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

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Abstract

Ten iron-biofortified bean varieties were released in Rwanda between 2010 and 2012 to address iron deficiency in the country. This study evaluates the treatment effect of adoption of the most popular of these varieties, RWR2245, on household bean supply (bean yield and bean production), bean consumption (from own production and purchases), bean sales and being a net seller of beans. Because the adoption decision could be endogenous, we use an instrumental variable approach to quantify the impacts of adoption. RWR2245 provides a yield gain (measured as multiplication ratio, i.e. quantity harvested/quantity planted) of 49% over traditional bush bean varieties. This yield gain increases households' consumption and sales of beans. Growing RWR2245 for at least one out of two annual growing seasons increases the number of months households consume beans from own production over a 12 month period by 0.66 months (20 days), reduces the number of months households purchase beans for consumption by 0.68 months (21 days), and increases the probability of selling beans by 14%-34%. These findings are promising for the continued adoption of iron-biofortified beans in Rwanda and elsewhere and provide evidence that biofortified crops are an effective investment for nutrition, food security, and poverty reduction.

I. Introduction

The human body requires several essential vitamins and minerals that it cannot produce on its own; the lack of just one of these can result in a number of negative health consequences, including anemia, blindness, and an increased risk of maternal and infant mortality, among others. This situation, called micronutrient malnutrition and also known as “hidden hunger,” affects over a quarter of the world’s population (World Health Organization, 2018). The consequences of hidden hunger go beyond health outcomes; individuals who lack sufficient micronutrients can also suffer from impaired cognitive development, resulting in lower educational outcomes and productivity. Infants and young children can experience an entire lifetime of reduced earning opportunities due to micronutrient deficiency early in life (Alderman et al., 2006), perpetuating poverty. The global annual cost of hidden hunger has been estimated at up to 3% of global GDP (FAO, 2014).

For decades, policy makers have combatted hidden hunger by distributing vitamin and mineral supplements and fortifying processed foods with nutrients (World Health Organization, 2018). More recently, scientists turned to crop breeding technology to develop a new intervention to complement supplementation and fortification: biofortification, a process through which staple food crops are bred to be both high yielding and high in micronutrient content. Biofortification targets staple crops, as vulnerable populations typically consume them in large quantities, providing greater potential for improving nutrition. By 2017, over 150 biofortified varieties across 10 crops had been released in 30 countries (Bouis and Saltzman, 2017).

One such biofortified crop is iron-biofortified bean, designed to combat iron deficiency, which can cause anemia, fatigue, poor pregnancy outcomes, and other adverse health conditions (World Health Organization, 2018). Numerous randomized control trials have established that consumption of iron-biofortified crops reduces iron deficiency and improves functional outcomes (De Moura et al., 2014). Two studies found that consumption of iron-biofortified beans improved iron status after only a few months (Haas, 2014; Haas et al., 2016), and a meta-analysis of studies on iron-biofortified bean, rice, and pearl millet found iron-biofortification to be effective at improving iron status (Finkelstein et al., 2017). The benefits of biofortified crop consumption go beyond iron status; iron-deficient women who ate iron-biofortified beans experienced improved memory and ability to pay attention (Murray-Kolb et al., 2017), as well as a reduction in time spent in sedentary activity (Luna et al., 2015).

The first country selected for release and scaling-up of iron-biofortified bean varieties was Rwanda, a small country in East Africa that has a high population density and heavy reliance on agriculture. Rwanda has two cropping seasons per year, seasons A, which runs from September to January, and season B, which runs from February to August, and most farmers produce beans in both seasons (Asare-Marfo et al., 2016a). The country also has the highest per-capita consumption of beans in the world (FAO, 2017); beans make up 32% of calories and 64% of protein in the average diet (Mulambu et al., 2017). In collaboration with the International Center for Tropical Agriculture and HarvestPlus, the Rwanda Agricultural Board developed and released ten iron-biofortified bean varieties in Rwanda between 2010 and 2012. The varieties have approximately twice as much iron content as non-biofortified varieties, and are adapted to local conditions, high-yielding, and resistant to common pests and diseases. They cover a wide range of colors, sizes, and other characteristics to appeal to bean producers and consumers throughout the country. Two of the released varieties are bush bean varieties with potential yields of 2-2.5 t/ha (Katsvairo, 2014). The remaining eight varieties are climbing bean varieties. The climbing iron-biofortified varieties can yield between 3 and 4.5 t/ha but require additional inputs, including stakes, to achieve these high yield potentials (Katsvairo, 2014). Climbing varieties tend to be most popular in the North of the country, which is characterized by higher elevations, greater land scarcity, and colder temperatures.

Since 2012, HarvestPlus and its partners have distributed iron-biofortified bean planting material to small landholders in Rwanda through formal delivery approaches, including direct marketing, payback, and seed swap, which have been important in promoting fast and sustained adoption of iron-biofortified beans (Vaiknoras et al., 2017). Direct marketing consists of selling small packets of iron-biofortified seeds (ranging from 200 to 500 g) to farming households during local market days; over a quarter of a million households received iron-biofortified seeds through this mechanism by the end of 2015, the highest of any delivery approach (Mulambu et al., 2017). Through payback, which began in 2013, a smaller number of households received large quantities of seed in exchange for a promise of a share of their harvest. In 2015, payback was replaced by seed swap, a similar approach in which households exchanged some of their local bean grain saved as seed for iron-biofortified bean seed at the start of the growing season. By 2015, direct marketing was well distributed throughout the country and households in 10 out of Rwanda's 30 districts had participated in payback/seed swap. Iron-biofortified planting material also spreads through informal dissemination via social networks (Vaiknoras et al., 2017).

As a result of both formal and informal delivery, iron-biofortified beans are widely adopted in Rwanda; approximately 28% of rural households in the country grew an iron-biofortified bean variety in at least one season between 2012 and 2015 (Asare-Marfo et al., 2016b). The most popular iron-biofortified bean variety in Rwanda is RWR2245, a bush variety planted by over half of all iron-biofortified bean adopters in the country. RWR2245 has been the most widely disseminated variety; in most seasons, over 70% of iron-biofortified bean planting material disseminated was of RWR2245. The other iron-biofortified bush bean variety, RWR2154, has been planted by about 2% of total iron-biofortified bean adopters; the remaining adopters are spread across the eight climbing varieties (Asare-Marfo et al., 2016b).

This paper uses an instrumental variable (IV) approach to evaluate the treatment effect of RWR2245 adoption on outcomes representing household bean supply and consumption. We quantify the impact of adoption on yield, which is the first order effect of adoption, and then examine the effects of adoption on bean production, bean consumption from own production and purchases, bean sales, and the likelihood of being a net seller of beans. We construct IVs using data on the rollout of iron-biofortified bean dissemination through formal approaches (direct marketing and payback/seed swap), and informal dissemination. Formal approaches are strongly correlated with adoption but should not otherwise be correlated with our outcomes of interest, as rollout was not related to the bean production, consumption, or marketing characteristics of local communities. Informal dissemination, captured with the previous-season village adoption rate, is likely to be determined primarily by the presence of previous delivery approaches in the local area; therefore, while it is also strongly correlated with adoption, it should otherwise be exogenous to our outcomes of interest.

