The contribution of the CIAT genebank to the development of iron-biofortified bean varieties and well-being of farm households in Rwanda

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Abstract
Genebanks play an essential role in a world where agricultural biodiversity has been lost from farming habitats, malnutrition persists as global population continues to rise, and farm productivity is vulnerable to climate change. We demonstrate the importance of the genebank of the International Center for Tropical Agriculture (CIAT) to the development of seven iron-biofortified varieties of climbing bean and the impact of their adoption on farm households in Rwanda. First, we link iron-biofortified varieties of climbing beans directly to the genebank through pedigree analysis and key informant interviews with the breeders who developed them. Second, we apply various econometric models to test the impact of adoption on yield, consumption, and purchase of beans by farming households in Rwanda, building upon previous research on bush beans. We based the analysis on a dataset of nearly 1400 households, collected in 2015 by HarvestPlus. We found that the scope of the genetic diversity housed in the bean collection at CIAT was fundamental to developing successful iron-biofortified beans. We found significant positive effects of climbing varieties on yields; however, we did not find significant effects on the amounts of beans consumed by households or bean purchases. Our results suggest that it is possible to trace the journey of an accession from its introduction in the genebank to its final use by farmers and consumers. Positive effects on yield generate incentives for adoption of iron-biofortified bean varieties, potentially boosting micronutrient consumption. Further research is needed to understand the factors affecting the adoption and impacts of climbing bean varieties.

Keywords Genebank · Genetic resources · Iron-biofortified bean varieties · Adoption

1 Introduction
Genebanks play an essential role in a world where agricultural biodiversity has been lost from farming habitats, malnutrition persists as global population continues to rise, and farm productivity is vulnerable to climate change. The main purpose of a genebank is to conserve genetic materials that can be used by researchers, plant breeders, and farmers. Although genebank accessions have been used as parents in breeding programmes, the relationship between the original accessions and the improved varieties grown by farmers is not always well documented, and pedigrees of bred varieties are often not reported back to the genebank.

To better understand the importance of genebanks, a fundamental first step is to trace the journey of the genes embodied in an accession from its collection as a seed sample and introduction into a genebank to its distribution and use. Among the multiple channels of its potential use, we trace accessions here from the breeding programmes to production by farmers and consumption by final consumers. In low-income agricultural systems, like those found in Rwanda, small-holder farmers are both producers and consumers of beans.
This means that for many farm households, the majority of their production is used for home consumption.

This study analyzes a specific crop species conserved at the genebank of the International Center for Tropical Agriculture (CIAT)—the ‘common bean’ (*Phaseolus vulgaris*). The common bean is a major staple in the diets of Latin American and African populations, providing a highly nutritious food that contains not only protein, fiber, and complex carbohydrates but also the vitamins and micronutrients that are essential to overcome the problem of hidden hunger. Beans are an indispensable source of iron and provide income for millions of people, specifically in Africa and Latin America. About 400 million people in the tropics eat beans as a part of their daily diet (CIAT 2019).

In a number of countries, including Rwanda, anemia remains a serious public health problem and biofortification is one of the nutritional strategies that has the potential to become a sustainable, inexpensive, and effective solution for iron deficiency at population level (Haas et al. 2016).

For this reason, our analysis focuses on the iron-biofortified bean varieties developed through the collaboration of the CIAT, HarvestPlus (HP), Virginia Tech, and the Rwanda Agriculture Board (RAB) and distributed to sub-Saharan Africa, specifically in Rwanda, the first country where they were introduced. Among the 10 iron-biofortified varieties released by CIAT, HP, and RAB between 2010 and 2012, we focus on seven climbing varieties: CAB2, RWV3316, RWV3317, RWV3006, RWV2887, MAC44, and MAC42.

We build on recent work by Vaiknoras et al. (Vaiknoras and Larochelle 2018; Vaiknoras et al. 2019), who tested the impact of the adoption of an iron-biofortified variety of bush bean, RWR2245, on the yield, consumption and bean purchases of farming households in Rwanda. As in Vaiknoras and Larochelle (2018), we used nationally representative data on bean producers collected by HP in collaboration with CIAT, Virginia Tech, and RAB in 2015. Our approach is similar to Vaiknoras and Larochelle (2018): we share the same underlying dataset and comparable indicators of adoption outcome. The key differences, however, are that we study climbing varieties of bean rather than bush varieties and include some innovative aspects. In particular, we take into account not only the effects of iron-biofortified climbing varieties on farming households, but also the breeding process, pedigrees of the varieties, and the role that CIAT’s genebank played in the process. Compared to bush beans that normally give a large harvest over a short period, climbing beans have a quite long harvest period and can be harvested more than once per season. However, climbing beans require additional inputs, such as stakes, to achieve good output levels (Katsvairo 2014).

The main reasons for choosing the seven climbing varieties listed above are that: 1) each variety has parents from CIAT’s genebank collection; (2) climbing beans have higher yield potential than bush beans and would be a good delivery mechanism for biofortification, especially in the Great Lakes region where they are more likely to be adopted; and (3), there is no previous study on the impact of iron-biofortified varieties of climbing bean on farm yields, production, and consumption in Rwanda. Furthermore, to our knowledge, no previous research has sought to link farm-level outcomes directly to CIAT’s genebank. At this stage, literature on the farm impact of iron-biofortified varieties remains scant. In 2015, HP, CIAT, RAB, and Virginia Tech conducted two studies. The purpose of the first study was to understand the adoption and diffusion patterns that occurred during the past few years; the aim of the second study was to establish the reach of iron-biofortified bean varieties among Rwandan bean farmers since they were released in 2010 (Asare-Marfo et al. 2016a, 2016b).

In this study, we address these lacunae and document the direct connection between CIAT’s genebank and the biofortified varieties that can improve the nutrition quality of farming families who depend to a large extent on their own production for food, such as those of rural Rwanda. We address the basic question, ‘How do genebanks play a role in the improvement of nutrition quality of beans?’ We use the example of seven varieties of climbing bean to illustrate the journey of the genes embodied in a genebank accession through the development of an improved variety to Rwanda farming families who grow, harvest, and consume them.

Here is the pathway to our study outcomes: by exploiting the immense crop genetic diversity housed at CIAT’s genebank, breeders were able to select germplasm from a wide range of varieties and screen them for high levels of zinc and iron. Varieties that showed high levels of zinc and iron were then used in breeding programmes to generate varieties with higher micronutrient levels while also retaining other important, fundamental traits, such as resistance to disease and characteristics that appeal to farmers and consumers. Once those varieties were disseminated and their cultivation and consumption increased, it was possible to observe and measure their impact on farmers and consumers.

## 2 Background

### 2.1 CIAT’s genebank

CIAT started its bean collection in the 1970s, following a global mandate of a network of research centres known as the CGIAR (Daniel Debouck, personal communication). Since then, CIAT’s genebank has received bean germplasm from 144 countries and distributed beans to 110 countries. CIAT’s bean collection includes almost 38,000 accessions and focuses on landraces, wild species, and wild ancestors of cultivated crops (CIAT Bean Database 2018; Daniel Debouck, personal communication).

