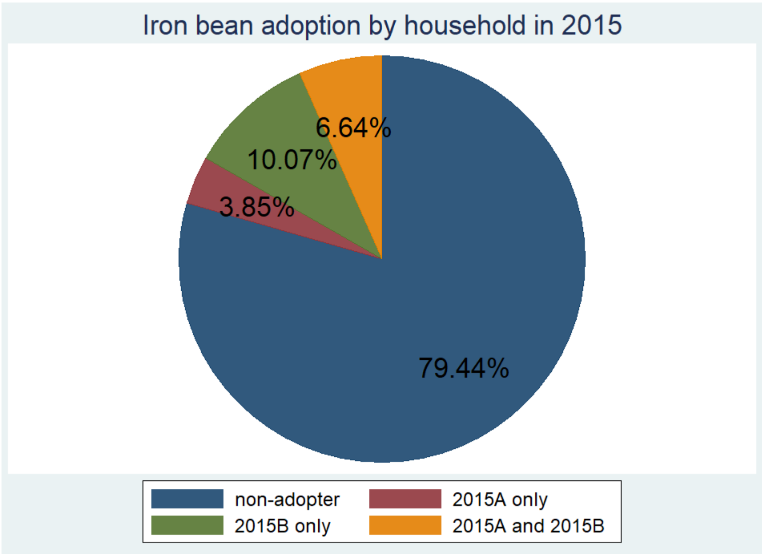

Figure 4: Iron bean adoption by household in 2015

Plot, input, market, and household variables

Both bush and climbing iron bean varieties are less likely to be planted with recycled planting material and more likely to be grown with other bean varieties and by a household member with some education than local varieties (table 2). Compared to local varieties, organic and chemical fertilizers are more likely to be used for the cultivation of bush iron varieties and climbing iron varieties are more often grown on a steep slope.

Table 2: Descriptive statistics for variables that vary by variety of bush and climbing, local and iron beans

	Bush		Climbing	
	Iron	Local	Iron	Local
	Mean (sd) or % yes	Mean (sd) or % yes	Mean (sd) or % yes	Mean (sd) or % yes
Recycled	27.10%	38.97% **	27.78%	52.44% ***
Stake type				
None			16.45%	11.96%
Trees, grass			42.69%	45.41%
Poles, sticks			40.86%	42.63%
Slope				
Flat	9.76%	7.77%	9.94%	16.34% *
Gentle	11.14%	14.55%	17.65%	22.18%
Moderate	40.23%	35.14%	33.16%	35.57%
Steep	38.86%	42.55%	39.24%	25.91% **
Intercrop	59.03%	65.72%	43.95%	42.58%
Only bean	65.67%	78.97% **	53.07%	76.20% ***
Walk time	18.12 (32.72)	15.48 (22.99)	13.85 (25.22)	15.46 (21.74)
Labor	44.01%	39.35%	40.04%	30.26% *
Organic fertilizer	82.56%	70.93% **	87.64%	87.55%
Chemical fertilizer	17.22%	8.29% **	25.73%	27.33%
Sex of plot worker (1= female)	66.29%	67.16%	68.32%	67.23%
Education of plot worker				
None	22.87%	29.51% *	20.22%	31.46% **
Primary	64.90%	64.12%	72.85%	61.41% **
Secondary	12.23%	6.36% **	6.93%	7.14%
Experience of plot worker	25.39 (13.78)	27.11 (16.44)	27.33 (13.20)	26.08 (16.30)
	225	688	217	635

Note: * = significance at 10%; ** = significance at 5%; *** = significance at 1% of differences in means.

Households who grew an iron bean in either season of 2015 live in villages with lower bean prices on average compared to households that did not grow an iron bean in 2015 (table 3). They also live further from roads and at a lower elevation than non-adopters. Finally, adopters have on average more education, are wealthier, own more agricultural equipment, and live in villages where a greater share of households obtain information from agricultural extension. Finally, adopters live in sectors that had more direct marketing approaches in 2015A and in villages with a higher rate of adoption in 2014B.