The literature identifies many impact pathways through which agricultural interventions can improve nutrition (Webb, 2013). Two commonly identified pathways are improvements in nutrition through (1) increased consumption of own produced food, particularly if that food is highly nutritious; and (2) increased household incomes via sales of own produced food, which can be spent on healthy foods, such as animal source proteins, or other health-related goods (Pandey et al., 2016; Webb, 2013). These pathways stem directly from increased agricultural productivity, which provides households with an increase in production which they can then choose to consume, improving their nutrition through pathway (1), or sell, contributing to enhanced nutrition through pathway (2), or a combination of both. In the case of iron-biofortified beans, consumption of own produced beans can have a particularly strong impact on nutrition due to their increased iron content compared to traditional varieties; these health benefits have been well-established (De Moura et al., 2014) However, the literature has not yet widely explored the impacts of adoption on earlier links along the impact pathway.

Our paper fills this gap in the literature. In our impact-pathway framework, adapted from others in the literature (Pandey et al., 2016), adoption of RWR2245 affects households initially through higher bean productivity. Therefore, it is crucial to quantity the impact of adoption on yield to strengthen evidence of higher-order impacts, which depend on the additional harvested quantity that households achieve as a result of adoption. Improved productivity of beans may cause households to increase the portion of their land they devote to beans in order to take full advantage of increased yields, or reduce the portion of land they devote to beans if they are land constrained and wish to increase production of other crops. Households may choose to consume all or a fraction of their additional bean harvest, improving nutrition through pathway (1) and/or sell the extra production, contributing to better nutrition via pathway (2). For households that are net buyers of beans, the increased harvests should reduce the quantity of bean they must purchase to meet household consumption needs, increasing their income available to spend on other goods, and improving their self-sufficiency in bean production, which can protect them against price fluctuations in the market and promote food security. For autarkic households that neither purchase nor sell beans, the increase in harvest may induce them to begin selling beans and become net sellers of beans. For current net sellers of beans, adopters can increase their quantity sold. An increase in consumption from own production as a result of adoption will improve nutrition all else held equal, as adopters' harvested bean grain will be higher in iron content than it would have been absent adoption. Reductions in purchases, increases in sales and in the probability of being a net seller can improve household incomes, economic, and food security. By quantifying the impacts of RWR2245 adoption, this study will inform the development and promotion of future biofortification strategies and help policy makers allocate resources most efficiently.

The next section describes our data and is followed by explanation of our identification strategy, including our reduced form equations, variables, estimation techniques, and descriptive statistics. We then outline our results and conclude with policy implications of our findings.

II. Data and Empirical Specification

II.a Data source

This study uses nationally representative data of bean producers in Rwanda collected in two stages in 2015. The first stage, a listing exercise, occurred in May and June 2015 during season 2015B; 120 villages were randomly selected and each household in these villages, totaling 19,575, was interviewed regarding their iron-biofortified bean adoption histories from 2010-2015B. In order to assist respondents in accurately identifying iron-biofortified beans, enumerators showed them seed samples of each of the ten varieties, one by one. They asked respondents if they had ever seen or heard of the variety, if they had ever grown it and if so, which growing season they first adopted 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 bean (i.e. bush or climbing).

Twelve households from each village (six iron-biofortified bean adopters and six non-adopters, when possible) were re-interviewed for the main household survey, which took place in September 2015, a few months after season 2015B harvest. For each household, the respondent was the person who knew the most about bean cultivation. Enumerators collected information on every bean variety the household grew in season 2015B, including whether it was an iron-biofortified, improved (but not biofortified) or local/traditional variety, quantity of seed planted to each, quantity of grain harvested of each variety, and characteristics of the plot on which the household planted each variety. For each plot cultivated by the household in that season, the respondent reported the size, distance from their home, and input usage. Respondents also reported the months, out of the last 12, that the household consumed beans from their own production, the months that they purchased beans for consumption, and the average quantity of beans consumed from each source per month during these months. They also reported their total sales of beans in the last 12 months. Finally, the survey collected additional information on household demographics, housing characteristics, and asset ownership.

We use two additional sources of data: a community survey and the HarvestPlus Rwanda country program's records of the locations, in each season, of direct marketing approaches used. The community survey interviewed village leaders regarding village characteristics, access to extension, and whether anyone in the village participated in the payback or seed swap delivery approach and if so, what season they first began doing so. Direct marketing delivery records provide the number of direct marketing approaches in each sector (an administrative division) and in each season.

After dropping observations with missing data, outlier values, and likely misclassified bean varieties, our sample includes 1,383 households that grew an average of 1.6 varieties in total (.8 bush varieties) in 2015B, totally 2,227 beans (1,129 bush beans).

II.b Measurement of outcome indicators and treatment variables

We measure yield using the 2015B multiplication ratio (quantity harvested/quantity planted), calculated for each bush variety grown by households in our sample in 2015B. We use multiplication ratio as a proxy for yield because the former is less vulnerable to measurement errors associated with plot size, which are accentuated with small plots as is the case for Rwanda. We restrict our sample to bush varieties because we are primarily interested in comparing the yield of RWR2245 to local bush varieties. To capture the effect of adoption on yield, we measure adoption at the variety level, since some households grew more than one bush bean variety in 2015B" we specify whether each variety is RWR2245, a local bush bean variety, or another improved bush variety other than RWR2245. We expect that households will achieve higher multiplication ratios of RWR2245 compared to local bush varieties.

Our other outcome variables are measured at the household level. We measure bean production using the quantity of bean seed planted in 2015B in kg as a proxy for land area under beans. We capture bean consumption from own production using two variables: the number of months in the 12 months prior to data collection that households consumed beans from own production and the average quantity per adult equivalent[1], in kg, in each of these months. Likewise, bean purchases are captured using the number of months, in the past 12 months, that the household purchased beans for consumption, and the average quantity purchased per adult

[1] Adult equivalents are calculated based on a scale obtained by USAID Dary, O., Hainsworth, M., 2008. The Food Fortification Formulator: Technical Determination of Fortification Levels and Standards for Mass Fortification. USAID, Washington, DC.

equivalent, in kg, in each of these months. Bean sales are measured as the total quantity of beans sold in the past 12 months, per adult equivalent in kg. Whether the household is a net seller of beans is determined by comparing total bean purchases in the past 12 months with total bean sales; a household is a net seller if total sales exceeded total purchases.

We capture the effects of adoption on these outcomes by measuring adoption at the household level over the 12 months prior to data collection, which covers the seasons 2015A and 2015B; households are considered to be adopters if they grew RWR2245 in either or both of these seasons. We have no expectation apriori of the effect of adoption on land devoted to beans. Households may wish to increase land under beans to further take advantage of higher yields, but may be too land constrained to be able to shift more land toward beans; households may instead reduce land under beans in order to devote land to other crops. We hypothesize that adoption, through higher yield, will increase bean consumption from own production while reducing consumption of purchased beans (either by changing the number of months households consume beans from either source or the average monthly quantity), increase sales, and increase the probability of being a net seller of beans.