The distribution of genetic resources began in 1973 and was accomplished by the scientists of CIAT’s bean...
programme, with the main purpose of testing for adaptation or reaction to diseases. Initially, distribution was largely towards national scientists of Colombia, Central America, Ecuador, and Peru. During the 1980s, CIAT increased bean research activities in sub-Saharan Africa. By April 2018, CIAT had distributed 449,707 bean accessions worldwide, of which 14,547 were distributed to countries in sub-Saharan Africa and 376,964 to Latin American countries. Over the decades, seed samples were sent to different kind of users, including national and regional genebanks, national agriculture research services, non-governmental organizations (NGOs), regional organizations and universities, private individuals, commercial companies, and other CGIAR centres. Some samples were also distributed directly to farmers upon request.

The accessions distributed worldwide were mainly used for applied research, breeding processes, basic research, and agronomy. About 40% of the total samples distributed since 1973 was used for the improvement of bean varieties. In sub-Saharan Africa, 11% of the accessions were used for species improvement, and most these were used in applied research or agronomy. Between 1978 and 2018, CIAT sent 645 accessions (433 unique materials) to Rwanda, with seed origins from 28 countries. Fifty four percent of them were climbing varieties, 73% of round shape and 20% of black colour. Those accessions were mainly used in applied research and agronomy, and only 4% were used in breeding processes.

The historical role of CIAT’s genebank in the development of bean varieties that are high in micronutrients is undeniable. In fact, CIAT holds the largest bean collection in the world (Johnson et al. 2003). According to Steve Beebe, the current leader of CIAT’s bean programme, it was possible to screen over 1000 genotypes of crop wild relatives conserved at CIAT’s genebank to identify varieties with high iron and zinc contents, thereby providing the major input for the biofortification programme, which started in early 1990s (Beebe et al. 2000).

### 2.2 Bean production and consumption in Rwanda

The choice of Rwanda as a target country for this study is appropriate given the importance of beans in Rwandan diets, the phenotypic diversity of common beans in the Great Lakes region, CIAT’s role in restoring germplasm after the Rwandan genocide of the 1990s, and the fact that Rwanda was selected by HP as the first country for release of iron-biofortified beans.

Rwanda also has the highest per capita consumption of beans in the world, which is around 29 kg per person per year (Larochelle et al. 2014). At the same time, anaemia remains a public health problem in Rwanda. According to the data collected by the Demographic and Health Surveys Program in 2014–2015, about 21% of children between 0 and 5 years old and almost 16% of reproductive-aged women suffer from iron deficiency, which is classified as severe or moderate for 15% of the children and for almost 4% of the women (DHS 2015).

Biofortification is more cost efficient in countries where production and consumption of the targeted crop is high (Meeinkashi et al. 2010). The Great Lakes region benefits from bimodal rainfall, and therefore, common bean can be planted twice a year and the total production is high (Blair et al. 2009). Phenotypic diversity of common beans is impressive in the Great Lakes regions due to the fact that much of the common bean crop is grown as varietal mixtures with consumers accepting a wide range of seed colours (Lamb and Hardman 1985; Sperling 2001). However, common bean diversity in the area has been threatened by various circumstances. For example, agronomic developments led to some emphasis on single component varieties. Social disorders and civil wars, such as the Rwandan genocide, were devastating (Blair et al. 2009).

According to the Food and Agriculture Corporate Statistics Database, the production of dry beans in Rwanda has increased continuously over time, and the average annual production of the last decade (2007–2017) was 385,102 t with a total production of 4.2 million tonnes (FAOSTAT 2019). The values of dry bean production in Rwanda from 1961 until 2017 have been increasing except for the fall in production between 2014 and 2017. The production of dry bean harvested over the hectares of land cultivated, was fairly stagnant over time, with a slight increase between 2005 and 2011. On average, the yield was about 785 kg/ha from 1961 until 2017 and increased to 911 kg/ha in the last decade (2007–2017).

Biofortification of beans is a viable strategy for improving iron deficiency, particularly in areas where beans are consumed heavily, levels of iron deficiency represent a serious risk to people’s health and childhood development, and where most beans are grown by farming families who consume their own production. The potential impact of biofortification as a solution for malnutrition is evidenced in a study by Haas et al. (2016). In this study, a total of 195 university women in Rwanda aged 18–27 with iron deficiency were randomly assigned to receive either iron-biofortified beans developed at CIAT or standard unfortified beans. For 128 days, they were fed the two types of beans. The authors show that iron-biofortified beans significantly improved iron status in Rwandan women, increasing their level of haemoglobin, serum ferritin concentrations, and body iron.

CIAT, HP, and partners introduced the iron-biofortified varieties included in this study between 2010 and 2012. They distributed planting material in Rwanda through different formal and informal delivery approaches between 2012 and 2015 by HP and its partners, such as NGOs, agrodealers, schools, churches and local markets. The most successful
delivery approach was direct marketing, which began in 2012 and reached farmers in all districts of the country in season B of 2012 and for four subsequent seasons thereafter, during 2013 and 2014. Iron-biofortified varieties were delivered in nearly all parts of the country, and it was estimated that approximately 28% of rural households in the country grew an iron-biofortified bean in at least one season between 2012 and 2015 (Asare-Marfo et al. 2016b).

3 Data and methods

3.1 Analysis of the breeding process for iron-biofortified varieties

The first phase of this study linked the climbing varieties CAB2, RWV3316, RWV3317, RWV3006, RWV2887, MAC44 and MAC42 to CIAT’s genebank and explored the role of the genebank in the development of iron-biofortified beans. Data regarding the varieties were not immediately available due to the high dispersion of information. Hence, we had to collect the data from different channels, including: (1) research of past literature, (2) pedigree and genealogy information, (3) annual reports of CIAT’s bean programme, and (4) personal communication with bean breeders in Rwanda and the CIAT. It was possible to retrace the pedigrees of all varieties using several sources: the Pan-Africa Bean Research Alliance website, the catalogue of advanced bean lines from CIAT by Rodríguez et al. (1994), available at CIAT’s library, and the database of the bean programme of CIAT.

Through the work of Rodríguez et al. (1994) and personal communication with the staff at CIAT’s bean program, we identified the key breeders of the above-mentioned varieties but could only establish contacts with two out of the six breeders.

Finally, through the database available from CIAT’s Genetic Resources Program website, we were able to collect information regarding the characteristics of the varieties used as parents of iron-biofortified lines.

3.2 Analysis of the effect of adoption on well-being of farm households

3.2.1 Household-level data

This study uses nationally representative data on bean producers in Rwanda collected by HP, in partnership with RAB and CIAT. Data were collected in two stages in 2015, following the distribution of iron-biofortified varieties that started in 2010 for four varieties (two bush varieties, the climbing variety MAC44, and the iron-biofortified climbing variety RWV1129) and continued in 2012 for the remaining climbing varieties (CAB2, RWV3316, RWV3317, RWV3006, RWV2887, and MAC42).

The first round of survey data collection took place in May and June of 2015. During this round, we interviewed all randomly selected households from 120 villages. In total, 19,575 households were interviewed about their history of adoption of iron-biofortified bean varieties. In the second stage, which took place in September 2015, we randomly selected 12 households from each village for a second interview for the main household survey. When possible, six iron-biofortified bean adopters and six non-adopters were selected to have a good balance in the size of the two groups. The enumerators collected 1397 interviews, asking information about the composition of the households, the person deciding about the plot and bean production, the varieties cultivated, and the production of beans, bean consumption, the adoption history, the characteristics of the house. This study analyses the information included in the main household survey, collected during the second stage of data collection. Further information on data collection can be found in the Main Survey Report and Listing Exercise Report by Asare Marfo et al. (Asare-Marfo et al. 2016a; Asare-Marfo et al. 2016b).

