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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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Abstract

Genebanks play an essential role in a world where a substantial part of agricultural biodiversity has been lost from farming habitats, malnutrition persists with a global population that 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 (CAB2, RWV3316, RWV3317, RWV3006, RWV2887, MAC44, MAC42) and the impact of their adoption on farm households in Rwanda. First, we link iron-biofortified varieties of climbing 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 their adoption on the yield, consumption and purchase of beans by farming households in Rwanda, building upon previous research on bush beans. Analysis is based on a dataset of nearly 1400 households, collected in 2015 by Harvest Plus. We find that the scope of the genetic diversity housed in the bean collection at CIAT was fundamental to developing successful iron-biofortified beans. However, in contrast to findings of Vaiknoras and Larochelle (2019) regarding bush beans, we could find only weakly significant effects of climbing varieties on yields but not on production and consumption of households. 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. Further research is needed to understand the differential factors affecting the adoption and impacts of climbing and bush bean varieties.

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Contents

1 Introduction

Genebanks play an essential role in a world where a substantial part of agricultural biodiversity has been lost from farming habitats, malnutrition persists with a global population that 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 programs, 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 programs to production by farmers and consumption by final consumers. In low income agricultural systems such as Rwanda, smallholder 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's Bean Program website). However, in a number of countries, including Rwanda, anemia still represents an important 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 2016).

For this reason, our analysis focuses on the iron-biofortified bean varieties developed through the collaboration of the International Center for Tropical Agriculture (CIAT), HarvestPlus (HP), Virginia Tech, and Rwanda Agriculture Board (RAB) and distributed to Sub-Saharan Africa, specifically in Rwanda, the first country where they were released. Among the ten 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, MAC42.**

We build on recent work by Vaiknoras et al. (2018; 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 Harvest Plus in collaboration with CIAT, Virginia Tech and RAB in 2015. Our approach has much in common with that of Vaikoras and Larochelle (2018), sharing the same underlying dataset and comparable indicators of adoption outcome. The key differences 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, the 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 reason for choosing the seven climbing varieties listed above are the following: 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 was to understand the adoption and diffusion patterns that have occurred in the past few years; the aim of the second was to establish the reach of iron-biofortified bean varieties among Rwandan bean farmers since these varieties were released in 2010 (Asare-Marfo et al. 2016a; 2016b).

We thus address these lacunae. This work documents 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 food crops?"* 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 farming families who grow them and also consume the harvest in Rwanda.

Here is the pathway: 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. The latter were used in breeding programs to generate varieties with higher micronutrient levels, while also retaining other fundamental traits known to be important, such us resistance to disease and characteristics that appeal to farmers and consumers. Once those varieties are disseminated and their cultivation and consumption rise, it is possible to observe and measure impact on farmers and consumers.

The next section provides preliminary information about the work of CIAT's genebank and about bean production and consumption in Rwanda. Section 3 describes data collection and methods. Sections 4 and 5 present the main results of the analysis and discuss them. Section 6 concludes.

2 Context

2.1 CIAT's genebank

CIAT started its bean collection in the 1970s, following a global mandate of a network of research centers formerly known as the Consultative Group on International Agricultural Research (CGIAR) (D. Debouck, personal communication). Since then, CIAT's genebank has received materials 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 Genetic Program website; Daniel Debouck, personal communication).

The distribution of genetic resources began in 1973 and was accomplished by the scientists of CIAT's bean program, 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 (NARS), non-governmental organizations (NGOs), regional organizations and universities, private individuals, commercial companies, and other CGIAR centers. 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 in all years was used for the improvement of bean varieties (Figure 1). In Sub-Saharan Africa, 11% of the accessions were used for species improvement and the majority of these in applied research or agronomy (Figure 2). Between 1978 and 2018, CIAT sent 645 accessions (433 unique materials) to Rwanda, with seed origins from 28 different countries (Figure 3). 54% of them were climbing varieties, 73% of round shape and 20% of black color. Those accessions were mainly used in applied research and agronomy and only 4% was used in breeding processes (Figure 4).

The historical role of CIAT's genebank in the development of bean varieties which are high in micronutrients is undeniable. In fact, CIAT holds the largest bean collection in the world (Johnson, 2003). According to Steve Beebe, the current leader of CIAT's Bean Program, 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, providing the major input for the biofortification program which started in early 1990s (Beebe

2000). Given the considerable diversity in CIAT's genebank collection, it was possible to screen varieties originating in many areas of the globe and differing in a number of characteristics, ranging from their aspect, to their resistance to disease, and their nutritional values.

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 the diet, the phenotypic diversity of common beans in the Great Lakes Region, CIAT's role in restoring germplasm after the 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 kilograms (kg) per person per year (Palmer 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 (DHS) 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.

Biofortification is more cost-efficient in countries where production and consumption of the targeted crop is high (Meenakshi et al. 2007). 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 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 colors (Lamb and Hardman, 1985; Sperling, 2001). However, common bean diversity in that 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 2009) (see Box 1 at the end of this section).

According to FAOSTAT, 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 tons with total production of 4.2 million tons. Figure 5 reports the values of the production of dry beans in Rwanda from 1961 until 2017, which has been increasing except for the fall in production in 1994 to 34,800 tons during the Genocide. The data on the hectares of land cultivated to bean production also show a persistent rise over time, with an average of 426,692 hectares in the decade 2007-2017. Finally, bean yield, calculated as the quantity of dry bean harvested over the hectares of land cultivated, was fairly stagnant over time, with a slight increase between 2005 and 2011 (Figure 6). On average, the yield was about to 785 kg/ha from 1961 until 2017 and 911 kg/ha in the last decade (2007-2017).

In a context where beans are consumed heavily, where the 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, biofortification of beans is a viable strategy. The potential impact of biofortification as a solution for malnutrition is evidenced in a study conducted 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 Fe-Beans developed at CIAT or standard unfortified beans. For 128 days, they were fed with the two types of beans. The authors show that iron-biofortified beans significantly improved iron status in Rwandan women, increasing the level of haemoglobin, serum ferritin concentrations and BI.

CIAT, HP and their partners released the iron-biofortified varieties included in this study between 2010 and 2012 and distributed planting material in Rwanda through different formal and informal delivery approaches between 2012 and 2015. The most successful delivery approach was direct marketing, which began in 2012. 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 of 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 latter in the development of iron-biofortified beans. Data regarding the varieties were not immediately available due to the high dispersion of information. Hence, it was necessary to collect the data from different channels including: (1) research of past literature, (2) collection of information on pedigrees and genealogy of the varieties, (3) research in the annual reports of CIAT's bean program, and (4) personal communication with bean breeders in Rwanda and at CIAT. It was possible to retrace the pedigrees of all varieties using several sources: Pan-Africa Bean Research Alliance (PABRA) website, the *Catalogue of advanced bean lines from CIAT* by M.A. Rodriguez et al. (1994) available at CIAT's library, and the database of the Bean Program of CIAT.