II.c. Reduced form equations

We estimate the impacts of adoption on multiplication ratio (M_{ij}) at the variety-level using the following reduced-form equation, where *i* refers to households and *j* refers to bush bean varieties within households:

$$M_{ij} = D_0 + D_1 T_{ij} + \mathrm{D}_2 I_{ij} + \mathrm{D}_4 H_{M_i} + e_{ij} \qquad (1)$$

The treatment variable is T_{ij}, a categorical variable equal to 0 if the variety is a local bush variety, 1 if the variety is an improved bush variety other than RWR2245, and 2 if the variety is RWR2245. We control for agricultural inputs used in bean cultivation and characteristics of the plot on which variety j is grown, I_{ij}, and household-level variables, H_i, that could influence productivity and potentially be correlated with adoption of RWR2245. Covariates capturing plot characteristics and input usage are the source of planting material (i.e. recycled seed from the family's planting material or from any other source, including friends and relatives, local markets, agrodealers, farmers groups or cooperatives, or other HarvestPlus delivery approaches), slope of the plot (flat, gentle, moderate, or steep), whether the plot was intercropped, the distance from the plot to the household (in minutes walking), application of organic fertilizer, and application of chemical fertilizer. We also include the sex, literacy, and years of experience growing beans of the household member who makes planting decisions for the plot. These plot-level covariates can vary within the household. The household-level covariates, which do not vary within households, in the yield regressions include dwelling elevation, as this can affect weather, soil, and access to inputs and information, the number of adults in the household as a proxy for labor availability, the count of agricultural equipment owned, and access to extension, measured as the percent of households at the village level that get advice from extension to avoid endogeneity.

We estimate treatment effects for the remainder of our outcome variables, O_i, at the household level, again controlling for household level variables (H_i) that could affect the outcomes of interest and be correlated with adoption of RWR2245.

$$O_i = D_0 + D_1 A_i + \mathrm{D}_4 H_{Oi} + e_i \qquad (2)$$

Here, our treatment variable is A_i. This is a dummy variable equal to one if the household grew RWR2245 in either season 2015A or 2015B (or both), and zero otherwise. We control for a different set of household-level covariates, some overlapping with those in equation (1) in these regressions, because we expect different variables to influence these outcomes. These include the price of bean during the time of high bean availability in 2015 -collected at the village level to avoid endogeneity-, distance to the nearest city of 50,000 people (in km) and population density (in people/square km) as proxies for market access, elevation (in meters), number of household members, the sex, literacy and age of the respondent, size of land cultivated in 2015B (in hectares), a wealth index created using polychoric components analysis, a count of agricultural equipment owned, livestock ownership measured in tropical livestock units[2], and access to extension. Finally, we control for whether the household grew climbing beans in 2015B, as climbing beans have higher yields on average than bush beans (and could thus impact production, consumption, and sales of beans). This variable will also capture the vast majority of adoption of other iron-biofortified bean varieties, most of which are climbing varieties.

In all regressions, we also include province fixed effects to control for differences in bean productivity, production, consumption, marketing, infrastructure, and so on, between provinces. This is particularly important because the prevalence of delivery approaches and RWR2245 adoption also varies by province.

If any household or variety-level factors or characteristics exist that are not captured in our reduced form equations (1) and (2), then error terms, e_{ij} and e_i, may be correlated with the dependent variables. Examples could include unobserved farmer ability or access to resources that our models don't capture. This endogeneity will cause our treatment effect estimates to be biased. Therefore, we use IV methods that remove the correlation between the error terms and dependent variables in order to estimate unbiased treatment effects.

[2] [b] 1 cow = 0.5; 1 sheep = 0.1; 1 goat = 0.1; 1 pig = 0.2; 1 chicken = 0.01; 1 rabbit = 0.02.

II.d. Instrumental Variables

IV methods are commonly used to estimate treatment effects when the treatment variable may be endogenous to the outcomes of interest, as they do not require the assumption that the error terms be uncorrelated with the dependent variables. The challenge of using an IV approach is that it requires identifying one or more variables that are both relevant, or related to the treatment variable, and valid, or otherwise uncorrelated with the outcome of interest. Because iron-biofortified 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 sum of direct marketing approaches in a household's sector in 2015A and 2015B, a dummy variable set to one if anyone in the household's village participated in payback or seed swap, and the village adoption rate of RWR2245 in 2014B, which proxies for the availability of RWR2245 within one's social network one season prior to our time period of interest. We use the adoption rate of RWR2245 in 2014B because it can directly influence adoption in 2015A and 2015B, as households commonly obtain planting material from social sources. Direct marketing and the previous-season adoption rate in the village are highly correlated with adoption of iron-biofortified varieties, while the presence of payback within the village is correlated with a lower probability of disadoption of the varieties (Vaiknoras et al., 2017). However, they should not be correlated with our outcomes of interest other than through their effect on adoption since the locations for formal delivery approaches were not chosen based on bean yields, consumption or marketing characteristics of the small landholders in the area, and farmers had no influence over their placement. We test the validity of the IVs using a series of diagnostic tests for two-stage least squares (2SLS) regressions for each outcome of interest

II.e. Estimation

We estimate ordinary least squares (OLS) models for the continuous outcomes of interest: multiplication ratio, quantity of bean seeds planted, and quantity of beans consumed from own production and purchased per month. We assume log-linear functions for these outcomes because their distributions are highly skewed to the right. For this reason, 17 observations of multiplication ratios of zero had to be dropped, leaving 1,112 bush bean varieties in our sample. For the number of months consumed from own production, we estimate a Poisson model and for the number of month beans were purchased, we estimate a zero-inflated Poisson model because some households did not purchase beans over the past 12 months. For quantity sold, we estimate a double hurdle model, also called Craggit (Burke, 2009), because some households did not sell any beans. The double hurdle model estimates a probit model in the first stage and a truncated normal regression model in the second stage and then allows the 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 selling and the quantity of 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 using a control function (CF) approach, as this is more efficient than 2SLS estimation when the endogenous variable is non-linear (Imbens and Wooldridge, 2007). We first estimate an ordered probit for the variety level adoption specification and a probit model for the household level adoption specification to explain RWR2245 adoption that include the explanatory variables specific to each outcome of interest and the IVs. We calculate the generalized residuals from this first stage 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 (Wooldridge, 2014). Wooldridge (2015) states that the use of CF methods in the case of binary endogenous explanatory variables and nonlinear outcome models is controversial, but also argues that a CF approach is simpler than maximum likelihood estimation, and requires assumptions that are no less general. This approach is similar to the "two-stage residual inclusion" approach proposed by Terza et al. (Terza et al., 2008; Wooldridge, 2014).

All regressions include standard errors that are robust to heteroscedasticity. Standard errors are clustered at the household level for the multiplication ratio OLS regression and its corresponding control function since several households cultivate more than one bean variety, resulting in more than one observation per household. For all other models, standard errors are clustered at the village level. Because iron-biofortified bean adopters were oversampled during data collection, we also use sampling weights for all descriptive statistics and regressions.

II.f. Fixed effects for multiplication ratio analysis

We take advantage of the panel nature of the multiplication ratio data and use household fixed effects (FE) on a reduced sample of partial adopters, i.e. households who grew RWR2245 and at least one other bush bean variety in 2015B, to handle the possible endogeneity of the adoption decision. Fixed effects eliminate household-level unobserved heterogeneity; by reducing our sample to partial adopters, we should eliminate any remaining selection bias of adoption. This provides a robustness check for the effects of RWR2245 adoption on productivity.

II.g. Descriptive Statistics

Adoption measures

Excluding observations of multiplication ratios of zero, our sample of 1,383 households grew 1,112 bush bean varieties in 2015B; 13% of these were RWR2245, 68% were local bush varieties, and 19% were other improved bush varieties, including the other iron-biofortified bush variety, RWR2154 which made up less than 1% of varieties in our sample (figure 1). About 13% of households grew RWR2245 between seasons 2015A and 2015B; 3% in 2015A only, 6% in 2015B only, and 4% in both seasons (figure 2). Most of these households grew RWR2245 for the first time in 2015; 39% of 2015 RWR2245 growers had grown RWR2245 in a previous season. Only 6% of households that did not grow RWR2245 in 2015 had grown it in a previous season. Adoption of RWR2245 varies greatly by province; 23% of households in the East, 16% in the South, 13% in Kigali, 4% in the West, and 1% in the North grew RWR2245 in 2015.