Rwanda has two bean growing seasons: season A, which usually runs from September through January, and season B, which lasts from February to June. For this study, we had data only on planting and harvesting values for season B in 2015. However, we had data on bean consumption for the entire year (from September 2014 until September 2015) and the data regarding the adoption history of households.

This analysis considers only those farming families who grew either local bean varieties or at least one iron-biofortified climbing variety in 2015 that could be directly traced to CIAT’s genebank. The households growing the variety RWV1129 were excluded from the sample, as this is an iron-biofortified climbing variety originating from a pure line selection of local landraces and is not directly related to CIAT’s genebank. In addition, households that grew non-iron-biofortified improved varieties were excluded from the sample due to lack of knowledge about those varieties.

Of the 1397 households included in the original sample, 360 (25.8%) had grown a climbing iron-biofortified variety at least once between 2010 and 2015. These households grew a bush iron-biofortified variety at least once (23.7%). Our final dataset, which excludes households growing variety RWV1129, households growing improved varieties that are not iron biofortified, and sample outliers, shows similar adoption rates for bush and climbing iron-biofortified varieties in 2015. In season 2015A, 2% of the households grew at least one bush variety of iron-biofortified beans and the same

These are the results of adoption after checking a sample of the varieties received by farmers against X-ray fluorescence results of iron content of beans to confirm that farmers had correctly identified the variety as iron-biofortified.
percentage grew at least one climbing variety of iron-biofortified bean. In season 2015B, 11% of the households grew at least one bush variety of iron-biofortified bean and 7% grew at least one climbing variety of iron-biofortified bean. Finally, 8% of the households grew at least a bush variety of iron-biofortified bean in both seasons, and the same occurs for climbing varieties. Among the climbing varieties, the most frequently adopted were MAC44 and RWV3316. Table 1 reports details on the adoption of iron-biofortified varieties.

The analytical sample includes 971 non-adopters and 219 adopters of iron-biofortified climbing varieties in the 2015 survey dataset. If we take into account only the second season of 2015, we have 429 non-adopter households and 203 adopters.

### 3.2.2 Variables description

For the purpose of direct comparison with the analysis of bush varieties of beans by Vaiknoras and Larochelle (2018), we used the same dependent variables and similar econometric models to measure the effects of adoption of iron-biofortified climbing varieties on yield, bean consumption, and bean purchases. A description of the variables used in the models is provided in Table 2.

Adoption is defined in two ways, depending on the unit of observation in the analysis. When the unit of analysis is the bean plot, adoption means that an iron-fortified climbing bean is grown on the plot. At the household level, adoption is defined as whether or not an iron-fortified climbing bean is grown on at least one of the bean plots managed by household members. Households in the sample have an average of between one and two bean plots. We considered bean area shares allocated to iron-biofortified varieties as an adoption variable, but the raw data did not permit its viable construction.

Yield was measured using the 2015B multiplication ratio, which was calculated as the ratio of the quantity of beans harvested on the quantity of planted seeds in season 2015B. Using this ratio as a proxy for yield allowed us to avoid measurement errors associated with plot size (Vaiknoras and Larochelle 2018). Since the distribution of the multiplication ratio is highly skewed, it was preferable to use its natural logarithm. Given that some households grew more than one climbing variety in season 2015B, yield effects were considered at household-by-variety level and adoption was defined simply by specifying whether each variety is an iron-biofortified variety with ancestors at CIAT’s genebank or a local variety. After excluding all bush varieties, the variety RWV1129, and the non-iron-biofortified improved varieties from the sample, the final sample was composed of 826 observations, including 635 local varieties and 191 iron-biofortified varieties.

Several dependent variables were used to estimate the effect of adoption on consumption and purchases: the number of months prior to the survey when households consumed beans from their own harvests, the average quantity per adult male

### Table 1  Adoption of iron-biofortified varieties (climbing and bush varieties)

| Time            | Iron-biofortified bush varieties | % of total | Iron-biofortified climbing varieties (excluding RWV1129) | % of total | N  |
|-----------------|----------------------------------|------------|----------------------------------------------------------|------------|----|
| 2010–2015       | 331                              | 24%        | 325                                                      | 23%        | 1397¹ |
| 2015            |                                   |            |                                                          |            |     |
| Season 2015A only | 24                               | 2%         | 23                                                       | 2%         | 1190² |
| Season 2015B only | 126                              | 11%        | 88                                                       | 7%         | 1190² |
| Both 2015A and 2015B | 91                              | 8%         | 92                                                       | 8%         | 1190² |

Households that grew at least one iron-biofortified variety in 2010–2015

| Variety   | Type | Yes/No | N   | %  |
|-----------|------|--------|-----|----|
| RWR2245   | Bush | yes    | 1397| 23%|
| MAC44     | Climbing | 123   | 1397¹ | 9%  |
| RWV3316   | Climbing | 73    | 1397¹ | 5%  |
| RWV3317   | Climbing | 32    | 1397¹ | 2%  |
| RWV1129   | Climbing | 35    | 1397¹ | 3%  |
| RWR2154   | Bush | 16     | 1397¹ | 1%  |
| CAB2      | Climbing | 29    | 1397¹ | 2%  |
| RWV2887   | Climbing | 22    | 1397¹ | 2%  |
| MAC42     | Climbing | 20    | 1397¹ | 1%  |
| RWV3006   | Climbing | 26    | 1397¹ | 2%  |

Source: authors, based on 2015 Rwanda adoption survey data, HP/CIAT/Virginia Tech

Note: Sample sizes explained in text
equivalent, the number of months in which households had to purchase beans in the market, and the average quantity purchased in kg. Higher levels of production can lead households to consume more beans from their own production, and in turn, receive health benefits from the consumption of varieties enriched in iron and zinc.

The effects on consumption and purchase were evaluated at the household level, defining as adopters those households who grew at least one climbing bean variety in season 2015B, which is the only season for which we have complete information on all bean varieties grown by the household. In this case, we dropped those households that grew only bush varieties, variety RWV1129, or only non-iron-biofortified improved varieties. This left a remaining 632 household samples, of which 429 did not adopt any iron-biofortified climbing varieties, either in 2015A or in 2015B, and 203 were adopters, as they adopted an iron-biofortified climbing variety at least once in 2015. Of the adopters, 23 households adopted