Table 3: Descriptive statistics for household variables of adopters and non-adopters

	Adopters	Non-adopters
Variables	Mean (sd) or % yes	Mean (sd) or % yes
Price of bean (RWF) ***	272.61 (75.61)	294.88 (76.54)
Price of maize (RWF) **	147.82 (49.64)	157.46 (54.11)
Price of SP (RWF)	86.92 (35.63)	82.25 (58.28)
Local market (%)	42.21 (37.75)	42.88 (34.83)
Distance to road (km) **	1566.50 (1346.58)	1320.76 (1347.82)
Distance to city (km)	37733.22 (21288.36)	36688.89 (20316.84)
Elevation (m) ***	1615.47 (195.63)	1707.34 (257.50)
Household size	5.01 (2.07)	4.80 (2.02)
Sex of decision maker (1 = female)	62.56%	62.93%
Education of decision maker		
None ***	23.29%	34.42%
Primary *	66.26%	59.35%
Secondary **	10.44%	6.23%
Age of decision maker	44.05 (13.74)	44.77 (15.98)
Land size (ha)	0.52 (0.71)	0.46 (0.78)
Wealth		
1 *	15.62%	21.32%
2 *	16.47%	21.21%
3	18.25%	20.32%
4	23.57%	18.84%
5 **	26.08%	18.31%
Equipment **	1.37 (0.80)	1.20 (0.77)
Livestock (TLU)	0.53 (0.78)	0.41 (0.93)
Extension (%) **	69.28 (25.09)	63.80 (27.59)
Direct markets 2015A **	0.67 (1.91)	0.43 (1.09)
Direct markets 2015B	0.11 (0.57)	0.07 (0.45)
Village adoption rate 2014B ***	0.16 (0.13)	.09 (0.09)
	462	921

Note: * = significance at 10%; ** = significance at 5%; *** = significance at 1% of difference in means.

IV. Treatment effect estimation

We are interested in estimating the average treatment effect on the treated (ATT) of iron bean adoption on multiplication ratio, consumption, purchases, sales, and the probability of being a net seller of beans. The theoretical framework predicts that both observed and unobserved factors that affect these outcomes will also affect the adoption decision, resulting in biased estimates of the effect of adoption from these correlations. We use a regression framework to explain how we purge this correlation to obtain unbiased estimates.

IV.a. Reduced Form Equations

The theoretical model described in section II is made estimable by the development of reduced form equations of bean multiplication ratio ($\boldsymbol{M_{ij}}$), consumption ($\boldsymbol{C_i}$), purchases ($\boldsymbol{P_i}$), and sales ($\boldsymbol{S_i}$), and being a net seller of beans ($\boldsymbol{N_i}$),

Explanatory variables for the multiplication ratio include land and input variables ($\mathbf{I}_{ij}$) and household characteristics ($\boldsymbol{H_i}$). The random error term, $\boldsymbol{e_{ij}}$, is assumed to be uncorrelated with the covariates.

$$\boldsymbol{M_{ij}} = D_0 + D_1\boldsymbol{T_{ij}} + \mathrm{D}_2\mathbf{I}_{ij} + \mathrm{D}_4\boldsymbol{H_i} + \boldsymbol{e_{ij}} \quad (4)$$

Our variable of interest in equation (4) is $\mathbf{T}_{ij}$, which represents the type (iron, other improved, or local) of the varieties grown by household *i*.

Consumption, purchases, sales, and being a net seller are represented in the general model below, where $\boldsymbol{O_i}$ stands for the outcome of interest. These depend on adoption of iron beans ($\boldsymbol{A_j}$) in 2015, market ($\boldsymbol{M_i}$) and household ($\boldsymbol{H_i}$) characteristics. The random error term, $\boldsymbol{e_i}$, is again assumed to be uncorrelated with the covariates. However, because the adoption decision could be correlated with unobserved factors such as household preferences, this assumption may not hold and adoption could be endogenous to the model.

$$\boldsymbol{O_i} = D_0 + D_1\boldsymbol{A_j} + \mathrm{D}_2\boldsymbol{M_i} + \mathrm{D}_4\boldsymbol{H_i} + \boldsymbol{e_i} \quad (5)$$

By controlling for observed factors that correlate both with our outcomes of interest and iron bean adoption, we eliminate overt bias in our estimation of D_1 in each equation. However, in order to obtain an unbiased estimate of D_1, we must assume that we also have no hidden bias, or that that there are no factors in the random error term that are correlated with $\mathbf{T}_{ij}$ or $\boldsymbol{A_j}$**.** This may not hold as there could be unobserved characteristics such as inherent farmer ability or preferences that are not controlled for that could be correlated with iron bean adoption and the dependent variables. We therefore use an IV approach to address potential hidden bias and obtain unbiased estimates.