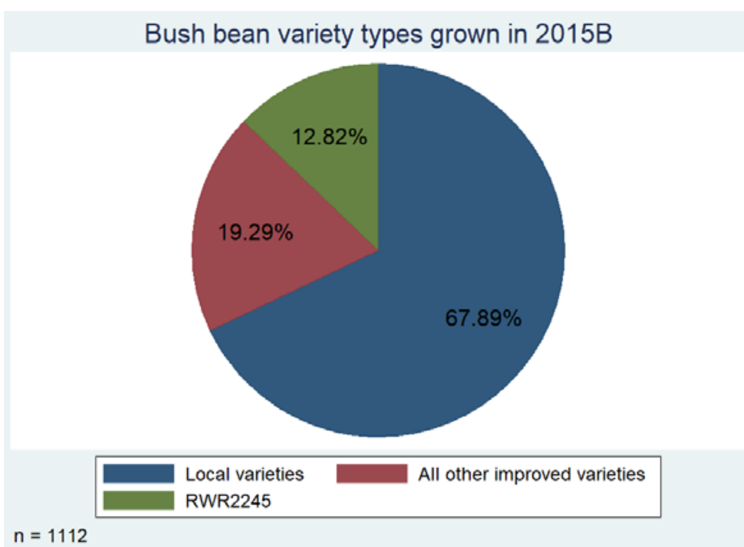

Figure 1: Bean variety types grown in 2015B

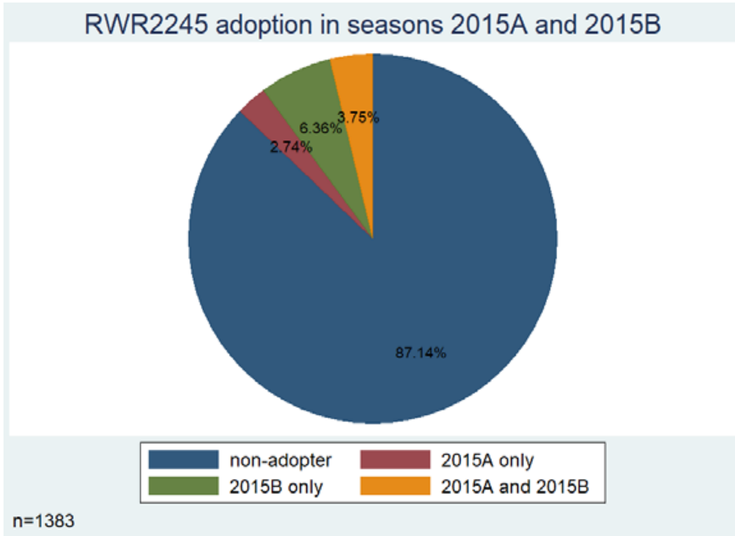

Figure 2: RWR2245 adoption by household in 2015

Outcome variables

The average multiplication ratio (quantity harvested/quantity planted) is 8.25 for RWR2245, 8.26 for other improved bush bean varieties, and 6.74 for local bush beans (figure 3). The average multiplication ratio of RWR2245 and other improved varieties is higher than that of local varieties at a 5% significance level. Households that planted RWR2245 in 2015 planted 16.32 kg of bean seeds in 2015B, while non-growers planted 14.14 kg (figure 4). This difference is significant at a 10% level.

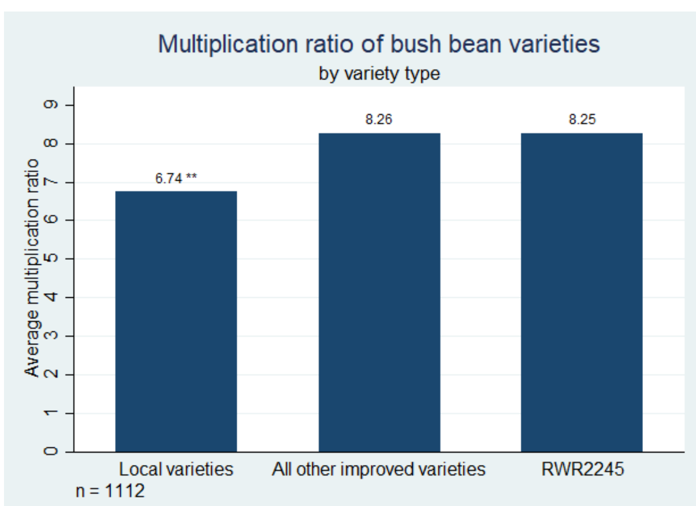

Figure 3: Average multiplication ratio of bush varieties

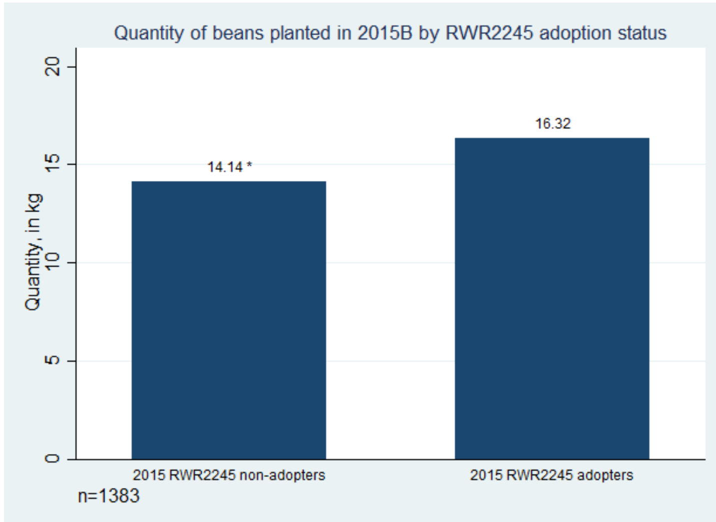

Figure 4: Quantity of beans planted in 2015B

Households that grew RWR2245 in 2015 consumed beans from own production for 8.59 months on average in the past 12 months, which is 1.3 months (about 40 days) longer than households that did not grow RWR2245 that year (significant at 5%). RWR2245 growers also purchased beans for about 1.3 months fewer than non-growers (table 1). However, quantities consumed within each month did not vary by adoption status. Households that grew RWR2245 in 2015 were more likely to sell beans, sold higher quantities of beans, and were more likely to be net sellers of beans, than households that did not grow RWR2245 that year. Figure 5 shows consumption trends by month; consumption from own production is most prevalent in January and February, following Season A harvest, and in June and July, which follows Season B harvest (Asare-Marfo et al., 2016b). The most apparent differences between RWR2245 growers and non-growers appear in October and November, when RWR2245 non-growers are more likely to consume from purchases than from own production and the opposite is true for RWR2245 growers.