| Variables | Definition |
|-----------|------------|
| **Multiplication ratio** | The multiplication ratio is measured as the quantity of kg of beans harvested on the quantity of kg of seeds planted in season 2015B |
| **N. months consumed from own production** | Number of months in which a household consumed beans from its own production |
| **Log of consumption from own production (kg)** | Kg of beans consumed by a household from its own production |
| **N. months purchased beans** | Number of months in which a household purchased beans from the market |
| **Log of purchases per month (kg)** | Kg of beans purchased by a household from the market |
| **Iron-biofortified variety (1 = Yes 0 = No)** | Expresses whether a variety is iron-biofortified or not. |
| **Recycled seed (1 = Yes)** | Identifies whether the planting material came from recycled seed from the household’s planting material vs. any other source |
| **Slope** | Slope of the plot (flat, gentle, moderate, or steep) |
| **Stake** | Whether a stake was used or not to support the growth of climbing beans and what kind of stake (trees, stovers, maize stalks, Napier grass, sticks or poles) |
| **Intercrop** | Whether other crops were cultivated in the same plot |
| **Use of organic fertilizer (1 = Yes)** | Application of organic fertilizer |
| **Use of chemical fertilizer (1 = Yes)** | Application of chemical fertilizer |
| **Gender of the person deciding about the plot (1 = female)** | Gender of the person deciding about the plot |
| **The person deciding about the plot is literate (1 = Yes)** | Level of education of the person deciding about the plot |
| **Experience of the person deciding about the plot (in years)** | Level of experience of the person deciding about the plot, measured in years |
| **Elevation (10 m)** | Dwelling elevation measure in meters |
| **Number of adults in the household** | Number of adults in the household used as a proxy for labour force in the farm |
| **Equipment owned (count)** | Count of the agricultural equipment owned by the household |
| **Region** | Region of the country where the household is located: Kigali (central), south, west, north, or east |
| **Adopted climbing iron-biofortified variety (1 = Yes)** | Indicates whether a household adopted a climbing iron-biofortified variety. It is used to define adoption |
| **Bush bean grower** | Defines whether the household is also growing bush varieties |
| **Distance to city** | Measure the distance from the households’ house to the closest urban centre in kilometres |
| **Age of respondent** | Age of the person answering the survey questions measured in years |
| **Gender of respondent** | Gender of the person answering the survey questions |
| **Literacy ratio** | Ratio of literate people in the household measured as the number of family members who know how to read, write, or either, compared to the number of members who do not know how to read, write, or either |
| **Land size (ha)** | Size of the farm measured in hectares |
| **Wealth quintile (base = 1)** | Wealth index created using polychoric components analysis by Vaiknoras (2017) using information regarding households’ assets and housing characteristics |
| **Tropical Livestock Unit** | Count of the livestock units owned by the household |

**Source:** authors, based on 2015 Rwanda adoption survey data, HP/CIAT/Virginia Tech
iron-biofortified beans in season 2015A, 88 households in season 2015B and 92 in both seasons.

3.2.3 Econometric methods

Due to the different nature of the dependent variables, we needed to adopt different econometric models. To account for possible estimation bias and to ensure the robustness of our results, we estimated the effect of the adoption of an iron-biofortified variety on yield using four different econometric methods. The first method implemented was the Ordinary Least Square (OLS). The estimating equation can be specified as follows:

\[ Y = \alpha + \beta T + \gamma I + \delta H + \epsilon. \]

This method implies the regression of a treatment dummy variable, \( T \), on the outcome of interest, \( Y \), while controlling for agricultural inputs used in bean cultivation and characteristics of the plot where the variety is grown, \( I \). Plot characteristics include the slope, whether the plot was intercropped, the walking distance from the household to the plot, the use of organic or chemical fertilizer, and in the case here of climbing beans, the type of stakes. \( H \) in Eq. 1 represents those household-level variables that could influence productivity and potentially be correlated with the adoption of iron-biofortified climbing varieties, such as the gender of the person making the most important decisions regarding the plot, his or her working experience in number of years, the number of adults in the households, and the equipment owned by the household. Finally, we also control for the geographic region, dividing the country in the south, Kigali (central), west, north, and east.

Coefficients estimated by OLS may be biased if adoption is endogenous. Endogeneity results from the correlation of the error term with the dependent variable. If we reject exogeneity of adoption, it is more appropriate to use a quasi-experimental method that controls for the correlation between the error term and the dependent variable. For this reason, the second method implemented was instrumental variables (IVs) estimation with two-stage least squares (2SLS), which allows us to test and control for endogeneity.

IV estimation was conducted with 2SLS under \textit{ivreg2} in STATA 15. The use of this approach requires the identification of one or more IVs. To be valid, the IVs should be strongly, individually, and jointly correlated with adoption in the first stage regression but not correlated with the error term in the second outcome equation. Using the \textit{ivreg2} command, diagnostic tests include the Kleibergen-Paap LM statistic for under-identification, the Cragg Donald F statistic for finding out whether a particular endogenous regressor is weakly identified, the Hansen J test as an overidentification test of all instruments, and a Hausman test of endogeneity.

While the relevance of the instrument to the potentially endogenous variable can be tested statistically as part of \textit{ivreg2}, the exclusion restriction is met by logical argument. The two IVs used here are those suggested by Vaiknoras and Larochelle (2018): the sum of direct marketing approaches in a household’s sector in 2015A and 2015B and the previous village adoption rate of iron-biofortified climbing varieties. HP direct marketing was one of the main sources of iron-biofortified planting material (Asare-Marfo et al. 2016a); hence, to capture proximity to promotion and sales locations of iron-biofortified beans, Vaiknoras et al. (2019) counted the number of direct marketing approaches in a given sector (an administrative unit) in each season. Since social networks and local markets were two of the most important sources of iron-biofortified planting material, we used the previous village adoption rate of iron-biofortified climbing varieties as a proxy for the availability of those varieties within one’s social network one season prior to our period of interest (Vaiknoras and Larochelle 2018). This variable has a strong impact on current-season adoption on an individual farmer but should not have a direct effect on farmers’ yields, making it a good instrument (Vaiknoras and Larochelle 2018). The IVs were incorporated first through the 2SLS method and then by using maximum likelihood to explicitly account for the binary nature of the endogenous regressor. Through this method, the first stage regression becomes a latent-variable model, similar to a probit model.

Finally, we estimated the impact of adoption on yield using a control function (CF) approach. CF is a statistical method used to correct for endogeneity problems by modelling the endogeneity in the error term, and is more efficient than the standard IV approach when the endogenous variables are non-linear (Wooldridge 2015a). CF methods usually require fewer assumptions than maximum likelihood and are computationally simpler (Wooldridge 2015a). As a first stage, we estimated a probit model by regressing the instruments on the adoption of iron-biofortified climbing varieties. We used the same instruments as in the IV method. If, by rejecting the null hypothesis that the coefficient on the residual is equal to zero, we reject exogeneity, and we control for endogeneity by including the generalized residual from the first stage in the second stage regressions with other covariates. In the CF approach, the significance of the coefficient of the generalized residuals is the only test of endogeneity.

For the variables related to consumption and purchase of beans, this study used different methods. In the case of the quantity (kg) of beans purchased and consumed each month, per adult equivalent, it was possible to use the same methods used to measure the effects on yield due to the continuous nature of the dependent variable. Specifically, the estimation was conducted with OLS and compared with the results of the CF approach.
Since the number of months during which households consumed beans from their own production is a count dependent variable, the most appropriate model to use was the Poisson model (Wooldridge 2015b). This model is used when the dependent variable $y$ takes on relatively few values, including zero, and it expresses the probability of a given number of events occurring in a fixed interval of time. Finally, in the case of the number of months in which households purchased beans from the market, a zero-inflated Poisson model was preferred over the Poisson estimation. This model accounts for the excess zero-count data in unit time and its use was adequate, since 323 households, of which 253 were non-adopters and 70 were adopters, had not purchased beans in the 12 months preceding the interview. We also performed the Vuong’s test to prove that the zero-inflated Poisson model was a better fit in this case, rather than the Poisson model.