IV.b. Instrumental Variables

The challenge of using an IV approach is that it requires identifying one or more variables that are both relevant, related to the treatment variable, and valid, or otherwise uncorrelated with the outcome of interest. Because iron beans are disseminated to farmers through delivery approaches that are exogenous to the bean-growing and marketing characteristics of households, we have a uniquely appropriate set of IVs.

We use three IVs: the total number of direct marketing approaches in a household's sector in 2015A and 2015B, and the village adoption rate in 2014B, which proxies for the availability of iron beans within one's social network. The village adoption rate in 2014B reflects the presence of formal delivery approaches in 2014B and in prior seasons as well as village adoption in previous seasons. These IVs have been found to be highly correlated with adoption of iron bean varieties in Rwanda (Vaiknoras et al., 2017). Moreover, they should not be correlated with our outcomes of interest other than through their effect on household adoption, since the locations for direct marketing were not chosen based on bean yields or other bean production characteristics, consumption or marketing characteristics of the local area, and local residents had no influence over their placement.

We further test the validity of the IVs using a series of diagnostic tests for two state least squares (2SLS) regressions for the multiplication ratio (bush and climbing separately), quantity of bean consumed, purchased and sold.

IV.c. Estimation

We estimate OLS models for the continuous outcomes of interest: multiplication ratio and consumption from own-production. We assume log-linear functions for these outcomes because their distributions are highly skewed to the right. We run multiplication ratio regressions separately for bush and for climbing beans. For purchases and sales, we estimate a double hurdle model, also called Craggit (Burke, 2009). The double hurdle model consists of a probit model in the first stage and a truncated normal regression model in the second stage, which are estimated separately. It then allows full average partial effects on the unconditional quantity of the outcome to be calculated (Burke, 2009). Unlike the tobit model, the double hurdle model does not require explanatory variables to have the same effect on the probability of purchasing/selling and the quantity of purchases/sales. We test the double hurdle model against the tobit model to determine which model fits the data best. For the probability of being a net seller, we estimate a probit model.

We incorporate the IVs by using a control function approach, as this is more efficient than 2SLS estimation when the endogenous variable is non-linear (Imbens and Wooldridge, 2007). We first estimate a probit model to explain iron bean adoption that includes the explanatory variables for our outcomes of interest and the IVs. We calculate the generalized residuals from the probit model and include them as an additional regressor in the regressions explaining the outcomes of interest. The inclusion of the generalized residuals allows us to control and test for endogeneity of adoption. A t-test of the generalized residuals tests the null hypothesis of exogeneity.

All regressions include standard errors that are robust to heteroscedasticity. Standard errors are clustered at the household level for multiplication ratio OLS and control function regressions, since many households have more than one observation, and at the village level for consumption, purchase and sales analyses.

IV.d. Fixed effects for multiplication ratio analysis

We take advantage of the panel nature of the multiplication ratio and use household fixed effects on a reduced sample of partial adopters, i.e. households who grew at least one iron bean and one non-iron bean in 2015B, to handle the possible endogeneity of the adoption decision. By reducing our sample to partial adopters, we eliminate the bias associated with unobserved heterogeneity at the household level. This provides a robustness check for the effects of iron bean adoption on productivity.

V. Results

V.a. Instrument validity and model fit

Diagnostic tests provide evidence that our IVs are valid (table 4). The null hypothesis of the Kleibergen-Paap rk LM statistic test that the model is underidentified is rejected in each model. The null hypothesis of weak IVs is rejected for each outcome using the Cragg-Donald F statistic. Finally, the Hansen J test for overidentification fails to reject the null hypothesis for each outcome, indicating that the IVs are not correlated with the error term of the regression.