Table 1: Descriptive statistics for outcome variables

Variable	2015 RWR2245 adopters	2015 RWR2245 non-adopters
No. months consumed from own production	8.59 (3.30) **	7.29 (3.24) **
No. months purchased	2.79 (2.99) ***	4.12 (3.24) ***
Consumption from own production per month (in kg)	4.05 (2.27)	3.93 (2.23)
Purchases per month (in kg)	3.02 (1.79)	3.19 (2.26)
Sold beans (1 = yes)	0.63 (0.48) ***	0.37 (0.48) ***
Total sales, last 12 months (in kg)	19.90 (33.34) **	9.77 (26.22) **
Net seller (1 = yes)	0.55 (0.50) ***	0.37 (0.48) ***
N	245	1125

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

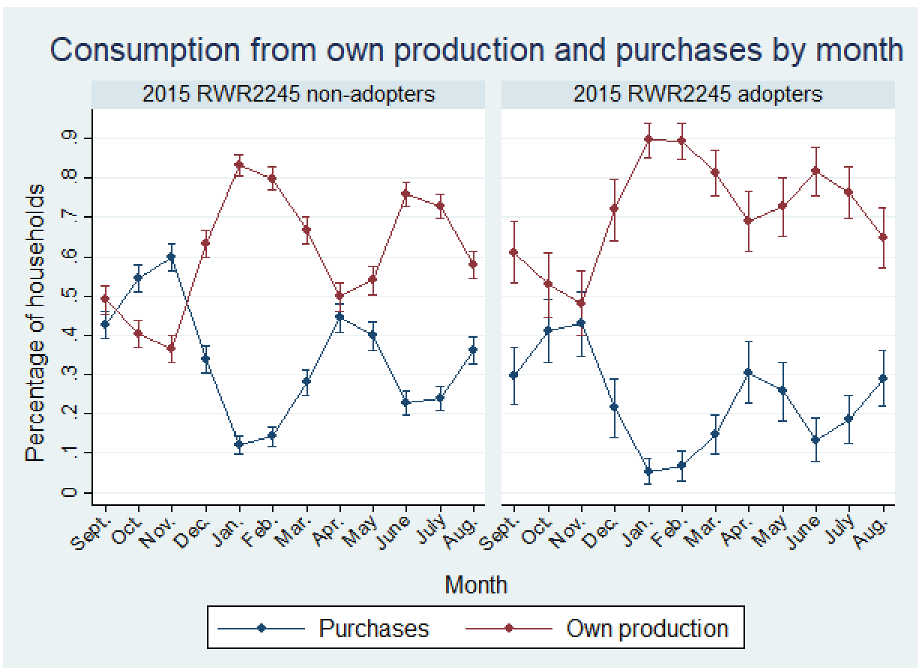

Figure 5: Consumption and purchases of beans by month and RWR2245 adoption status

Delivery approaches

HarvestPlus and partners did not deliberately target delivery approaches toward areas with greater bean productivity, consumption, or marketing, but we compare areas in which these delivery interventions took place to others to determine whether they differ systematically in any way that could affect these outcomes. Delivery approaches are more prevalent in some areas of the country than others; in 2015, 57% of households in the Northern province, 24% in the West, 22% in the East, 8% in the South, and none of the households in Kigali had a direct marketing approach in their sector. Payback and seed swap were most prevalent in the South; 12% of households in that province have had payback or seed swap in their village compared to 8% of households in the East, 6% in the West, and none in the North and Kigali.

Most household characteristics, including literacy, wealth, and land size, do not vary by whether the households had a direct marketing approach in their sector or payback/seed swap in their village. Households who live in sectors with a direct marketing approach live further from cities, at higher elevations, and in villages with higher bean prices and greater access to extension on average, while households who live in villages with a payback/seed swap approach face lower bean prices and live at a lower elevation, and are less likely to grow climbing beans. Many of these differences can be explained by differences across province. Within provinces, bean price and propensity to grow climbing beans only varies by villages with and without payback/seed swap in the South. Prices are higher and households are further from cities in sectors with direct marketing only in the South. Elevation and access to extension are higher for households in sectors with a direct marketing approach only in the South and West, while access to extension is lower for these households in the North and East. Therefore, once province is controlled for, as it is in our models, there are few systematic differences for households with and without delivery approaches in their sector or village. This lends support that data on formal delivery approaches can provide valid IVs for RWR2245 adoption.

Plot, input, market, and household variables

RWR2245 is less likely to be grown from recycled planting material, and more likely to be grown using organic and chemical fertilizer than local bush bean varieties (table 2). Households who grew RWR2245 in either season of 2015 were much less likely to have grown a climbing bean variety in 2015B than those that did not (table 3). They also live in villages with lower bean prices on average, and at a lower elevation, compared to households that did not grow RWR2245. RWR2245 growers are more likely to be literate, to be in the top wealth quintile, and to own more agricultural equipment. Finally, adopters are more likely to live in villages where someone participated in payback/seed swap and that had a higher adoption rate of RWR2245 in 2014B.

Table 2: Descriptive statistics of plot-level variables for RWR2245 and local bush varieties

	RWR2245	Local bush varieties
	Mean (sd)	Mean (sd)
Recycled seed (1 = yes) **	0.27 (0.45)	0.39 (0.49)
Slope		
Flat	0.10 (0.30)	0.08 (0.27)
Gentle	0.11 (0.32)	0.14 (0.35)
Moderate	0.39 (0.49)	0.35 (0.48)
Steep	0.39 (0.49)	0.43 (0.49)
Intercrop (1 = yes)	0.60 (0.49)	0.66 (0.48)
Walking time to household (in minutes)	18.18 (33.07)	15.58 (23.07)
Organic fertilizer use (1 = yes) **	0.83 (0.37)	0.71 (0.45)
Chemical fertilizer use (1 = yes) **	0.17 (0.38)	0.07 (0.27)
Sex of plot decider (1= female)	0.59 (0.49)	0.61 (0.49)
Literacy of plot decider (1=yes)	0.65 (0.48)	0.59 (0.49)
Experience of plot worker (in years)	25.92 (14.19)	27.50 (16.70)
	211	679

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

Table 3: Descriptive statistics of household-level variables for 2015 RWR2245 growers and non-growers

	RWR2245 2015 growers	RWR2245 2015 non-growers
Variables	Mean (sd) or % yes	Mean (sd) or % yes
Climbing bean grower (1 = yes)	0.19 (0.40)	0.60 (0.49)
Price of bean (RWF) ***	260.60 (69.04)	294.68 (77.00)
Distance to city (km)	36.50 (21.51)	36.96 (20.37)
Population density (people/square km)	481.04 (541.23)	489.90 (494.57)
Elevation (10m) ***	156.90 (15.97)	170.61 (25.47)
Household size	4.96 (2.08)	4.82 (2.03)
Sex of bean decision maker (1 = female)	0.62 (0.49)	0.63 (0.48)
Literacy of bean decision maker (1 = yes) **	0.69 (0.46)	0.59 (0.49)
Age of bean decision maker (in years)	44.57 (13.83)	44.63 (15.79)
Land size (ha)	0.55 (0.70)	0.46 (0.77)
Wealth		
1	0.18 (0.38)	0.20 (0.40)
2	0.16 (0.37)	0.21 (0.41)
3	0.17 (0.38)	0.20 (0.40)
4	0.20 (0.40)	0.20 (0.40)
5 **	0.28 (0.45)	0.19 (0.39)
Equipment owned (count) **	1.38 (0.56)	1.21 (0.78))
Livestock (TLU)	0.55 (0.75)	0.42 (0.90)
Extension (%) **	66.06 (24.62)	64.76 (27.53)
Direct markets 2015A and 2015B (#)	0.58 (1.98)	0.55 (1.37)
Village had payback/seed swap (1 = yes) **	0.13 (0.34)	0.06 (0.24)
Village RWR2245adoption rate 2014B (%) ***	0.11 (0.10)	0.04 (0.07)
	250	1,133

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

III. Results

III.a. Instrument validity, endogeneity tests, 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. In the yield regressions the generalized residual is statistically significant (table 5), indicating that adoption is endogenous to the multiplication ratio (Wooldridge, 2014). For all remaining regressions, the generalized residual is not statistically significant (tables 6-9), indicating that adoption is not endogenous to these outcomes and our non-CF estimation results are equally valid as our control function results, and likely more efficient (Wooldridge, 2014). Therefore, we will discuss the results of these models for which adoption is considered exogenous.