4 Results

4.1 Breeding process and pedigrees

Iron-biofortified bean varieties are a result of a long process that began during the 1990s and involved several universities and international institutions, including CIAT’s genebank. The relationship between the genebank at CIAT and the iron-biofortified bean programme started in 1995 (S. Beebe, personal communication). At that time, the International Food Policy Research Institute (IFPRI) supported a project at the bean programme to do an initial evaluation of the germplasm kept at CIAT’s genebank. The sources of the breeding programme of iron-biofortified varieties were the primary gene pool, crosses with a secondary gene pool, and crosses with a tertiary gene pool, all of which came from the bean collection at CIAT. The initial evaluation was conducted on the first core collection of 1040 accessions, and the seeds were then sent to the University of Adelaide in Australia for the evaluation of micronutrients. During this first screening, it was found that some of CIAT’s genebank materials had very high iron and zinc content (ranging from 30 to 110 ppm iron and 25–60 ppm zinc) and those varieties became the first source parents for the development of iron-biofortified varieties. The high iron genotypes, G14519 and G21242, from CIAT using genebank materials. Table 3 reports further details of these two gene pools. The varieties MAC42 and MAC44 were developed in the early 2000s at CIAT with genebank materials. The pedigrees of these two varieties are similar. MAC42 and MAC44 come from the union of the genebank accession G12722, a commercial climbing variety from Colombia and AND930, a bred line developed by Julia Kornegay at Central Florida University. The pedigrees are reported in detail, along with other variety characteristics, in Sellitti et al. (2019). Our interviews with experts (personal communications with Daniel Debouck, previous leader of CIAT’s Genetic Resources Program, Steve Beebe, current leader of CIAT’s bean programme, and with the bean breeders Bodo Raatz, Louis Butare and Floride Mukamuhirwa) confirmed that CIAT’s genebank played an essential role in the advancement of the breeding programme. Given the immense bean diversity maintained by the genebank, it was possible to screen over a thousand varieties for desirable traits. Furthermore, Louis Butare mentioned the important role that CIAT’s genebank played during the Seeds of Hope initiative and claimed that it would not have been possible to have such vibrant breeding activity in Rwanda without that initiative.

From this analysis, it was possible to confirm that all the varieties from this study are directly related to CIAT’s genebank. The varieties MAC42 and MAC44 were developed in the early 2000s at CIAT with genebank materials. The pedigrees of these two varieties are similar. MAC42 and MAC44 come from the union of the genebank accession G12722, a commercial climbing variety from Colombia and AND930, a bred line developed by Julia Kornegay at CIAT using genebank materials. Table 3 reports further details on the characteristics and breeding of iron-biofortified varieties.

Overall, we found 12 genebank accessions used by different breeders to generate bred lines used in the final breeding of MAC varieties. The 10 genebank accessions used were: G12722, G21720, G6616, G4523, G76, G6533, G14013, G11891, G4505, G5704, G4452 and G5709. Six of these

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2 For more information on the gene pools of common beans, see Debouck (1999) and CWR (2019).

3 See Soren et al. (2016) for a summary of biofortification work on common beans.
accessions originated in Colombia, one in the Dominican Republic, two in the United States, one in Brazil, one in Mexico, and one in Peru. The variety G76 was also part of the core collection that was screened in the early 1990s.

The varieties RWV3316, RWV3317, RWV3006, and RWV2887 were the result of the combination of the CAB2 variety, developed at CIAT by Julia Kornegay, with either a local Rwandan variety or another CIAT’s breed variety. CAB2 was sent to Rwanda from CIAT breeding programme and then locally multiplied for tests, after which it was bred with some local varieties for adaptation (Floride Mukamuhirwa, personal communication).

CAB2 was developed in the early 1990s and was a very important progenitor in the development of iron-biofortified varieties in Rwanda. It was the result of the breeding between the genebank accession G20557 and the improved variety VCB81010 of Jeremy H.C. Davis, whose progenitors were G3467 and G2540 from CIAT’s genebank. G20557 is a bush variety from Kenya, G3497 is a climbing variety from Mexico, and G2540 is a climbing variety from Congo. RWV3316 and RWV2887 were developed through the crosses of CAB2 with LAS400, a variety by Julia Kornegay, which resulted from the cross of G12670 and G12666 kept at CIAT’s genebank. Both G12670 and G12666 varieties originated from Colombia.

Finally, RWV3317 and RWV3006 are the result of crosses between CAB2 and local Rwandan landraces, NGWIN and BUBERUKA. While it was not possible to confirm whether those local varieties were also kept at CIAT’s genebank, CIAT has likely played an indirect role in this breeding process. In fact, according to Louis Butare (personal communication), the Rwandan bean breeder involved in the development of the above-mentioned varieties, the role of the genebank at CIAT was to speed up the restoration of the bean genetic diversity in Rwanda after the large loss of genetic materials during the Rwanda genocide. This resulted in the breeding of iron-biofortified beans through crosses with CAB2 and with many other varieties available at CIAT. Without the backup materials from CIAT’s genebank, it would have taken much longer to re-invigorate the breeding programme (Louis Butare, personal communication).

### 4.2 Adoption effects

Initial tests were performed to see whether the differences in the dependent variables and in the plot- and household-level characteristics between adopters and non-adopters were statistically significant. First, the Shapiro-Wilk test and the Levene’s test were performed to check for normality of the distribution and homogeneity of variance, respectively. To compare means of household characteristics, t-tests were conducted for parametric variables and the Mann-Whitney-Wilcoxon test for non-parametric variables (Wilcoxon 1945; Mann and Whitney 1947). Table 4 shows the results of the comparison between the dependent variables for consumption and purchase of beans for iron-biofortified adopters versus non-adopters. Average yields of iron-biofortified climbing varieties and local varieties of bean are also reported.

On average, the multiplication ratio for iron-biofortified varieties was higher than for local varieties. Furthermore, households growing iron-biofortified varieties consumed beans from their own production for 8.21 months on average and purchased beans from the marked for 3.4 months. On the contrary, growers of local varieties consumed beans from their own production for 7.3 months and purchased them for 4.33 months. The differences in the means between the dependent variables of the control and treatment groups are all statistically significant at least at 5% significance level.

Table 5 shows the differences in characteristics of the control variables used in the estimation of the effects of adoption on yield. Differences in the slope and elevation of the plot, in the number of adults in the household, and in whether recycled seeds were used and intercrop rotation was done were statistically significant. The differences between the means of the remaining variables were not statistically significant. Statistics for household-level characteristics are included in Table 6. Adopter households significantly differed from non-adopters in size of household, land areas, wealth quintile,

### Table 3 Description of iron-biofortified varieties

| Variety | Iron content | Breeder          | Final crosses          | Progenitors from CIAT | Adoption rate (as % of total households) |
|---------|--------------|------------------|------------------------|------------------------|------------------------------------------|
| CAB2    | 76 ppm       | Julia Kornegay   | G20557 x VCB81020      | G20557, G3467, G2540   | 2%                                       |
| RWV3316 | 92 ppm       | Louis Butare     | CAB2 x LAS400          | G20557, G12670, G12666, G3497, G2540 | 5%                                       |
| RWV3317 | 74 ppm       | Louis Butare     | NGWIN x CAB2           | G20557, G3467, G2540   | 2%                                       |
| RWV3006 | 76 ppm       | Louis Butare     | CAB2 x BUBERUKA        | G20557, G3467, G2540   | 2%                                       |
| RWV2887 | 85 ppm       | Louis Butare     | CAB2 x LAS400          | G20557, G3467, G2540, G12670, G12666 | 2%                                       |
| MAC42   | 91 ppm       | Matthew Blair    | AND930 x G12722        | G12722, G4505, G5704, G4452, G5709, G6616, G4523, G76, G6533, G14013, G21720, G11891 | 9%                                       |
| MAC44   | 78 ppm       | Matthew Blair    | AND930 x G12722        |                         |                                          |

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The contribution of the CIAT genebank to the development of iron-biofortified bean varieties and well-being of farm households in Rwanda

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and in the agriculture equipment owned. We included those variables as controls in all our estimations.