Table 4: Instrument diagnostic test results for multiplication ratio, consumption, purchases, and sales

	M. Bush Test Statistic or p-value	M. Climbing Test Statistic or p-value	Cons. Test Statistic or p-value	Purchases Test Statistic or p-value	Sales Test Statistic or p-value
Underidentification test					
Kleibergen-Paap rk LM statistic	9.186	25.385	17.060	17.727	17.727
Chi-sq (4) P-val	0.010	0.000	0.001	0.001	0.001
Weak identification test					
Cragg-Donald Wald F statistic	7.10	19.864	13.476	13.780	13.780
Sanderson-Windmeijer test p-value	0.006	0.000	0.001	0.001	0.001
Overidentification test					
Hansen J statistic	1.397	1.235	1.507	1.169	3.090
Chi-sq (3) P-val	0.237	0.539	0.471	0.555	0.211

The value of R^2 or pseudo R^2 for each OLS and probit model (tables 5, 6 and 7) are below 0.2, indicating that much of the variation in these outcomes comes from unobserved or unsobservable characteristics such as soil quality, farmer ability, and household preferences. Since we address the endogeneity of iron bean adoption, these unobserved factors should not bias our treatment effect estimates.

A likelihood ratio test confirms that the double hurdle model fits our data better than the tobit model. The test that the restrictions of the tobit model hold are rejected for both purchases and sales (p = 0.000 for each).

V.b. Multiplication ratio results

For both bush and climbing bean control function regressions, the generalized residual is not statistically significant, meaning that adoption is not endogenous to the multiplication ratio and OLS results are equally valid and more efficient than control function results (table 5).

Table 5: OLS and control function (CF) results for bush and climbing bean multiplication ratios

	Bush beans			Climbing beans		
	OLS	CF OLS	FE	OLS	CF OLS	FE
Adjusted R2	0.088	0.088		0.093	0.094	
R2 within			0.137			0.104
R2 between			0.006			0.0004
R2 overall			0.003			0.0002
Iron bean	0.222***	0.630	0.177**	0.143	0.486*	0.192
	(0.084)	(0.515)	(0.085)	(0.089)	(0.275)	(0.200)
Improved bean	0.226***	0.230***	0.233	0.052	0.052	0.159
	(0.084)	(0.085)	(0.145)	(0.078)	(0.078)	(0.172)
Recycled	0.197***	0.231***	0.145	0.096	0.138*	0.121
	(0.063)	(0.075)	(0.113)	(0.068)	(0.076)	(0.201)
Stake type (base = none)						
Trees, stalks, grass				0.199*	0.195	-0.172
				(0.119)	(0.120)	(0.378)
Poles, sticks				0.245**	0.239*	0.583***
				(0.124)	(0.124)	(0.188)
Slope (base = steep)						
Moderate	0.129	0.141	0.440	-0.211*	-0.212*	-0.136
	(0.144)	(0.144)	(0.353)	(0.119)	(0.119)	(0.369)
Gentle	0.036	0.021	0.506	-0.169*	-0.184	0.200
	(0.135)	(0.136)	(0.342)	(0.100)	(0.101)	(0.262)
Flat	0.209	0.207	0.993***	-0.153	-0.175	-0.264
	(0.133)	(0.133)	(0.335)	(0.106)	(0.108)	(0.604)
Intercrop	-0.053	-0.041	0.210	-0.022	-0.013	0.006
	(0.067)	(0.068)	(0.199)	(0.072)	(0.072)	(0.227)
Only varieties	0.036	0.070	0.646***	0.162**	0.196**	0.346
	(0.091)	(0.104)	(0.202)	(0.077)	(0.085)	(0.231)
Walk time	-0.003*	-0.003*	0.001	-0.002	-0.002	-0.002
	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)	(0.004)
Labor	0.068	0.064	0.222	0.014	0.006	0.166
	(0.079)	(0.078)	(0.265)	(0.074)	(0.075)	(0.176)
Organic fertilizer	-0.139	-0.175	-0.253	0.033	0.022	-0.471
	(0.085)	(0.093)	(0.216)	(0.085)	(0.085)	(0.441)
Chemical fertilizer	0.074	0.033	0.520**	0.159*	0.163**	0.251
	(0.113)	(0.126)	(0.257)	(0.081)	(0.081)	(0.620)
Elevation	-0.000*	-0.000*		-0.000	-0.000	
	(0.000)	(0.000)		(0.000)	(0.000)	
Household size	-0.003	-0.001		0.019	0.018	