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

	Yield	Beans planted	Months consumed	Log Quantity Consumed	Months purchased	Log Quantity purchased	Total Sales
Underidentification test							
Kleibergen-Paap rk LM statistic	17.675	28.626	28.626	29.336	28.626	15.198	28.626
Chi-sq (4) P-val	0.000	0.000	0.000	0.000	0.000	0.002	0.000
Weak identification test							
Cragg-Donald Wald F statistic	7.896	22.847	22.847	23.493	22.847	13.496	22.847
Sanderson-Windmeijer test p-value	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Overidentification test							
Hansen J statistic	3.033	1.927	1.497	5.457	3.081	3.707	1.785
Chi-sq (3) P-val	0.219	0.382	0.473	0.065	0.214	0.157	0.410

The likelihood ratio test that the restrictions of the tobit model hold are rejected (p = 0.000) for the sales regression, confirming that the double hurdle model fits our data better than the tobit model.

III.b. Supply indicator results

Holding other factors constant, households achieve multiplication ratios from RWR2245 that are 49% (100*($e^{.401}$ - 1)) higher than from local bush varieties on average according to CF OLS estimates, significant at a 1% level (table 5). The FE estimated treatment effect of adoption is 20%, statistically significant at a 5% level. The FE treatment effect may be lower than the CF OLS estimate due to the reduced sample; households who are partial adopters (i.e. grew both RWR2245 and another variety) may achieve lower yield gains from adoption. Other improved varieties provide a yield gain of about 21% above local varieties according to CF OLS estimates and 37% according to FE results. Being grown from recycled grain, the literacy of the person who makes decisions for the plot, ownership of agricultural equipment and access to extension are correlated with a greater multiplication ratio. In the reduced sample, growing beans on a flat or gentle slope and applying chemical fertilizer both correlate with greater multiplication ratio.

The average multiplication ratio for local varieties is 6.74; a 40% increase provides a multiplication ratio of 9.44. On average, households that grow bush beans planted 15.57 kg of bush beans in 2015B; if these were entirely planted to local bush varieties, households would harvest 104.94 kg of beans. Converting all planted bush beans from local bush varieties to RWR2245 would provide a harvest of 146.98 kg, an increase of 42.04 additional kg of beans as a result from going to zero adoption of improved varieties to full adoption of RWR2245.

Adoption of RWR2245 has no effect on the quantity of bean seed planted (table 6). Households that live further from cities, have greater household size, cultivate more land and have more wealth and livestock planted more beans in 2015B, while households at higher elevations planted fewer beans.

Table 5: OLS, CF, and FE results for multiplication ratio

	OLS Coefficient (Robust std. err.)	CF OLS Coefficient (Robust std. err.)	FE Coefficient (Robust std. err.)
Adjusted R2	0.113	0.125	
R2 within			0.145
R2 between			0.002
R2 overall			0.001
Type (base = local)			
Other improved	0.189**	0.207**	0.312**
	(0.081)	(0.080)	(0.137)
RWR2245	0.183**	0.401***	0.182**
	(0.082)	(0.085)	(0.087)
Recycled seed (1 = yes)	0.235***	0.235***	0.191
	(0.062)	(0.061)	(0.121)
Slope (base = steep)	0.000	0.000	0.000
Moderate	0.138	0.150	0.323
	(0.138)	(0.136)	(0.263)
Gentle	0.044	0.051	0.534**
	(0.130)	(0.129)	(0.266)
Flat	0.145	0.161	0.956***
	(0.128)	(0.126)	(0.226)
Intercrop (1 = yes)	-0.111	-0.096	0.269
	(0.068)	(0.067)	(0.214)
Walk time to household (in minutes)	-0.003*	-0.003*	0.001
	(0.002)	(0.002)	(0.003)
Organic fertilizer use (1 = yes)	-0.097	-0.122	-0.243
	(0.082)	(0.080)	(0.252)
Chemical fertilizer use (1 = yes)	0.087	0.066	0.502**
	(0.113)	(0.113)	(0.236)
Sex (1 = female)	-0.051	-0.060	0.150
	(0.072)	(0.071)	(0.362)
Literate (1 = yes)	0.271***	0.273***	-0.742
	(0.078)	(0.078)	(0.771)
Experience (in years)	0.001	0.001	-0.076
	(0.002)	(0.002)	(0.105)
Elevation (10m)	-0.001	-0.001	0.000
	(0.002)	(0.002)	(.)
Number of adults	0.004	0.003	0.000
	(0.028)	(0.028)	(.)
Equipment owned (count)	0.107**	0.107**	0.000
	(0.045)	(0.045)	(.)
Extension (%)	0.005***	0.005***	0.000
	(0.002)	(0.002)	(.)
Generalized residual		-0.056***	
		(0.006)	
Constant	0.988*	1.029**	3.168
	(0.386)	(0.381)	(2.199)
N	1112	1112	336

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.

Table 6: OLS and CF OLS results for log of total kg of beans planted in season 2015B

	Log of total kg beans planted 2015 B	
	OLS Coefficient (Robust std. err.)	CF OLS Coefficient (Robust std. err.)
Adj. R2/Pseudo R2	0.217	0.217
Adopted 2015 (1 = yes)	0.022	0.193
	(0.097)	(0.305)
Climbing bean grower (1 = yes)	0.009	0.030
	(0.073)	(0.077)
Price of bean (RWF)	-0.000	-0.000
	(0.001)	(0.001)
Distance to city (km)	0.007**	0.008**
	(0.003)	(0.003)
Population density (people/square km)	0.000	0.000
	(0.000)	(0.000)
Elevation (10m)	-0.007***	-0.007***
	(0.002)	(0.002)
Household size	0.039***	0.039***
	(0.014)	(0.014)
Sex (1 = female)	-0.113*	-0.114
	(0.058)	(0.058)
Literate (1 = yes)	-0.003	-0.011
	(0.062)	(0.063)
Age (in years)	-0.000	-0.000
	(0.002)	(0.002)
Land size (ha)	0.165***	0.166***
	(0.056)	(0.056)
Wealth (base = 1)		
2	0.098	0.097
	(0.079)	(0.078)
3	0.137	0.135
	(0.085)	(0.086)
4	0.304***	0.300***
	(0.090)	(0.090)
5	0.292***	0.284***
	(0.099)	(0.100)
Equipment owned (count)	0.046	0.040
	(0.044)	(0.045)
Livestock (TLU)	0.105***	0.105***
	(0.024)	(0.024)
Extension (%)	-0.001	-0.001
	(0.002)	(0.002)
Generalized residual		-0.103
		(0.156)
Constant	2.816***	2.795***
	(0.395)	(0.398)
N	1383	1383

III.c. Consumption indicator results

Growing RWR2245 in at least one growing season of 2015 increases the length of time households consume beans from home production by .66 months (equivalent to 20 days) (table 7), while reducing the length of time households consume beans from purchases by .69 months (equivalent to 21 days) in a year (table 8). However, adoption of RWR2245 has no effect on the average quantity of bean consumed from own production or purchased each month (table 7). This suggests that adoption does not change the total quantity of beans consumed by households, but changes the source of bean consumed, moving away from purchases towards own production. Growing RWR2245 also increases the probability of selling beans by between 14% (OLS results) and 34% (CF OLS results), but does not affect the total quantity sold as estimated by either the truncated regression or the craggit partial effects (table 9). It also increases the likelihood of being a net seller of beans by 8%, but the coefficient is significant at only the 10% level. The lack of significance of results for quantities consumed, purchased, and sold could partially be explained by a difficulty for households in recalling these quantities over a 12-month period, while it should be easier to remember if and when they did consume from own production, purchase and sell beans.