Regression results are reported in Tables 8–10. Table 8 shows the results of the estimation of the effect of adopting an iron-biofortified variety connected to CIAT’s genebank on yield. The first column reports the OLS coefficients, while the second and the third column report the results of IV, with 2SLS and maximum likelihood estimations, respectively. Finally, the fourth column reports the coefficients of the CF approach. We can reject the null hypothesis of the Kleibergen-Paap LM statistic, concluding that the model is not under identified. The null hypothesis of weak instruments is rejected using the Cragg Donald F Statistics. The Hansen J tests indicates that the instruments are not correlated with the error terms, as it fails to reject the null hypothesis of overidentification. Finally, the Hausman test fails to reject the null hypothesis of exogeneity for all but the yield equation. However, for each outcome, we estimate IV and or CF models as a robustness check. Results of the tests on the instruments are reported in Table 7.

OLS and OLS CF regressions reveal that the effect on yield of adopting at least one iron-biofortified climbing variety over cultivating uniquely local varieties is positive and statistically significant at 5% significance level. Results are slightly weaker with the IV models when we control for endogeneity.

Table 9 reports regressions when testing the effects of adoption on household bean consumption. The first three columns report the results of the adoption on the number of months during which households consumed beans from own production, estimated with OLS, Poisson, and CF Poisson methods, respectively. In contrast to Vaiknoras et al. (Vaiknoras and Larochelle 2018; Vaiknoras et al. 2019), our results were not statistically significant, and these results are consistent across models. The fourth and fifth columns report the results of the regression testing effects of adoption on monthly consumption per adult equivalent. Coefficients

Table 4  Descriptive statistics for dependent variables

| Variable                                      | Local varieties | N  | Iron-biofortified varieties | N  |
|-----------------------------------------------|-----------------|----|-----------------------------|----|
| Multiplication ratio***                      | 1.77 (0.76)     | 626| 1.97 (1.98)                 | 187|
| N. months consumed from own production ***   | 7.3 (3.28)      | 429| 8.21 (3.05)                 | 203|
| Log of consumption from own production (kg) **| 1.48 (0.43)     | 429| 1.41 (0.44)                 | 203|
| N. months purchased beans ***                | 4.33 (3.28)     | 429| 3.4 (2.99)                  | 203|
| Log of purchases per month (kg) ***          | 1.01 (0.64)     | 429| 0.82 (0.65)                 | 203|

Source: authors, based on 2015 Rwanda adoption survey data, HP/CIAT/Virginia Tech

Standard errors are reported in parentheses. ***, **, *: differences in means are statistically significant at 1, 5, or 10% significance level, respectively.

Table 5  Descriptive statistics for plot-level control variables

| Variable                                      | Iron-biofortified varieties | Local varieties |
|-----------------------------------------------|----------------------------|----------------|
| Recycled seed (1 = Yes) ***                   | 0.33 (0.47)                | 0.52 (0.5)     |
| Slope ***                                     | 3.03 (0.98)                | 2.78 (1.01)    |
| Intercrop (1 = flat) *                        | 0.5 (0.5)                  | 0.43 (0.5)     |
| Walking time to household (in minutes)        | 12.75 (23.7)               | 14.5 (21.5)    |
| Use of organic fertilizer (1 = Yes)           | 0.92 (0.27)                | 0.89 (0.31)    |
| Use of chemical fertilizer (1 = Yes)          | 0.27 (0.44)                | 0.27 (0.44)    |
| Gender of the person deciding about the plot (1 = female) | 0.63 (0.5) | 0.6 (0.5) |
| The person deciding about the plot is literate (1 = Yes) | 0.68 (0.46) | 0.57 (0.5) |
| Experience of the person deciding about the plot (in years) | 26.3 (13.9) | 27 (16.3) |
| Elevation (10 m)***                           | 171.44 (26.5)             | 182.25 (24.82)|
| Number of adults **                           | 3.15 (1.4)                | 2.9 (1.41)     |
| Equipment owned (count)                       | 1.4 (0.82)                | 1.31 (0.78)    |
| N                                            | 191                       | 635            |

Source: authors, based on 2015 Rwanda adoption survey data, HP/CIAT/Virginia Tech

Standard errors are reported in parentheses. ***, **, *: differences in means are statistically significant at 1, 5, or 10% significance level, respectively.
estimated with OLS and CF OLS have the negative sign but are not statistically significant. However, the signs of coefficients are as expected in all models.

Finally, Table 10 reports the results of regressions testing on the effects of the adoption of iron-biofortified climbing varieties on the numbers of months during which the households purchased beans from the market, estimated through the zero-inflated Poisson and zero-inflated Poisson CF methods. The $p$ values of the Vuong’s test revealed that using zero-inflated Poisson was preferable than the Poisson model. Coefficients are negative in sign, showing that the adoption reduces the need of purchasing beans from the market. Again, the signs are as expected in theory, but the results are not statistically significant. Likewise, the effect of adoption on monthly purchases is negative and not statistically significant. As an extra check, we also tested the effect of adoption on total bean consumption by multiplying the quantity consumed per month by the number of months consumed. Although the econometric approach was simpler, statistical results were no stronger.

### 5 Conclusion

This study traced the impact pathway of seven iron-biofortified varieties of climbing bean, from the selection of their parents at CIAT’s genebank to their adoption at farms, in order to answer the question, ‘How do genebanks play a role in the improvement of nutrition quality of beans?’ We examined seven iron-biofortified bean varieties developed through a cooperation between CIAT, HP, Virginia Tech, and RAB. The work on biofortification aims to offer a solution to the problem of hidden hunger: the lack of essential micronutrients in the diets of poor households in developing countries. We
Table 8  OLS, IV and CF results for effects of adoption on yield