Through Rodriguez's work and through 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 in the website of CIAT's genetic resources program, it was possible to collect information regarding the characteristics of the varieties used as parents of iron-biofortified lines.

3.2 Analyzing adoption effects on well-being of farm households

3.2.1 Data source

This study uses nationally representative data on bean producers in Rwanda collected by Harvest Plus, in partnership with RAB and CIAT. Kate Vaiknoras provided the cleaned database for the study and data analysis was conducted using STATA 15.

Data were collected in two stages in 2015. The survey followed the distribution of iron-biofortified varieties that started in 2010 for four varieties (including two bush varieties, the climbing variety MAC44 and the iron-biofortified climbing variety RWV1129) and continued in 2012 for the remaining climbing varieties studied here. The first round of data collection took place in May and June of 2015. During this round, all households of 120 villages randomly selected were interviewed. In total, 19,575 households were interviewed regarding their history of adoption of iron-biofortified bean varieties. In the second stage, which took place in September 2015, 12 households from each village were randomly selected for a second interview, the main household survey. When possible, six iron-biofortified bean adopters and six non adopters were selected, in order to have a good balance in the size of the two groups. The enumerators collected 1,397 interviews, asking information regarding 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 and the main sources of information. Further information on data collection can be found in the Main Survey Report and Listing Exercise Report by Asare Marfo et al. (2016a; 2016b).

Rwanda has two bean growing seasons – season A that usually runs from September through January, and season B that 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 coming 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 1,397 households included in the original sample, 360 (25.8%) had grown a climbing iron-biofortified variety at least once between 2010 and 2015[1] and 331 households had grown 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 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

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.

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 1 and 2 bean plots.

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.

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

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[1] These are the results of adoption after checking a sample of the varieties received by farmers with the XRF machine, to test the iron content of beans and confirm that farmers had correctly identified the variety as iron-biofortified.

beans in the market and the average quantity purchased in kg. Taking into account the effect on consmption and purchases is important for our work as we assume that higher levels of production can lead households to consume more beans from own production and, in turn, receive health benefits from the consumption of varieties enriched in iron and zinc.

Given that some households grew more than one climbing variety in season 2015B, adoption and yield effects are considered at varietal level, specifying whether each variety is an iron-biofortified variety with ancestors at CIAT's genebank or a local variety. After excluding from the sample all bush varieties, the variety RWV1129 and the non-iron-biofortified improved varieties, the final sample was composed of 826 observations, including 635 local varieties and 191 iron-biofortified varieties.

By contrast, the effects on consumption and purchase were evaluated at household level for 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 or only variety RWV1129 or only non-iron-biofortified improved varieties, remaining with a sample composed of 632 households, 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 them, 23 households adopted iron-biofortified bean 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, it was necessary to adopt different econometric models.

3.2.3.1 Impact on yield

To account for possible estimation bias and to ensure the robustness of the 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:

$$(1) Y_{it} = \alpha + \beta T_{ij} + \gamma I_{ij} + \delta H_i + \varepsilon_{ij}$$

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_{ij}. 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. H_i in equation 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 South, Kigali, 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 (IV) estimation with two-stage least squares.

For this reason, the second method implemented was the instrumental variable (IV), as it allows for endogeneity. The estimation through IV requires the implementation of two stages. First, one regresses the treatment on the instrument Z, the other covariates and a disturbance, u_i. This process is known as the *first-stage regression* (Khandker 2009):

$$(2)\; T_i = \beta Z_i + \gamma I_{ij} + \delta H_i + u_i$$

The predicted treatment from this regression, $\hat{T}$, is included in the treatment equation (1):

$$(3) Y_{it} = \alpha I_{ij} + \beta(\hat{Z}_i + \hat{\gamma} I_{ij} + \hat{\delta} H_i + u_i) + \rho H_i + \varepsilon_{ij}$$

We estimated the model with *ivreg2* in STATA 15. The use of this approach requires the identification of one or more instrumental variables. To be valid, the instrumental variables 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 *ivreg2* command, diagnostic tests include: the underidentification test done with Kleibergen-Paap LM statistic, the weak identification test useful as a diagnostic for whether a particular endogenous regressor is weakly identified using the Cragg Donald F statistics, the Hansen J test as an overidentification tests of all instruments and an the Hausmann test of endogenous regressors.

While the relevance of the instrument to the potentially endogenous variable can be tested statistically as part of *ivreg2*, the exclusion restriction is met by logical argument. The two instrumental variables 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. Harvest Plus direct marketing was one of the main sources of iron-biofortified planting material (Asare-Marfo, D., 2016); 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-biofortifed planting material, we used the previous village adoption rate of iron-biofortified climbing varieties, used as a proxy for the availability of those varieties within one's social network one season prior to our period of interest (Vaiknoras, 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 a good instrument (Vaiknoras, 2018).

The instrumental variables 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 approach (CF). 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 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, 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.

3.2.3.2 Effects of consumption of iron-biofortfied beans and on bean purchases

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 not adopters and 70 were adopters, had not purchased beans in the 12 months preceding the interview.

4 Results

4.1 Preliminary information on the breeding process

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 bean collection kept at CIAT's genebank substantially expanded during the early 1990s. This propelled CIAT scientists to develop core collections using characterization data, geographic, and genetic information. The core collections have been extensively used since then to find not only resistance to diseases, but also nutritional traits (D. Debouck, personal communication).

The relationship between the genebank at CIAT and the bean program related to iron-biofortified beans started in 1995 (S. Beebe, personal communication). At that time, IFPRI supported a project at the bean program to do an initial evaluation of the germplasm kept at CIAT's genebank. The sources of the breeding program of iron-biofortified varieties were the primary gene pool, crosses with a secondary gene pool, and crosses with a tertiary gene pool -- all coming from the bean collection at CIAT. The initial evaluation was conducted on the first core collection of 1,040 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 30-110 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's genebank were selected to initiate crosses (Blair, 2013).

In addition, scientists also screened advanced lines within two gene pools – the Andean and the Mesoamerican. This screening was essential to identify potential commercial type parents, as many of the high-iron or high-zinc lines from the core collection were of noncommercial seed type (Blair 2013). Moreover, it was also important to screen local germplasm of the countries involved in biofortification. Further screening included a range of Andean varieties, a regional collection of eastern and southern Africa released varieties and a large collection (over 350 entries) of Rwandan genotypes, part of which were likely recovered after the Rwanda Genocide through the initiative known as "Seeds of Hope" (see Box 1). Finally, screening of related species such as *Phaselous coccineus* or *Phaseolus dumosus* and *Phaseolus acutifolius*, has been used to identify high iron content genotypes in the secondary and tertiary gene pools, respectively.