Households that grow climbing beans consume beans from own production for more months than those that do not, which is not surprising, as these households likely achieve higher yields than households that do not. The price of beans is negatively correlated with the probability of selling beans; high bean prices may reflect low availability of beans sold in the area. Distance from an urban area is positively correlated with selling and being a net seller, and negatively correlated with bean purchases. Population density is negatively correlated with consuming from own production and selling beans, but positively correlated with bean purchases. Households at higher elevations consume less from own production and more from purchases, while also being less likely to sell beans or be a net seller of beans. Household size is negatively correlated with consumption from own-production and being a net seller of beans, and positively correlated with bean purchases. Age of the respondent increases consumption from own production and reduces both bean quantity purchased and sold; this suggests that older bean growers are less likely to participate in the market for beans in any capacity. Households that cultivate more land sell higher quantities of beans. Finally, household resources measured through wealth, and agricultural equipment and livestock ownership are positively correlated with consumption from own production, sales and/or being a net seller of beans, while being negatively associated with bean purchases.

Alternative specifications of adoption provide consistent results. If adoption is defined as a continuous variable equal to the number of seasons in 2015 that the household grew RWR2245 (0, 1, or 2), OLS results estimate that growing RWR2245 for an additional season increases the months of consumption from own production by 0.57 months, reduces the number of months bean is purchased by 0.61 months, and increases probability of selling and being a net seller by 11% and 8% (each significant at at least 5%). If we only consider households that grew RWR2245 in both seasons of 2015 as adopters, adoption increases the probability of selling beans and being a net seller by 19% and 21%, respectively, reduces the number of month beans are purchased by 1.31, and increases the number of months beans are consumed from own production by 1.23 months, roughly double the estimated effects of growing RWR2245 for one season. Regardless of how adoption is defined over the two growing seasons, results indicate that households replace some purchases with own consumption, and likely have some surplus to sell, although we are unable to quantify the increase in quantity sold.

In months households consume bean from own production, monthly bean consumption averages 12.99 kg. Increasing the number of months of consumption from own production by 1.23 would therefore require an additional 15.98 kg of beans produced over 2015A and 2015B to meet this additional consumption; this is well within reach given the estimated yield gains of RWR2245, and would even leave a surplus for sales. Adoption should thus improve household nutrition through the increase in iron content in the harvested beans of RWR2245 adopters compared to varieties they are likely to purchase on the market. It should also improve household income by reducing purchases and increasing sales, giving both net purchases and net sellers of beans additional money to spend on other foods or health-related goods.

Table 7: Regression results for quantity consumed from own-production and purchases

	Months consumed from own production		Quantity (kg) consumed each month, per adult equivalent	
	Poisson marginal effects (Delta method Std. Err.)	CF Poisson marginal effects (Delta method Std. Err.)	OLS coefficient (robust Std. Err.)	CF OLS coefficient (robust Std. Err.)
Adj. R2			0.107	0.107
Log psuedolikelihood	-3990921.8	-3990015.7		
Adopted 2015 (1 = yes)	0.662**	1.594*	0.016	0.129
	(0.271)	(0.828)	(0.056)	(0.207)
Climbing bean grower (1 = yes)	0.596**	0.716***	-0.050	-0.036
	(0.031)	(0.260)	(0.048)	(0.052)
Price of bean (RWF)	-0.002	-0.002	-0.000	-0.000
	(0.002)	(0.001)	(0.000)	(0.000)
Distance to city (km)	0.010	0.012	-0.001	-0.001
	(0.007)	(0.008)	(0.002)	(0.002)
Population density (people/square km)	-0.001***	-0.001***	-0.000	-0.000
	(0.000)	(0.001)	(0.000)	(0.000)
Elevation (10m)	-0.026***	-0.026***	-0.001	-0.001
	(0.005)	(0.005)	(0.001)	(0.001)
Household size	-0.166***	-0.168**	-0.088***	-0.088***
	(0.055)	(0.055)	(0.008)	(0.008)
Sex (1 = female)	-0.206	-0.214	-0.082**	-0.083**
	(0.215)	(0.213)	(0.040)	(0.040)
Literate (1 = yes)	0.283	0.236	0.087*	0.082
	(0.224)	(0.223)	(0.052)	(0.053)
Age (years)	0.026***	0.025***	0.000	0.000
	(0.007)	(0.007)	(0.001)	(0.001)
Land size (ha)	0.416**	0.420**	0.022	0.022
	(0.180)	(0.180)	(0.023)	(0.023)
Wealth quintile (base = 1)				
2	0.170	0.170	0.098	0.096
	(0.324)	(0.324)	(0.067)	(0.067)
3	0.746*	0.746*	0.109	0.108
	(0.330)	(0.330)	(0.069)	(0.070)
4	1.374***	1.374***	0.123	0.120*
	(0.322)	(0.322)	(0.067)	(0.067)
5	1.718***	1.718***	0.006	0.000
	(0.358)	(0.358)	(0.065)	(0.065)
Equipment owned (count)	0.650***	0.650***	0.001	-0.003
	(0.108)	(0.108)	(0.023)	(0.025)
Livestock (TLU)	0.166	0.166	0.063***	0.063***
	(0.105)	(0.105)	(0.013)	(0.013)
Extension (%)	0.005	0.005	0.000	-0.000
	(0.004)	(0.004)	(0.001)	(0.001)
Generalized residual		-0.562		-0.068
		(0.206)		(0.124)
Constant (coefficient)	2.287***	2.271***	1.850***	1.837***
	(0.162)	(0.162)	(0.207)	(0.211)
N	1383	1383	1370	1370