|                                | OLS        | IV         | IV (ML)    | CF OLS     |
|--------------------------------|------------|------------|------------|------------|
| Iron-biofortified variety (1 = Yes 0 = No) | 0.166**    | 1.056*     | 0.357      | 0.090**    |
|                                 | (0.084)    | (0.575)    | (0.220)    | (0.035)    |
| Recycled seed (1 = Yes)         | 0.111      | 0.216**    | 0.055      | −0.058*    |
|                                 | (0.073)    | (0.108)    | (0.065)    | (0.031)    |
| Slope (base = steep):           |            |            |            |            |
| Moderate Slope (15° to 30°)     | −0.222*    | −0.255**   | −0.155*    | −0.053     |
|                                 | (0.119)    | (0.120)    | (0.093)    | (0.052)    |
| Gentle slope (5° to 14°)        | −0.150     | −0.195*    | −0.170*    | 0.005      |
|                                 | (0.101)    | (0.104)    | (0.087)    | (0.031)    |
| Flat (< 5°)                     | −0.154     | −0.218*    | −0.043     | 0.047      |
|                                 | (0.105)    | (0.112)    | (0.092)    | (0.034)    |
| Type of stakes used (base = none) |          |            |            |            |
| Trees, maize stalks, Napier grass, stovers | 0.344***   | 0.316**    | 0.204**    | 0.106*     |
|                                 | (0.128)    | (0.135)    | (0.096)    | (0.063)    |
| Poles or sticks                 | 0.346***   | 0.311**    | 0.267***   | 0.144**    |
|                                 | (0.127)    | (0.135)    | (0.098)    | (0.065)    |
| Intercrop (1 = flat)            | 0.030      | 0.036      | 0.029      | −0.018     |
|                                 | (0.070)    | (0.072)    | (0.054)    | (0.026)    |
| Use of organic fertilizer (1 = Yes) | 0.001      | −0.084     | 0.131      | 0.026      |
|                                 | (0.097)    | (0.116)    | (0.092)    | (0.043)    |
| Use of chemical fertilizer (1 = Yes) | 0.254***   | 0.251***   | 0.223***   | −0.003     |
|                                 | (0.086)    | (0.087)    | (0.062)    | (0.032)    |
| Gender of the person deciding about the plot (1 = female) | 0.051      | 0.021      | 0.047      | 0.028      |
|                                 | (0.073)    | (0.082)    | (0.056)    | (0.031)    |
| The person deciding about the plot is literate (1 = Yes) | 0.241***   | 0.216***   | 0.234***   | 0.048      |
|                                 | (0.077)    | (0.083)    | (0.061)    | (0.032)    |
| Experience of the person deciding about the plot (in years) | −0.005**   | −0.005**   | −0.006***  | −0.001     |
|                                 | (0.002)    | (0.002)    | (0.002)    | (0.001)    |
| Elevation (10 m)                | 0.001      | 0.003      | 0.002      | −0.002***  |
|                                 | (0.002)    | (0.002)    | (0.001)    | (0.001)    |
| Number of adults in the household | 0.066**    | 0.054*     | 0.065***   | 0.030***   |
|                                 | (0.027)    | (0.029)    | (0.021)    | (0.010)    |
| Equipment owned (count)         | 0.000      | −0.022     | −0.058     | 0.026*     |
|                                 | (0.042)    | (0.047)    | (0.036)    | (0.015)    |
| Region (South = base)           |            |            |            |            |
| Kigali                          | −0.195     | −0.056     | −0.130     | −0.035     |
|                                 | (0.163)    | (0.183)    | (0.270)    | (0.052)    |
| West                            | −0.002     | 0.068      | −0.100     | −0.081*    |
|                                 | (0.107)    | (0.113)    | (0.078)    | (0.042)    |
| North                           | 0.092      | 0.147      | 0.051      | 0.000      |
|                                 | (0.102)    | (0.112)    | (0.076)    | (0.039)    |
| East                            | 0.400***   | 0.308*     | 0.234**    | 0.043      |
|                                 | (0.149)    | (0.173)    | (0.102)    | (0.058)    |
| Generalized residuals           |            |            |            | 0.270***   |
|                                 |            |            |            | (0.007)    |
| Constant                        | 1.013***   | 0.741      | 0.950***   | 1.103***   |
|                                 | (0.375)    | (0.454)    | (0.288)    | (0.108)    |
| N                               | 813        | 813        | 813        | 813        |

***, **, *: statistically significant at respectively 1%, 5%, or 10% significance level. Standard errors in parentheses

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focused on iron-biofortified climbing beans as target varieties and Rwanda as a target country.

First, we found that CIAT’s genebank was a key player in the development of iron-biofortified varieties. Through the

### Table 9: Poisson, OLS and CF results for consumption outcomes

|                                                       | Months consumed from own production | Quantity (kg) consumed each month, per adult equivalent |
|--------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|                                                        | OLS       | Poisson    | CF Poisson | OLS       | CF OLS    |
| Adopted climbing iron-biofortified variety (1 = Yes)   | 0.260     | 0.036      | 0.110      | −0.041    | −0.023    |
| (0.237)                                               | (0.031)   | (0.068)    | (0.038)    | (0.081)   |
| HH grew a bush variety in 2015B                        | 1.122***  | 0.145***   | 0.147***   | 0.026     | 0.027     |
| (0.288)                                               | (0.037)   | (0.037)    | (0.042)    | (0.042)   |
| Distance to city (km)                                 | 0.003     | 0.000      | 0.000      | 0.001     | 0.001     |
| (0.011)                                               | (0.001)   | (0.001)    | (0.002)    | (0.002)   |
| Household size                                         | −0.238*** | −0.031***  | −0.032***  | −0.060*** | −0.060*** |
| (0.066)                                               | (0.009)   | (0.009)    | (0.009)    | (0.009)   |
| Age of respondent (years)                             | 0.009     | 0.001      | 0.001      | 0.001     | 0.001     |
| (0.007)                                               | (0.001)   | (0.001)    | (0.001)    | (0.001)   |
| Gender of respondent (1 = female)                      | −0.305    | −0.042     | −0.048*    | −0.066**  | −0.068**  |
| (0.217)                                               | (0.028)   | (0.029)    | (0.032)    | (0.033)   |
| Ratio of literate people in the household              | 0.398     | 0.059      | 0.052      | 0.024     | 0.025     |
| (0.422)                                               | (0.057)   | (0.057)    | (0.066)    | (0.066)   |
| Farm size                                             | 0.685***  | 0.072***   | 0.070***   | 0.010     | 0.009     |
| (0.150)                                               | (0.015)   | (0.015)    | (0.020)    | (0.021)   |
| Wealth quintile (base = 1)                             |           |            |            |           |           |
| 2                                                      | 0.730*    | 0.114*     | 0.115*     | 0.046     | 0.046     |
| (0.391)                                               | (0.061)   | (0.061)    | (0.067)    | (0.067)   |
| 3                                                      | 1.430***  | 0.212***   | 0.203***   | 0.117     | 0.115     |
| (0.390)                                               | (0.058)   | (0.058)    | (0.071)    | (0.072)   |
| 4                                                      | 1.531***  | 0.225***   | 0.214***   | 0.136*    | 0.133*    |
| (0.377)                                               | (0.055)   | (0.055)    | (0.070)    | (0.071)   |
| 5                                                      | 2.317***  | 0.317***   | 0.304***   | 0.111     | 0.108     |
| (0.475)                                               | (0.065)   | (0.065)    | (0.072)    | (0.072)   |
| Tropical Livestock Unit                                | 1.111***  | 0.116***   | 0.112***   | −0.001    | −0.002    |
| (0.256)                                               | (0.028)   | (0.028)    | (0.035)    | (0.035)   |
| Region (base = South)                                  |           |            |            |           |           |
| Kigali                                                 | 1.363     | 0.155      | 0.171      | −0.025    | −0.020    |
| (1.558)                                               | (0.165)   | (0.172)    | (0.116)    | (0.117)   |
| West                                                   | −0.081    | −0.009     | −0.002     | −0.009    | −0.007    |
| (0.358)                                               | (0.049)   | (0.050)    | (0.057)    | (0.058)   |
| North                                                  | −0.038    | 0.001      | 0.005      | 0.062     | 0.063     |
| (0.431)                                               | (0.058)   | (0.058)    | (0.066)    | (0.068)   |
| East                                                   | 1.201*    | 0.144*     | 0.134*     | −0.030    | −0.033    |
| (0.651)                                               | (0.082)   | (0.080)    | (0.093)    | (0.093)   |
| Generalized residuals                                  | −0.053    |            |            | −0.013    |           |
| (0.045)                                               |            |            |            | (0.055)   |
| Constant                                               | 5.513***  | 1.738***   | 1.728***   | 1.616***  | 1.614***  |
| (0.722)                                               | (0.100)   | (0.100)    | (0.125)    | (0.127)   |
| N                                                      | 632       | 632        | 632        | 632       | 632       |