CIAT's genebank played an important role in the screening process due to the high bean diversity in its collection. Hence, breeders are able to work effectively on the following activities, which included: inheritance study of seed mineral accumulation, localization of iron within the seed and bioavailability tests, breeding of high mineral bean varieties.

BOX 1: THE GENOCIDE OF RWANDA AND THE SEEDS OF HOPE INITIATIVE

The Genocide of Rwanda was a mass slaughter of Tutsi during the Rwandan civil war. The war had started at the beginning of the 1990s, but the situation exacerbated when the plane that carried the presidents of Rwanda and Burundi was shot down on the 6th of April 1994. The initial rampage of social killings degenerated into racial recrimination and genocide against Tutsi, which lasted three months. During the Genocide, 10% of the population died, 30% moved to Tanzania and Zaire, and about 7% became internally displaced. Only 53% of the population was still "at home" after the Genocide. Consequently, in 1994, the grain and pulse harvests were down by 60% and production of root crops and plantains down by 30%. Beans productivity went down by 60%, with an estimated loss of 31.500 tons.

On the 26th of May 1994, the CIAT Bean Research Group met in Kampala, Uganda, as part of the normal review process for the CIAT Regional Program on Beans in Eastern Africa. Participants discussed the likely impact of the civil war in Rwanda on food security and availability of seed for planting. CIAT was concerned about the loss of varietal diversity in farmers' seed stocks and about the indiscriminate introduction of poorly non-adapted varieties of beans into Rwanda by relief agencies and NGOs. As a response, CIAT, along with other IARC centers, presented the SEEDS OF HOPE initiative to potential donors and NARS in countries bordering Rwanda.

CIAT was endorsed as the implementing agency of SOH and through its genebank it was possible to recover 165 Rwandan landraces, 19 released varieties and improved varieties in diffusion, 95 advanced breeding lines, 2 released varieties from Uganda and 2 from Rwanda.

4.2 Analysis of the pedigrees

We collected information regarding the pedigrees and the genealogy of the iron-biofortified varieties of climbing bean (CAB2, RWV3316, RWV3317, RWV3006, RWV2887, MAC44, and MAC42). The pedigrees are reported in Annex 1 of this paper. From this analysis, it was possible to confirm that all of these varieties 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, with AND930, a bred line developed by Julia Kornegay at CIAT using genebank materials.

Overall, we can find 10 genebank accessions used by different breeders to generate bred lines that were used in the final breeding of MAC varieties. The 10 genebank accessions used are: G12722, G21720, G6616, G4523, G76, G6533, G14013, G11891, G4505, G5704. Four of those varieties are from Colombia, one from the Dominican Republic, two from the United States, one from Brazil, one from Mexico and one from 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 are the result of the combination of the variety CAB2, developed at CIAT by Julia Kornegay, with either a local Rwandan variety or another CIAT's bred variety. CAB2 was sent to Rwanda from CIAT breeding program and then locally multiplied for tests, following which it was bred with some local varieties for adaptation (Floride Mukamuhirwa, personal communication).

CAB2 is a variety 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 a climbing variety from Congo. RWV3316 and RWV2887 were developed through the crosses of CAB2 with LAS400, a variety by Julia Kornegay, resulted from the cross of G12670 and G12666 kept at CIAT's genebank and both coming 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 big loss of genetic materials during the Rwanda Genocide. This resulted to the breeding of iron-biofortified beans through crosses with CAB2 and with many other varieties available at CIAT. Without that backup materials from CIAT's genebank, it would have taken much longer to invigorate the breeding program (Louis Butare, personal communication).

4.3 Results

4.3.1 Descriptive statistics

Initial tests were performed to see whether the differences in the dependent variables and in the plot-level 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 1947). Table 2 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 3 shows the differences in characteristics of the control variables used in the estimation of the impact 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. Table 4 shows the differences in means of the household-level characteristics. Adopter households significantly differed from non-adopters in size of household, land areas, wealth quintile and in the agriculture equipment owned. We included those variables as controls in all our estimations.

4.3.2 Econometric analysis

Regression results are reported in Tables 5 to 7. Table 5 shows the results of the estimation of the effect of adopting an iron-biofortified variety connected to CIAT's genebank on the 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 control function approach. We can reject the null hypothesis of the Kleibergen-Paap LM statistic; hence the model is not underidentified. The null hypothesis of weak instruments is rejected using the Cragg Donald F Statistics while 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 Haussman test fails to reject the null hypothesis of exogeneity; hence, adoption is not endogenous to our outcomes of interest.

All regressions reveal that the effect of adopting at least an iron-biofortified climbing variety over cultivating uniquely local varieties is positive. However, as compared to the findings reported by Vaiknoras and

Larochelle (2018), results were not statistically significant with either the OLS or IV estimation. We found statistically significant results at the 10% level when using the CF approach.

Table 6 reports regressions 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 method, respectively. The coefficients are positive, but not statistically significant. 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 estimated with OLS and CF OLS have the expected negative sign but are not statistically significant.

Finally, Table 7 reports the results of regressions testing 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. Coefficients are negative in sign, showing that the adoption decreases the need of purchasing beans from the market. However, results are not statistically significant. Likewise, the effect of adoption on monthly purchases is negative and not statistically significant. Since numerous households purchased 0 kg of beans in the market, the logarithmic transformation of the dependent variable caused a loss of 158 observations. Hence, in the last estimation we could do a comparison only among those households that had purchased a quantity of beans higher than 0, remaining with a sample of 474 observations.

5 Discussion

The results of this first step in the analysis showed clearly the importance of CIAT's genebank in the development of improved varieties. All the varieties described in this study had ancestors at CIAT's genebank and their ancestors come from different countries: Kenya, Mexico, Congo, Colombia, Dominican Republic, USA, Peru and Brazil. For a breeder, it would have been extremely hard to obtain access to varieties originating from different areas without access to the materials kept at CIAT's genebank. This hypothesis was confirmed in our interviews with experts. From our personal communication with Dr. Daniel Debouck, previous leader of CIAT's Genetic Resources program, Dr. Steve Beebe, current leader of CIAT's Bean Program and with the bean breeders Bodo Raatz from CIAT's bean program and Louis Butare and Floride Mukamuhirwa from RAB, we learned that the development of iron-biofortified varieties would probably not have been possible without CIAT's genebank. Even if possible, it would have been extremely time-consuming and probably would have led to different results. According to the experts, CIAT's genebank played an essential role in the advancement of the breeding program and thanks to its immense bean diversity it was possible to screen over a thousand varieties to look for desirable traits. Furthermore, Louis Butare mentioned the important role that CIAT's genebank played during the Seeds of Hope initiative described in Box 1 and claimed that it would have been impossible to have such vibrant breeding activity in Rwanda without that initiative.