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

Table 8: Months purchased and quantity purchased results

	Months purchased		Quantity (kg) purchased each month, per adult equivalent	
	Zero-inflated Poisson marginal effects (Delta method Std. Err.)	CF Zero-inflated Poisson marginal effects (Delta method Std. Err.)	OLS coefficient (robust Std. Err.)	CF OLS coefficient (robust Std. Err.)
Adj. R2/Pseudo R2			0.124	0.123
Log psuedolikelihood	-3443614	-3442974		
Adopted 2015 (1 = yes)	-0.689**	-1.039	-0.109	-0.103
	(0.275)	(0.862)	(0.080)	(0.282)
Climbing bean grower (1 = yes)	-0.255	-0.283	-0.028	-0.027
	(0.262)	(0.279)	(0.063)	(0.067)
Price of bean (RWF)	0.001	0.001	-0.000	-0.000
	(0.001)	(0.001)	(0.000)	(0.000)
Distance to city (km)	-0.019***	-0.020***	-0.001	-0.001
	(0.007)	(0.007)	(0.002)	(0.002)
Population density (people/square km)	0.000**	0.001**	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Elevation (10m)	0.020***	0.020***	-0.000	-0.000
	(0.004)	(0.004)	(0.001)	(0.001)
Household size	0.259***	0.260***	-0.091***	-0.091***
	(0.047)	(0.047)	(0.010)	(0.010)
Sex (1 = female)	0.003	0.002	-0.073	-0.073
	(0.221)	(0.222)	(0.047)	(0.047)
Literate (1 = yes)	-0.227*	-0.218*	0.117*	0.117*
	(0.174)	(0.174)	(0.058)	(0.057)
Age (years)	-0.026***	-0.026***	0.001	0.001
	(0.006)	(0.006)	(0.001)	(0.001)
Land size (ha)	-0.247	-0.247	0.013	0.013
	(0.225)	(0.224)	(0.042)	(0.042)
Wealth quintile (base = 1)				
2	0.183	0.188	0.134*	0.134*
	(0.285)	(0.285)	(0.062)	(0.062)
3	-0.453	-0.451	0.100	0.100
	(0.296)	(0.297)	(0.072)	(0.072)
4	-1.039***	-1.030**	0.053	0.053
	(0.289)	(0.289)	(0.067)	(0.067)
5	-1.506*	-1.494*	0.119	0.119
	(0. 339)	(0.339)	(0.074)	(0.075)
Equipment owned (count)	-0.537***	-0.530***	0.047	0.047
	(0.120)	(0.121)	(0.038)	(0.039)
Livestock (TLU)	-1.035***	-1.033**	-0.052	-0.052
	(0.231)	(0.231)	(0.061)	(0.060)
Extension (%)	0.000	0.000	0.000	0.000
	(0.004)	(0.004)	(0.001)	(0.001)
Generalized residual		0.203		-0.004
		(0.458)		(0.156)
Constant	1.509***	1.527***	1.278***	1.277***
	(0.190)	(0.190)	(0.285)	(0.293)
N	1383	1383	1022	1022

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

Table 9: Regression results for sales and net seller

	Sold beans		Quantity sold		Net seller	
	Probit marginal effects (Delta method Std. Err.)	CF Probit marginal effects (Delta method Std. Err.)	Trunc. Reg. (Robust std. err.)	CF Trunc. Reg (Robust std. err.)	Probit marginal effects (Delta method Std. Err.)	CF Probit marginal effects (Delta method Std. Err.)
Adj. R2/Pseudo R2	0.134	0.138			0.187	0.187
Log psuedolikelihood	-923101.42	-921431.3	-2653601	-2653375.9	-852005.65	-852005.48
Adopted 2015 (1 = yes)	0.135***	0.345**	33.916	163.740	0.081*	0.083
	(0.045)	(0.156)	(62.916)	(331.997)	(0.045)	(0.123)
Climbing bean grower (1 = yes)	-0.044	-0.018	-13.299	8.473	0.026	0.026
	(0.037)	(0.040)	(97.811)	(82.664)	(0.036)	(0.038)
Price of bean (RWF)	-0.001**	-0.000	0.119	0.176	-0.000*	-0.000*
	(0.000)	(0.000)	(0.575)	(0.651)	(0.000)	(0.00)
Distance to city (km)	0.003**	0.004**	6.240	6.490	0.004***	0.004***
	(0.001)	(0.001)	(4.470)	(4.838)	(0.003)	(0.001)
Population density (people/square km)	-0.000**	-0.000**	-0.108	-0.101	-0.000	-0.000
	(0.000)	(0.000)	(0.096)	(0.092)	(0.000)	(0.000)
Elevation (10m)	-0.002**	-0.002*	-2.629	-2.513	-0.002***	-0.002***
	(0.001)	(0.001)	(2.209)	(2.094)	(0.001)	(0.001)
Household size	-0.006	-0.006	-93.709*	-94.218*	-0.037***	-0.037***
	(0.008)	(0.008)	(56.216)	(56.964)	(0.007)	(0.007)
Sex (1 = female)	-0.045	-0.047	-103.729	-108.252	0.021	0.021
	(0.031)	(0.031)	(73.164)	(78.743)	(0.031)	(0.031)
Literate (1 = yes)	-0.009	-0.018	133.923	124.461	-0.019	-0.019
	(0.035)	(0.035)	(114.633)	(102.822)	(0.031)	(0.031)
Age (years)	-0.003***	-0.003**	-1.582	-1.792	0.001	0.001
	(0.001)	(0.001)	(1.776)	(1.912)	(0.001)	(0.001)
Land size (ha)	0.017	0.018	91.131**	92.441**	0.034	0.034
	(0.023)	(0.023)	(43.694)	(45.497)	(0.026)	(0.026)
Wealth quintile (base = 1)						
2	0.015	0.013	-156.361	-158.407	-0.064	-0.064
	(0.038)	(0.037)	(117.826)	(118.187)	(0.036)	(0.036)
3	0.002	-0.000	-19.872	-23.539	0.062	0.062
	(0.050)	(0.050)	(114.390)	(112.665)	(0.040)	(0.040)
4	0.107**	0.101*	30.553	22.845	0.117**	0.117**
	(0.050)	(0.150)	(101.200)	(93.903)	(0.042)	(0.042)
5	0.126**	0.116*	198.332	192.053	0.282***	0.282***
	(0.057)	(0.057)	(133.631)	(125.535)	(0.049)	(0.050)
Equipment owned (count)	-0.021	-0.028	107.595**	101.212**	0.062***	0.062***
	(0.020)	(0.021)	(50.304)	(49.168)	(0.021)	(0.021)
Livestock (TLU)	-0.014	-0.013	25.921	23.689	0.122***	0.122***
	(0.029)	(0.029)	(36.378)	(34.906)	(0.032)	(0.032)
Extension (%)	0.001	0.001	1.093	0.926	0.001	0.001
	(0.001)	(0.001)	(0.981)	(1.079)	(0.000)	(0.001)
Generalized residual		-0.125		-76.707		-0.001
		(0.080)		(189.132)		(0.061)
Constant (coefficient)	1.204*	1.129*	-50.490	-84.185	0.455	0.454
	(0.532)	(0.531)	(366.366)	(387.259)	(0.466)	(0.460)
N	1383	1383	551	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.

IV. Conclusions

We find evidence that adoption of RWR2245 improves households' bean yields while not affecting the portion of their land they devote to bean cultivation, providing households with additional harvested beans they would not have otherwise had. Through this increase in bean harvest, adoption has the potential to improve nutrition by increasing consumption of own produced beans while reducing bean purchases, and by making households more likely to sell beans. Adoption does not appear to change total bean consumption; rather, it allows households to shift some of their consumption away from purchased beans toward own produced beans. This can improve nutrition in two ways: first, by increasing total iron consumption, because adopters' harvests of RWR2245 are likely to be higher in iron content than any beans they would purchase in the marketplace, and second, by increasing the income that the household has to spend on other foods. Increasing the likelihood that households sell beans further increases this income effect of adoption. Further research is needed to more directly estimate the impacts of biofortified crop adoption on household nutrition, including a food consumption survey to evaluate changes in iron intake resulting from adoption.

Due to the intensity of bean production and consumption in Rwanda, the impacts of RWR2245 adoption identified in this paper indicate substantial potential benefits for both adopters and for bean purchasing households who can purchase some of adopters' RWR2245 surplus. Because the benefits of adoption are likely to be concentrated within adopters and their neighboring communities, policy makers should target households and areas with high nutritional needs for dissemination of biofortified crops.

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