	(0.018)	(0.018)		(0.018)	(0.018)	
Sex	-0.086	-0.089	-0.577*	0.018	0.015	-0.152
(base = male)	(0.074)	(0.074)	(0.333)	(0.070)	(0.070)	(0.358)
Education (base = none)						
Primary	0.198**	0.182*	-0.362	0.204**	0.191**	0.592
	(0.092)	(0.094)	(0.517)	(0.081)	(0.082)	(1.154)
Secondary	0.144	0.104	-1.204	0.299**	0.301**	
	(0.145)	(0.152)	(0.662)*	(0.132)	(0.131)	
Experience	-0.000	-0.001	-0.079***	-0.000	-0.001	0.003
	(0.003)	(0.003)	(0.019)	(0.002)	(0.002)	(0.019)
Land size	0.010	0.010		0.051*	0.050	
	(0.056)	(0.056)		(0.028)	(0.028)	
Wealth (base = 1)						
2	-0.069	-0.069		0.124	0.126	
	(0.109)	(0.109)		(0.120)	(0.121)	
3	-0.192	-0.191		0.170	0.163	
	(0.123)	(0.123)		(0.123)	(0.123)	
4	-0.062	-0.066		0.287**	0.266**	
	(0.130)	(0.130)		(0.120)	(0.120)	
5	0.021	0.019		0.179	0.163	
	(0.117)	(0.117)		(0.133)	(0.133)	
Equipment	0.084	0.086		0.059	0.056	
	(0.051)	(0.051)		(0.043)	(0.043)	
Livestock	0.044	0.042		-0.045	-0.064	
	(0.031)	(0.030)		(0.070)	(0.072)	
Extension	0.004**	0.004**		0.002	0.002	
	(0.002)	(0.002)		(0.001)	(0.001)	
Generalized residual		-0.226			-0.205	
		(0.280)			(0.148)	
_cons	1.690***	1.572***	3.190**	1.200***	1.052**	1.317
	(0.352)	(0.374)	(1.074)	(0.319)	(0.342)	(1.518)
N	1112	1112	336	1082	1082	238

Note: * = significance at 10%; ** = significance at 5%; *** = significance at 1%. Standard errors are robust to heteroscedasticity for all models and clustered at the household level for OLS and CF OLS models.

Holding other factors constant, households achieve multiplication ratios from iron bush beans that are 25% (100*($e^{.223}$ - 1)) higher than from local bush varieties on average according to OLS estimates. This is similar to other improved varieties, which provide a multiplication ratio about 26% higher than local bush varieties. A Wald test confirms that there is no statistically significant difference between iron and other improved varieties. The FE estimated treatment effect of adoption is 19%, which is smaller than the OLS estimate; this is not surprising, given the different sample. According to the OLS and fixed effect model, there is no evidence that adoption of an iron climbing variety or other improved variety results in greater multiplication ratio than local varieties. One reason for this lack of significance could be that climbing beans are harvested over a longer period of time than bush beans, increasing recall errors regarding quantity harvested. The control function approach suggests a positive yield advantage for iron climbing beans over local varieties.

For bush beans, growing a variety from recycled grain, the education of the person who worked the plot, and access to extension are correlated with greater multiplication ratio in the OLS model. In the reduced sample, growing beans on a flat slope and planting only one bean variety on the plot are both correlated with greater multiplication ratio. More experience growing beans is correlated with a lower multiplication ratio; this could be due to the increase in age that comes with having more experience. For climbing varieties, the most important factors explaining the multiplication ratio are the use of stakes, growing only one variety on the plot, use of chemical fertilizer, the education level of the main plot worker, and household wealth.

V.c. Consumption, purchases, sales, and net seller results

The generalized residuals in the regressions for bean consumption from own-production, purchases (table 6) and sales (table 7) are not statistically significant. This indicates that iron bean adoption is not endogenous to these outcomes and that the double hurdle results without the generalized residuals are equally valid and more efficient.