While the varieties MAC42 and MAC44 were fully developed with material coming from CIAT's genebank, varieties such us RWV3317 and RWV3006 were the results of the combination between varieties coming from CIAT's genebank and Rwandan local landraces. We were interested in investigating whether the local varieties used, Ngwin and Buberuka, were part of Rwandan bean collection recovered through CIAT's genebank during the Seeds of Hope initiative. However, due to the limited available data, it was not possible to verify this information.

The first part of this study was limited by the difficulty in locating relevant information. Much information regarding the Seeds of Hope initiative was lost, as well as much information regarding the breeding process that led to the development of iron-biofortified varieties. Other reasons contributed to the challenges in data collection, including: (1) iron-biofortified varieties were developed during the time when recording of information is still paper-based and not easily available; (2) communication between CIAT's genebank and bean breeders is poor and breeders are not required to report back to the genebank how they are using the varieties requested; (3) written documentation has not been standardized and much information is recorded uniquely in the memories of experts. This crucial problem of communication generates a misalignment of objectives between CIAT's genebank and bean breeders.

The second part of the study provides the link from the genebank to farmers, showing the impact of the bred varieties on farm households. We followed the study by Vaiknoras and Larochelle (2018) that measured the impact of the bush variety RWR2245 on farmers' yield, bean consumption from own production and purchase of beans from the market. Vaiknoras and Larochelle (2018) found a positive and statistically significant impact of the adoption of RWR2245 on farmers' yield. They also showed that adopters consumed more beans from their own production and purchased less beans from the market compared to non-adopters.

We expected to find similar results in our analysis. However, compared to the results found by Vaiknoras and Larochelle (2018) we found only a weakly significant effect on yield. Possible reasons for this difference in results could be the pedigrees of the varieties, their development history and their adoption rates. In fact, the variety RWR2245 was the most adopted variety among the iron-biofortified varieties released by HP in collaboration with CIAT, RAB and Virginia Tech. Several households preferred it over other varieties for its yield, taste and maturity period. It is a pure line selection of local landraces, which means that the variety was already adapted to the Rwandan environment. Finally, being a local landrace, farmers are more likely familiar with RWR2245, explaining partly the higher level of adoption and productivity of this variety over the climbing varieties of bean studied here.

We believe that further study is necessary to understand the differential effects of bush and climbing bean varieties. Detailed information on farm inputs and risk preferences of farmers are also key to understanding yield effects since climbing beans, although have higher yield potential, require additional inputs. Further, the adoption of the studied varieties is likely to increase in the next years, given that in the Great Lakes regions it is very common to cultivate climbing beans. Other econometric issues could be investigated to advance this research, including the use of different instrumental variables, accounting for agro-ecological areas and frequency of harvest, and other ways to measure production and adoption levels.

6 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 food crops?"* 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 focused on iron-biofortified climbing beans as target varieties and Rwanda as a target country.

The analysis was divided into two parts: first, we confirmed the link between bred varieties and CIAT's genebank; second, we evaluated the impact of iron-biofortified varieties on farm households. In the first part, this study linked the iron-biofortified climbing varieties CAB2, RWV3316, RWV3317, RWV3006, RWV2887, MAC44 and MAC42 back to CIAT's genebank. Through the analysis of their pedigrees, it was possible to find their ancestors inside CIAT's genebank and to identify their characteristics and areas of origin. We did this with assistance from the principal breeders involved in the development of the varieties. Their expert knowledge regarding the breeding process and the role that CIAT's genebank played made it possible to confirm the link with the iron-biofortified climbing varieties.

CIAT's genebank was a key player in the development of iron-biofortified varieties. Through the diversity of its bean collection, it was possible to screen over 1000 varieties to look for important nutritional traits, namely 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 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.

The second part of the analysis of the work by Vaiknoras and Larochelle (2018) on the impact of the bush iron-biofortified variety RWR2245 on farmers. We evaluated the impact of iron-biofortified climbing varieties on the yield, on 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, as well as the number of months in which households needed to purchase beans from the market. The impact was measured through different estimation methods, namely OLS, IV, CF approach and Poisson model. Differently from Vaiknoras and Larochelle (2018), these climbing varieties did not show any statistically significant impacts on the outcomes of interest. Further investigation is needed to explain the contrasting results.

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. But 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 farmers with resistant iron-biofortified varieties, it is also important for governments and NGOs to sensitize farmers to the problem of malnutrition and to promote awareness on the importance of producing and consuming varieties high in micronutrients.

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8 Tables

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%	1397[1]
2015					
Season 2015A only	24	2%	23	2%	1190[2]
Season 2015B only	126	11%	88	7%	1190[2]
Both 2015A and 2015B	91	8%	92	8%	1190[2]

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

Variety	Type	Yes	No	N	%
RWR2245	Bush	315	1082	1397[1]	23%
MAC44	Climbing	123	1274	1397[1]	9%
RWV3316	Climbing	73	1324	1397[1]	5%
RWV3317	Climbing	32	1365	1397[1]	2%
RWV1129	Climbing	35	1362	1397[1]	3%
RWR2154	Bush	16	1381	1397[1]	1%
CAB2	Climbing	29	1368	1397[1]	2%
RWV2887	Climbing	22	1375	1397[1]	2%
MAC42	Climbing	20	1377	1397[1]	1%
RWV3006	Climbing	26	1371	1397[1]	2%

The table above reports information on the adoption of iron-biofortified varieties. The results were reported after checking a sample of the varieties received by farmers with XRF machine to test the iron content of beans and confirm that farmers has correctly identified the variety as iron-biofortified. The original sample was 1397 households. However, after getting rid of outliers we remain with 1383 households.

[1] Size of the original sample

[2] Size of the sample after getting rid of outliers, households growing variety RWV1129 and households growing improved varieties that were not iron-biofortified.

Table 2. 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
	2015 iron-biofortified climbing varieties non adopters		2015 iron-biofortified climbing varieties adopters	
N. months consumed from own production ***	7.3 (3.28)	429	8.21 (3.05)	203
Log of consumption from own production (kg) **	1.18 (0.6)	428	1.1 (0.6)	202
N. months purchased beans ***	4.33 (3.28)	429	3.4 (2.99)	203
Log of purchases per month (kg) **	0.91 (0.6)	335	0.78 (0.6)	139

Table 2 shows the mean of the dependent variables for adopters and non-adopters. Standard errors are reported in parenthesis. ***, **, *: differences in means are statistically significant at respectively 1%, 5%, or 10% significance level

Table 3. 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 (10m)***	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)
Extension (%) *	73.1 (24.2)	68.07 (28.13)
N	191	635

Table 3 shows the mean values for plot-level control variables for iron-biofortified varieties and local varieties. Standard errors are reported in parenthesis. ***, **, *: differences in means are statistically significant at respectively 1%, 5%, or 10% significance level.