***, **, *: statistically significant at respectively 1%, 5%, or 10% significance level. Standard errors in parentheses. N is the size of the sample, which is composed of households who grew at least one climbing bean variety in 2015.
diversity of its bean collection, it was possible to screen over 1000 varieties to look for high levels of zinc and iron. All the listed varieties are directly linked to CIAT’s genebank and their ancestors are extremely diverse in their origins and

| Table 10 | Zero-inflated Poisson, OLS and CF results for purchases outcomes |
|----------|-------------------------------------------------------------|
|          | Months purchased | Quantity (kg) purchased each month, per adult equivalent |
|          | Zero-inflated Poisson | Zero-inflated Poisson CF | OLS | OLS CF |
| Adopted climbing iron-biofortified variety (1 = Yes) | -0.078 | -0.063 | -0.083 | -0.099 |
|          | (0.048) | (0.114) | (0.054) | (0.117) |
| HH grew a bush variety in 2015B | -0.116** | -0.116** | -0.128* | -0.128* |
|          | (0.052) | (0.049) | (0.066) | (0.066) |
| Distance to city (km) | -0.004*** | -0.004*** | 0.001 | 0.001 |
|          | (0.002) | (0.002) | (0.002) | (0.002) |
| Household size | 0.040*** | 0.040*** | 0.002 | 0.003 |
|          | (0.011) | (0.011) | (0.012) | (0.012) |
| Age of respondent (years) | -0.003** | -0.003* | 0.001 | 0.001 |
|          | (0.001) | (0.002) | (0.002) | (0.002) |
| Gender of respondent (1 = female) | 0.032 | 0.031 | 0.003 | 0.004 |
|          | (0.044) | (0.040) | (0.056) | (0.055) |
| Ratio of literate people in the household | 0.017 | 0.016 | -0.046 | -0.045 |
|          | (0.076) | (0.089) | (0.086) | (0.088) |
| Farm size | -0.077* | -0.078* | -0.097*** | -0.096*** |
|          | (0.040) | (0.041) | (0.027) | (0.027) |
| Wealth quintile (base = 1) |          |          |          |          |
| 2 | -0.078 | -0.078 | 0.003 | 0.003 |
|          | (0.062) | (0.074) | (0.082) | (0.082) |
| 3 | -0.115* | -0.117 | -0.070 | -0.068 |
|          | (0.065) | (0.078) | (0.089) | (0.090) |
| 4 | -0.264*** | -0.267**** | -0.078 | -0.075 |
|          | (0.069) | (0.086) | (0.096) | (0.100) |
| 5 | -0.252*** | -0.254**** | -0.213** | -0.210** |
|          | (0.076) | (0.092) | (0.097) | (0.099) |
| Tropical Livestock Unit | -0.225*** | -0.226*** | -0.193*** | -0.192*** |
|          | (0.052) | (0.062) | (0.051) | (0.052) |
| Region (base = South) |          |          |          |          |
| Kigali | -0.582* | -0.579**** | -0.194 | -0.198 |
|          | (0.324) | (0.086) | (0.417) | (0.420) |
| West | 0.095 | 0.097** | -0.133* | -0.135* |
|          | (0.058) | (0.048) | (0.080) | (0.080) |
| North | 0.107 | 0.108* | 0.024 | 0.023 |
|          | (0.066) | (0.063) | (0.074) | (0.074) |
| East | -0.150 | -0.152 | -0.143 | -0.140 |
|          | (0.108) | (0.134) | (0.124) | (0.126) |
| Generalized residuals | -0.010 | -0.010 | 0.012 | 0.012 |
|          | (0.069) | (0.069) | (0.075) | (0.075) |
| Constant | 1.959*** | 1.958*** | 1.231*** | 1.234*** |
|          | (0.117) | (0.123) | (0.140) | (0.141) |
| N | 632 | 632 | 632 | 632 |

***, **, *: statistically significant at respectively 1%, 5%, or 10% significance level. Standard errors in parentheses. N is the size of the sample, which is composed of households who grew at least one climbing bean variety in 2015.
characteristics. In Rwanda, the essential role of CIAT’s genebank was magnified during the recovery of the bean diversity that was lost during the Rwandan genocide.

Second, we evaluated the effect of the adoption of iron-biofortified climbing varieties on yield, the number of months in which the households eat beans from their own production, the quantity of beans consumed per month, the quantity of beans purchased, and the number of months in which households needed to purchase beans from the market. We applied several econometric approaches. The impact was measured through different estimation methods, namely the OLS, IV, CF, and Poisson models. As in the analysis of bush beans by Vaiknoras and Larochelle (2018), these climbing varieties showed statistically significant impacts on yield. However, we found no statistically significant effects on consumption and purchase outcomes.

We believe that further study is necessary to understand the differential effects of bush and climbing bean varieties on the levels of consumption and purchases. Possible reasons for this difference in results could be the pedigrees of the varieties, their development history, or their adoption rates. However, we find our results on yield very encouraging. Higher levels of yields provide incentives to households to grow iron-biofortified varieties. As a result, we might see an increase in productions, and thus, in consumption of these varieties that are beneficial for people’s health. Furthermore, the adoption of the studied varieties is likely to increase in the next years, given that cultivating climbing beans is very common in the Great Lakes region. Other econometric issues could be investigated to advance this research and explore in depth the different results in the consumption and purchase of bean varieties.

We were able to assess the role that CIAT’s genebank played in the journey that led to the development of iron-biofortified varieties. In fact, an innovative aspect of this study is that we considered not only the final effects of adoption on the well-being of farm households but also the history of each variety in order to illuminate the important role of CIAT’s genebank in the process.

We provide evidence that CIAT’s genebank contributed to the improvement of nutrition quality of food crops, as it provided breeders with essential material for the development of iron-biofortified varieties that have the potential of improving nutrition in Rwanda. We showed that CIAT’s genebank provided the needed material to develop varieties that are higher in iron and zinc and simultaneously higher in yield, giving farmers the incentive of cultivating rather than other, less nutritious, varieties. However, we believe that there is scope for improvement. The breeding and development process of improved varieties could be accelerated with enhanced collaboration and more active exchange of information between breeders and genebanks. Finally, apart from providing smallholder farmers with resistant iron-biofortified varieties, it is also important for governments and NGOs to sensitize the farm communities to the problem of malnutrition and to promote awareness on the importance of producing and consuming varieties high in micronutrients.

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Authorship contribution The first author contributed to the research conceptualization and design, data gathering, data analysis, writing, and editing. The second author contributed to research conceptualization and design, data provision, and data analysis. The third and fourth authors contributed to research conceptualization and design, data analysis, writing, and editing. The last three authors contributed to research conceptualization and design, data provision, and data analysis.

Compliance with ethical standards

Conflict of interest The sixth author is currently the Genebank Manager of CIAT. The fifth and last authors are scientists at CIAT. The fourth author is an agricultural economist at the Crop Trust. The remaining authors declare no conflict of interest.

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