Table 6: Regression results for quantity consumed from own-production and purchases

	Consumption from own-production		Purchases			
	OLS	CF OLS	Probit (Hurdle 1)	Trunc. reg. (Hurdle 2)	CF Probit (Hurdle 1)	CF trunc. reg. (Hurdle 2)
Adj. R2/Pseudo R2	0.151	0.151	0.166		0.167	
Log pseudolikelihood			-747911.87	-4358841.8	-746987.17	-4357896.3
Adopted 2015A	-0.144	-0.143	-0.098	3.690	-0.097	3.767
	(0.212)	(0.211)	(0.236)	(9.570)	(0.235)	(9.557)
Adopted 2015B	0.037	-0.017	-0.220*	-2.309	-0.349**	-6.832
	(0.070)	(0.088)	(0.130)	(3.158)	(0.147)	(4.953)
Adopted 2015A and 2015B	0.144**	0.089	-0.495***	-5.529	-0.635***	-9.457
	(0.067)	(0.079)	(0.167)	(5.155)	(0.197)	(6.359)
Price of bean	-0.000	-0.000	0.001	-0.005	0.001	-0.007
	(0.000)	(0.000)	(0.001)	(0.018)	(0.001)	(0.018)
Price of maize	-0.001*	-0.001*	0.001	-0.003	0.001	-0.002
	(0.001)	(0.001)	(0.001)	(0.030)	(0.001)	(0.030)
Price of SP	0.001	0.001	0.001	0.007	0.001	0.007
	(0.001)	(0.001)	(0.001)	(0.015)	(0.001)	(0.015)
Local market	0.001	0.001	-0.001	-0.006	-0.001	-0.004
	(0.001)	(0.001)	(0.001)	(0.032)	(0.001)	(0.032)
Distance to road	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)
Distance to city	0.000	0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Elevation	-0.000***	-0.000***	0.001***	0.006	0.001***	0.006
	(0.000)	(0.000)	(0.000)	(0.005)	(0.000)	(0.005)
Household size	-0.113***	-0.113***	0.103***	-2.944***	0.105***	-2.885***
	(0.014)	(0.014)	(0.028)	(1.005)	(0.029)	(0.992)
Sex (base = male)	-0.128**	-0.125**	-0.121	0.782	-0.115	0.925
	(0.055)	(0.055)	(0.108)	(2.566)	(0.108)	(2.576)
Education (base = none)						
primary	0.144*	0.150*	0.112	0.929	0.131	1.290
	(0.081)	(0.081)	(0.119)	(2.865)	(0.120)	(2.803)
secondary	0.044	0.057	-0.110	5.207	-0.076	6.042
	(0.115)	(0.116)	(0.196)	(6.542)	(0.200)	(6.489)
Age	0.005**	0.005**	-0.009***	-0.141*	-0.009***	-0.132*
	(0.002)	(0.002)	(0.003)	(0.076)	(0.003)	(0.076)
Land size	0.088**	0.088**	-0.093	-1.034	-0.093	-1.000
	(0.037)	(0.037)	(0.000)	(0.000)	(0.074)	(0.000)
Wealth (base = 1)						
2	0.165	0.165	0.122	5.446	0.118	5.51
	(0.100)	(0.100)	(0.129)	(4.797)	(0.130)	(4.813)
3	0.220**	0.222**	-0.169	0.438	-0.165	0.666

	(0.098)	(0.098)	(0.144)	(3.656)	(0.145)	(3.661)
4	0.337***	0.337***	-0.240	-5.752	-0.239	-5.618
	(0.094)	(0.094)	(0.161)	(3.547)	(0.160)	(3.550)
5	0.231**	0.231**	-0.600***	-4.640	-0.604***	-4.481
	(0.099)	(0.099)	(0.155)	(4.725)	(0.156)	(4.737)
Equipment	0.105***	0.106***	-0.298***	-1.054	-0.294***	-1.044
	(0.035)	(0.035)	(0.065)	(1.493)	(0.065)	(1.494)
Livestock	0.126***	0.127***	-0.408***	-5.246	-0.407***	-5.178
	(0.043)	(0.043)	(0.101)	(3.787)	(0.101)	(3.753)
Extension	0.000	0.000	-0.000	-0.007	-0.000	-0.007
	(0.001)	(0.001)	(0.002)	(0.061)	(0.002)	(0.061)
Generalized residual		0.049			0.121	3.434
		(0.045)			(0.075)	(2.338)
Constant	3.929***	3.935***	-0.366	16.478	-0.349	16.732
	(0.341)	(0.341)	(0.577)	(10.675)	(0.576)	(10.686)
wald test of rho = 0						
sigma				19.315***		19.277***
				(3.839)		(3.827)
N	1370	1370	1383	1022	1383	1022

Note: * = significance at 10%; ** = significance at 5%; *** = significance at 1%. Standard errors are robust to heteroscedasticity and clustered at the village level. The 13 households that had no consumption from own-production were dropped from the consumption from own-production regression because the outcome is logged.