Table 4. Descriptive statistics for household-level control variables.

Variables	**2015 iron-biofortified climbing varieties adopters**	**2015 iron-biofortified climbing varieties non-adopters**
Distance to city (km)	35.6 (19.7)	36.9 (18.6)
Household size ***	5.46 (2.15)	4.8 (2.06)
Age of respondent (years)	44.12 (13.37)	45.03 (15.87)
Elevation in units of 10 meters	172.52(23.6)	181.9 (25.87)
Gender of respondent (1 = female)	0.67 (0.47)	0.62 (0.49)
Literacy of respondent (1=Yes)	0.69 (0.46)	0.59 (0.49)
Land size (ha) ***	0.61 (0.96)	0.39 (0.61)
Wealth quintile ***	3.51 (1.3)	2.94 (1.39)
Equipment owned *	1.41 (0.85)	1.26 (0.77)
Tropical Livestock Unit	0.6 (0.76)	0.4 (0.5)
N	203	429

Table 4 shows the mean values for household-level control variables for adopters and non-adopters. Standard errors are reported in parenthesis. ***, **, *: differences in means are statistically significant at respectively 1%, 5%, or 10% significance level.

Table 5. OLS, IV and CF results for multiplication ratio.

Multiplication ratio (quantity harvested/quantity planted)				
	(i)	**(ii)**	**(iii)**	**(iv)**
	OLS	**IV**	**IV (ML)**	**CF OLS**
Iron-biofortified variety (1=Yes; 0=No)	0.156	0.982	0.336	0.078*
	(0.084)	(0.612)	(0.225)	(0.033)
Recycled seed (1=Yes)	0.117	0.210	0.056	-0.046
	(0.074)	(0.109)	(0.066)	(0.031)
Slope (base=steep)				
Moderate	-0.224	-0.253*	-0.158	-0.058
	(0.120)	(0.120)	(0.092)	(0.051)
Gentle	-0.162	-0.196	-0.179*	-0.019
	(0.103)	(0.104)	(0.087)	(0.031)
Flat	-0.172	-0.220*	-0.059	0.011
	(0.105)	(0.109)	(0.093)	(0.032)
Type of stake used (base=none)				
	0.326*	0.311*	0.190*	0.071
Trees, maize stalks, napier grass stovers	(0.126)	(0.134)	(0.096)	(0.058)
Poles or sticks	0.338**	0.310*	0.258**	0.127*
	(0.126)	(0.134)	(0.098)	(0.062)
Intercrop (1=flat)	0.026	0.033	0.024	-0.025
	(0.070)	(0.072)	(0.054)	(0.026)

Use of organic fertilizer (1=Yes)	0.009	-0.074	0.139	0.038
	(0.097)	(0.119)	(0.092)	(0.041)
Use of chemical fertilizer (1=Yes)	0.259**	0.253**	0.223***	0.006
	(0.086)	(0.087)	(0.062)	(0.032)
Gender of the person deciding about the plot (1=female)	0.046	0.021	0.040	0.017
	(0.073)	(0.082)	(0.056)	(0.031)
The person deciding about the plot is literate (1=Yes)	0.235**	0.216**	0.229***	0.035
	(0.075)	(0.082)	(0.061)	(0.031)
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 (10m)	0.001	0.002	0.002	-0.002***
	(0.002)	(0.002)	(0.001)	(0.001)
Number of adults in the household	0.064*	0.054	0.064**	0.026*
	(0.027)	(0.029)	(0.021)	(0.011)
Equipment owned (count)	0.006	-0.018	-0.056	0.036*
	(0.043)	(0.048)	(0.036)	(0.016)
Extension (%)	0.001	0.001	0.001	0.002***
	(0.001)	(0.002)	(0.001)	(0.001)
Region (South=base)				
Kigali	-0.171	-0.058	-0.119	0.007
	(0.164)	(0.180)	(0.270)	(0.054)
West	-0.010	0.059	-0.107	-0.094*
	(0.106)	(0.113)	(0.078)	(0.040)
North	0.071	0.134	0.039	-0.037
	(0.101)	(0.115)	(0.077)	(0.037)
East	0.409**	0.319	0.248*	0.059
	(0.149)	(0.173)	(0.103)	(0.055)
Constant	0.891*	0.713	0.881**	0.893***
	(0.409)	(0.455)	(0.294)	(0.137)
Generalized residuals				0.270***
				(0.007)
N	813	813	813	813

***, **, *: statistically significant at respectively 1%, 5%, or 10% significance level. Standard errors in parenthesis. Each cell reports a different estimation of the treatment effect. Column (i) reports the results of the OLS estimation. Column (ii) reports the results of the instrumental variable (IV) estimates, calculated using the OLS methos in the first stage regression. In column (iii) we report the results of the instrumental variable estimates, calculated using the maximum likelihood estimation in the first stage regression. Column (iv) reports the estimates calculated through the control function approach. The outcome of interest is the multiplication ratio, which is used a proxy for yield and calculated as the ratio of the quantity of beans harvested on the quantity of beans planted. N is the size of the sample, which is composed of the bean varieties grown by the households.

Table 6. Poisson, OLS and CF results for consumption outcomes

	Months consumed from own production			Quantity (kg) consumed each month, per adult equivalent	
	(i)	(ii)	(iii)	(iv)	(v)
	OLS	Poisson	CF Poisson	OLS coefficient	CF OLS coefficient
Adopted Climbing HIB (1=Yes)	0.146	0.020	0.114	-0.065	-0.047
	(0.239)	(0.031)	(0.069)	(0.054)	(0.114)
Bush bean grower (1=yes)	0.982***	0.127***	0.131***	0.027	0.027
	(0.273)	(0.034)	(0.035)	(0.059)	(0.060)
Distance to city (km)	0.014	0.002	0.002	0.002	0.002
	(0.011)	(0.001)	(0.001)	(0.003)	(0.003)
Household size	-0.233***	-0.030***	-0.032***	-0.083***	-0.084***
	(0.065)	(0.009)	(0.009)	(0.012)	(0.012)
Age of respondent (years)	0.011	0.001	0.001	0.001	0.001
	(0.007)	(0.001)	(0.001)	(0.002)	(0.002)
Elevation in units of 10 meters	-0.020***	-0.003***	-0.003**	-0.002	-0.002
	(0.006)	(0.001)	(0.001)	(0.001)	(0.001)
Gender of respondent (1 = female)	-0.219	-0.029	-0.037	-0.079	-0.081
	(0.212)	(0.028)	(0.028)	(0.048)	(0.049)
Literacy of respondent (1=Yes)	-0.081	-0.013	-0.018	-0.015	-0.016
	(0.252)	(0.034)	(0.034)	(0.054)	(0.054)
Land size (ha)	0.676***	0.070***	0.067***	0.004	0.003
	(0.149)	(0.016)	(0.016)	(0.027)	(0.027)
Wealth quintile (base = 1)					
2	0.635	0.102	0.103	0.052	0.052
	(0.396)	(0.061)	(0.061)	(0.097)	(0.098)
3	1.394***	0.207***	0.195***	0.161	0.159
	(0.389)	(0.058)	(0.057)	(0.103)	(0.103)
4	1.558***	0.232***	0.217***	0.199*	0.196*
	(0.383)	(0.056)	(0.055)	(0.097)	(0.098)
5	2.191***	0.301***	0.285***	0.144	0.141
	(0.475)	(0.065)	(0.064)	(0.102)	(0.101)
Equipment owned	0.300	0.040*	0.040*	0.028	0.028
	(0.162)	(0.020)	(0.020)	(0.028)	(0.029)
Tropical Livestock Unit	1.062***	0.109***	0.104***	0.028	0.027
	(0.250)	(0.028)	(0.028)	(0.038)	(0.036)
Region (base = South)					
Kigali	1.119	0.117	0.143	-0.015	-0.010

	(1.392)	(0.142)	(0.151)	(0.174)	(0.176)
West	-0.083	-0.011	-0.002	-0.003	-0.001
	(0.355)	(0.049)	(0.050)	(0.080)	(0.082)
North	-0.102	-0.006	0.000	0.124	0.125
	(0.428)	(0.058)	(0.058)	(0.088)	(0.090)
East	0.274	0.021	0.019	-0.069	-0.069
	(0.698)	(0.087)	(0.088)	(0.144)	(0.144)
Generalized residuals			-0.067		-0.013
			(0.045)		(0.080)
Constant	8.804***	2.210***	2.155***	1.605***	1.594***
	(1.185)	(0.166)	(0.172)	(0.276)	(0.287)
N	632	632	632	630	630

***, **, *: statistically significant at respectively 1%, 5%, or 10% significance level. Standard errors in parenthesis. Columns (i), (ii) and (iii) report the estimation of the treatment effect on the number of months during which households consumed beans from their own production. Column (i) reports the estimates calculated with OLS model, column (ii) with the Poisson model, while column (iii) reports the results of the Poisson model with control function method. Columns (iv) and (v) report the results of the regression on the quantity of beans (in kg) consumed per month by the households. Column (iv) reports the coefficients calculated through the OLS regression, while column (v) reports the coefficient of the control function approach. N is the size of the sample, which is composed of households who grew at least one climbing bean variety in 2015.

Table 7. Zero inflated Poisson, OLS and CF results for purchases outcomes.

	Months purchased		**Quantity (kg) purchased each month, per adult equivalent**	
	(i)	**(ii)**	**(iii)**	**(iv)**
	Zero-inflated Poisson	**Zero-inflated Poisson CF**	**OLS**	**OLS CF**
Iron-biofortified climbing beans adopted in 2015 (1 = Yes)	-0.072	-0.047	-0.095	-0.115
	(0.043)	(0.093)	(0.055)	(0.118)
Bush bean grower (1 = Yes)	-0.088*	-0.083	-0.008	-0.012
	(0.044)	(0.043)	(0.059)	(0.063)
Distance to city (km)	-0.003	-0.003	-0.001	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)
Household size	0.032***	0.032***	-0.091***	-0.091***
	(0.008)	(0.008)	(0.010)	(0.010)
Age of respondent	-0.004**	-0.004**	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Gender of respondent (1 = Female)	0.053	0.052	-0.080	-0.078
	(0.035)	(0.036)	(0.043)	(0.044)
Literacy of respondent (1 = Yes)	-0.071*	-0.072*	0.087	0.088
	(0.034)	(0.034)	(0.048)	(0.048)
Land size (ha)	-0.074**	-0.075**	0.039	0.040
	(0.028)	(0.028)	(0.030)	(0.030)
Wealth quintile (base = 1)				
2	-0.043	-0.043	0.080	0.080
	(0.059)	(0.059)	(0.055)	(0.055)
3	-0.069	-0.071	0.111	0.112
	(0.061)	(0.061)	(0.059)	(0.058)
4	-0.151*	-0.154*	0.072	0.075
	(0.062)	(0.063)	(0.064)	(0.065)
5	-0.195**	-0.197**	0.070	0.072
	(0.069)	(0.069)	(0.068)	(0.067)
Equipment owned	-0.044	-0.044	0.030	0.031
	(0.027)	(0.027)	(0.035)	(0.035)
Tropical Livestock Unit	-0.155*	-0.155*	0.070	0.070
	(0.066)	(0.066)	(0.048)	(0.048)
Region (base = South)				
Kigali	-0.290	-0.288	0.206	0.204
	(0.212)	(0.213)	(0.106)	(0.106)
West	0.024	0.025	-0.085	-0.086

	(0.059)	(0.059)	(0.071)	(0.071)
North	0.044	0.045	0.106	0.105
	(0.061)	(0.061)	(0.083)	(0.083)
East	-0.096	-0.095	0.226**	0.225**
	(0.086)	(0.087)	(0.086)	(0.085)
Generalized residuals		-0.017		0.014
		(0.055)		(0.079)
Constant	2.054***	2.053***	1.177***	1.178***
	(0.095)	(0.094)	(0.149)	(0.150)
N	1190	1190	867	867

***, **, *: statistically significant at respectively 1%, 5%, or 10% significance level. Standard errors in parenthesis. Columns (i) and (ii) report the estimation of the treatment effect on the number of months during which households purchased beans. Column (i) reports the estimates calculated with the Zero-inflated Poisson model, while column (ii) reports the results of the Zero-inflated Poisson model with control function method. Columns (iii) and (iv) report the results of the regression on the quantity of beans (in kg) purchased per month by the households. Column (iii) reports the coefficients calculated through the OLS regression, while column (iv) reports the coefficient of the control function approach. N is the size of the sample, which is composed of households who grew at least one climbing bean variety in 2015.