Growing an iron bean in both 2015A and 2015B increases consumption from own-production by 14.4%. We examined the effect of adoption of the probability of purchasing and selling using a probit model. The models without the generalized residuals indicate that adoption in both seasons reduces the probability of purchasing beans by 13.0% and increases the probability of selling beans by 15.5%. Growing an iron bean in only 2015B reduces the probability of purchasing beans by 5.8% and increases the probability of selling beans by 13.5%. The average partial effect on the unconditional quantity of purchases is 3.9 kg (significant at a 5% level); and 9.2 kg for sales (significant at a 10% level). The low level of significance of this value could be due to the difficulty of recalling their exact quantity of bean sales. Growing an iron bean for only one season has no effect on consumption from own-production or on the unconditional quantity of purchases or sales. Adoption in both seasons increases the likelihood of being a net seller of beans by 13.8% and growing an iron bean in only 2015B increases the probability of being a net seller by 9.2%

The price of beans is negatively correlated with both the probability of selling beans and of being a net seller of beans, while the price of sweet potatoes is positively correlated with selling beans. This is surprising. It is possible that low bean prices are indicative of other characteristics of the village or wider area such as poverty that also discourage selling, and that sweet potato prices may be higher in areas where bean production and sales is more prevalent. Distance from an urban area is positively correlated with selling, quantity sold, and being a net seller. Household size is negatively correlated with consumption from own-production and positively correlated with purchasing and quantity purchased. Elevation is negatively correlated with consumption from own-production, selling and being a net seller, and positively correlated with purchases. Households with female bean decision makers are less likely to sell beans, while households with older decision makers consume more from own-production but are less likely to participate in the market for beans (via purchasing or selling) at all. Wealth, agricultural equipment and livestock ownership are all positively correlated with consumption from own-production and being a net seller and negatively correlated with purchasing beans. Households with more agricultural equipment also sell higher quantities of seed.