9 Figures

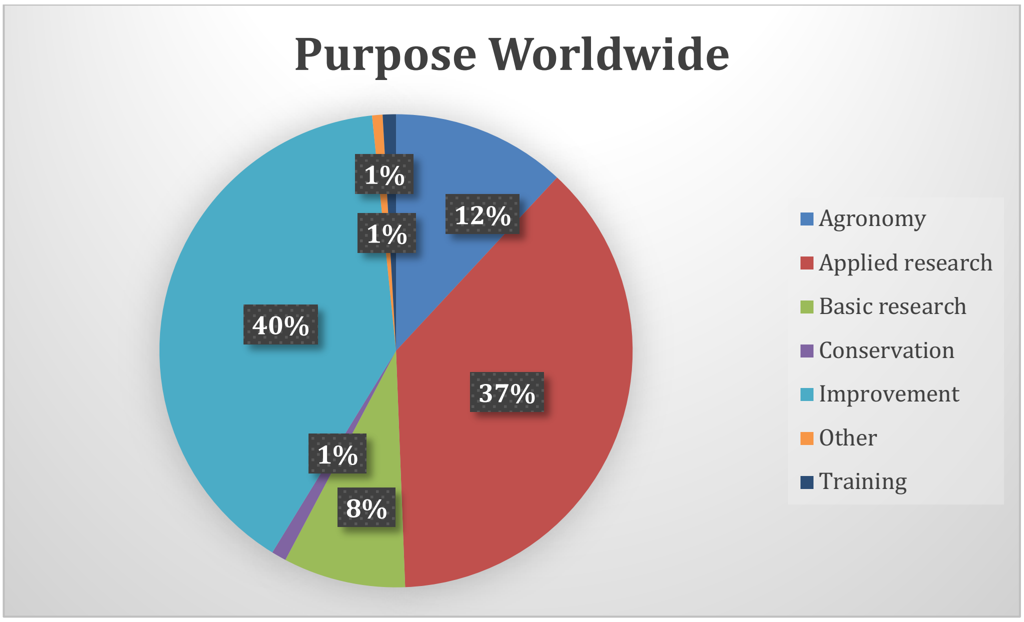


Figure 1. Use of bean accessions distributed worldwide (1978-2018). Source: International Center for Tropical Agriculture

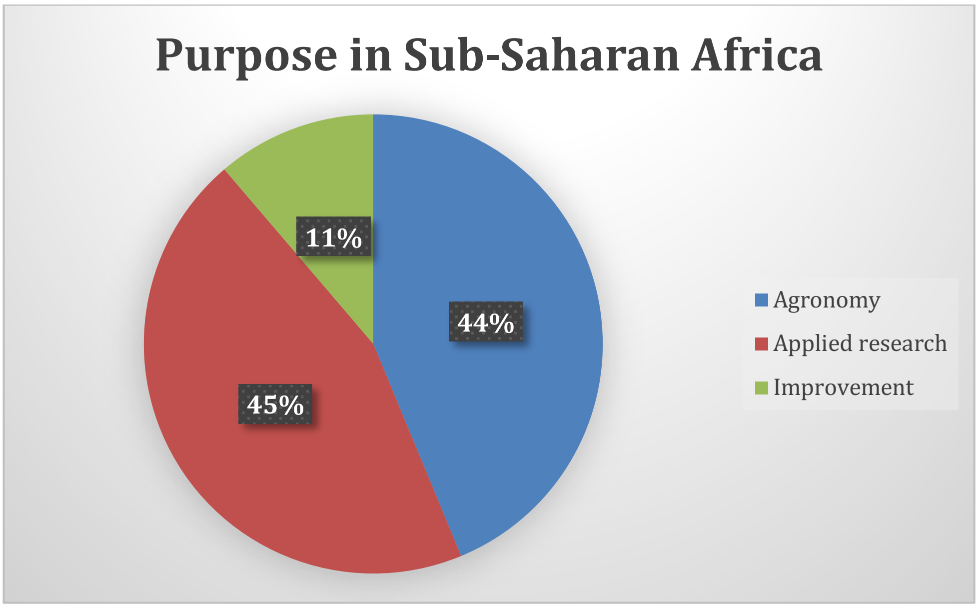


Figure 2. Use of bean accessions distributed in Sub-Saharan Africa (1978-2018). Source: International Center for Tropical Agriculture

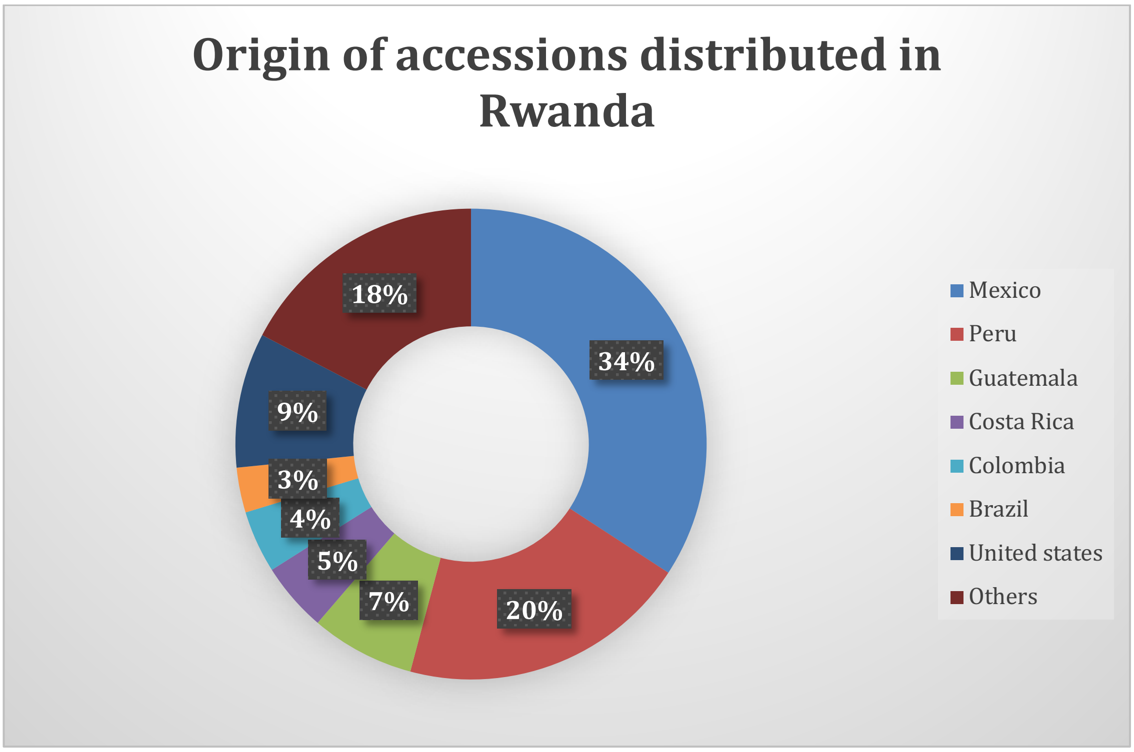


Figure 3. Countries of origin of accession distributed in Rwanda (1978-2018). Source: International Center for Tropical Agriculture