Table 7: Regression results for sales and net seller

	Sales				Net seller	
	Probit (Hurdle 1)	Trunc. reg. (Hurdle 2)	CF Probit (Hurdle 1)	CF trunc. reg. (Hurdle 2)	Probit	CF Probit
Pseudo R2	0.129		0.129		0.185	0.186
Log pseudolikelihood	-932585	-2649004	-932307.6	-2648960.2	-854121.9	-853157.9
Adopted 2015A	-0.109	318.904	-0.109	317.999	-0.131	-0.132
	(0.179)	(297.873)	(0.179)	(401.994)	(0.277)	(0.276)
Adopted 2015B	0.390***	41.194	0.324**	27.539	0.293**	0.416***
	(0.124)	(89.207)	(0.163)	(103.365)	(0.113)	(0.142)
Adopted 2015A and 2015B	0.451***	129.928	0.384**	116.072	0.431***	0.565***
	(0.155)	(121.694)	(0.183)	(150.747)	(0.138)	(0.187)
Price of bean	-0.002**	-0.187	-0.002**	-0.203	-0.001**	-0.001**
	(0.001)	(0.539)	(0.001)	(0.645)	(0.001)	(0.001)
Price of maize	-0.002	0.258	-0.002	0.251	-0.002*	-0.001
	(0.001)	(0.716)	(0.001)	(0.861)	(0.001)	(0.001)
Price of SP	0.002***	-1.823	0.002***	-1.815	-0.000	-0.000
	(0.001)	(1.932)	(0.001)	(2.621)	(0.001)	(0.001)
Local market	0.001	-2.731	0.001	-2.271	-0.000	-0.000
	(0.002)	(1.820)	(0.002)	(2.330)	(0.001)	(0.001)
Distance to road	0.000	0.023	0.000	0.023	0.000	0.000
	(0.000)	(0.026)	(0.000)	(0.018)	(0.000)	(0.000)
Distance to city	0.000***	0.007*	0.000***	0.006*	0.000***	0.000***
	(0.000)	(0.003)	(0.000)	(0.004)	(0.000)	(0.000)
Elevation	-0.001***	-0.178	-0.001***	-0.178	-0.001***	-0.001***
	(0.000)	(0.195)	(0.000)	(0.254)	(0.000)	(0.000)
Household size	-0.027	-130.374*	-0.027	-129.812	-0.124***	-0.126***
	(0.024)	(70.016)	(0.024)	(92.802)	(0.024)	(0.024)
Sex (base = male)	-0.162*	-174.286	-0.160	-172.041	0.051	0.046
	(0.096)	(132.122)	(0.096)	(136.275)	(0.099)	(0.099)
Education (base = none)						
primary	0.014	158.578	0.021	159.539	-0.024	-0.041
	(0.128)	(154.411)	(0.129)	(181.529)	(0.120)	(0.120)
secondary	-0.093	109.061	-0.079	110.820	-0.025	-0.054
	(0.191)	(158.041)	(0.193)	(170.346)	(0.201)	(0.204)
Age	-0.008**	-3.645	-0.008**	-3.604	0.004	0.003
	(0.003)	(2.683)	(0.003)	(3.063)	(0.003)	(0.003)
Land size	0.057	138.467*	0.056	138.853	0.115	0.116
	(0.067)	(67.670)	(0.066)	(87.994)	(0.087)	(0.087)
Wealth (base = 1)						
2	0.021	-203.568	0.019	-201.845	-0.258*	-0.256
	(0.119)	(179.555)	(0.119)	(142.302)	(0.138)	(0.140)
3	-0.047	-32.433	-0.044	-31.749	0.146	0.141
	(0.153)	(137.368)	(0.153)	(133.241)	(0.140)	(0.140)
4	0.249	-23.823	0.250*	-24.237	0.295**	0.294**

	(0.149)	(127.839)	(0.148)	(100.104)	(0.134)	(0.134)
5	0.246	296.608	0.246	296.301	0.747***	0.748***
	(0.160)	(215.735)	(0.160)	(233.696)	(0.147)	(0.148)
Equipment	-0.049	103.677**	-0.048	103.576**	0.211***	0.208***
	(0.060)	(45.807)	(0.060)	(52.590)	(0.064)	(0.064)
Livestock	-0.022	26.453	-0.021	26.271	0.427***	0.426***
	(0.094)	(49.832)	(0.094)	(40.704)	(0.103)	(0.103)
Extension	0.000	1.451	0.000	1.459	0.001	0.001
	(0.002)	(1.217)	(0.002)	(1.358)	(0.002)	(0.002)
Generalized residual			0.058	10.354		-0.114
			(0.086)	(54.972)		(0.085)
Constant	1.636**	-120.646	1.644**	-117.979	0.862*	0.849*
	(0.575)	(411.135)	(0.574)	(407.654)	(0.440)	(0.442)
sigma		132.767***		132.552**		
		(38.936)		(52.700)		
N	1383	551	1383	551	1383	1383

Note: * = significance at 10%; ** = significance at 5%; *** = significance at 1%. Standard errors are robust to heteroscedasticity and clustered at the village level.

VI. Conclusions

Due to the intensity of bean production and consumption in Rwanda, the impacts of iron bean adoption identified in this paper indicate potential benefits for its rural population. Increased multiplication ratios allow farmers to obtain more food from their land which they can choose to increase consumption or income through sales. Increased consumption of own-produced beans can improve household nutrition, particularly since these beans have increased iron content, and increase food security by making households less reliant on the market. This is further evidenced by the reduction in purchased beans for consumption. Selling beans can improve household income while being a net seller further improves household's economic and food security status.

Our results are promising for the future of iron bean and other biofortified crop adoption in Rwanda and elsewhere. For the case of iron bush beans, yield gains will promote continued adoption. Future research could examine the yields of iron climbing beans in more depth, in particular to determine whether certain iron climbing varieties provide yield gains over others. By increasing consumption of own-produced beans, the nutritional benefits of iron beans are concentrated within adopters. This means that policy makers can safely target households and areas where malnutrition is common to improve nutrition with promotion of biofortified crops.

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