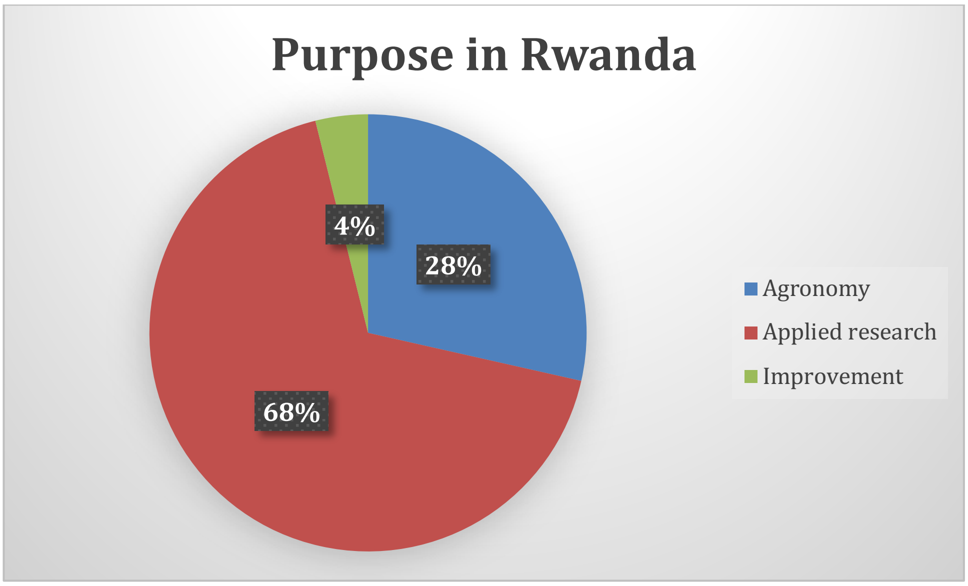


Figure 4. Use of bean accessions distributed in Rwanda (1978-2018). Source: International Center for Tropical Agriculture

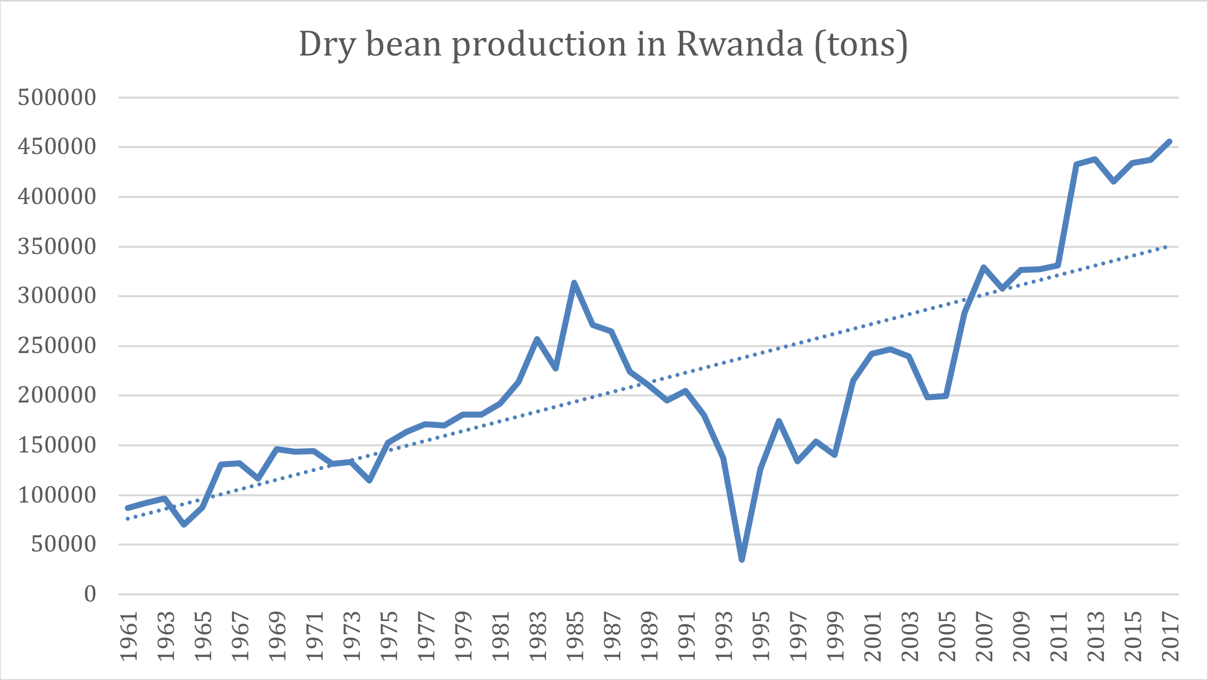


Figure 5. Production of dry beans in Rwanda, (1961-2017)**. Source: FAOSTAT data on crops production**

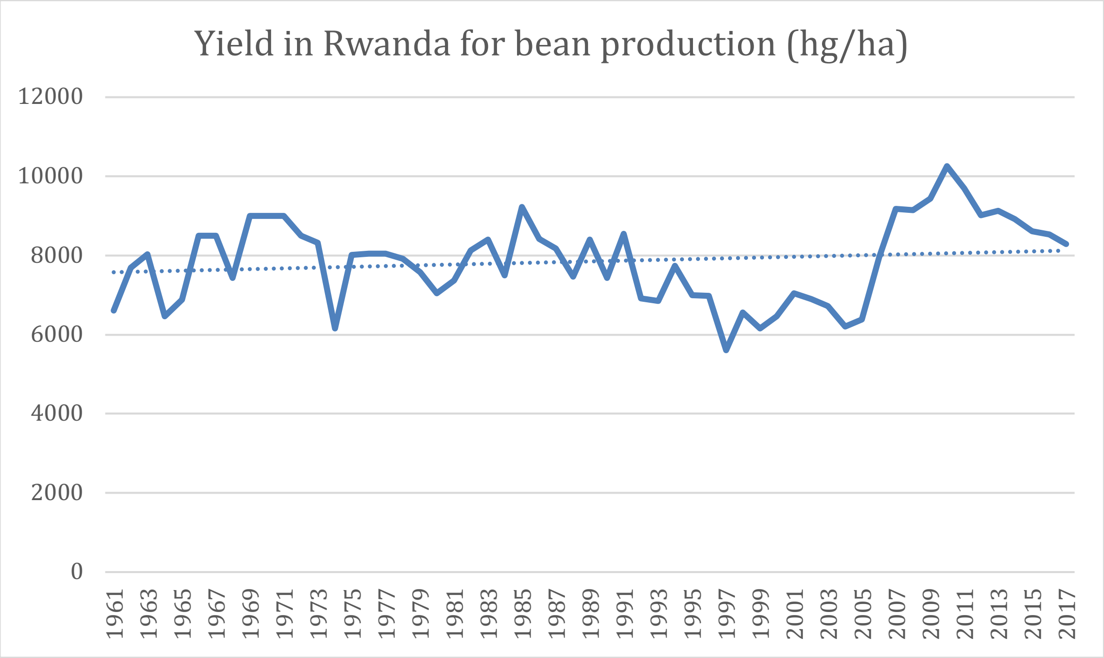
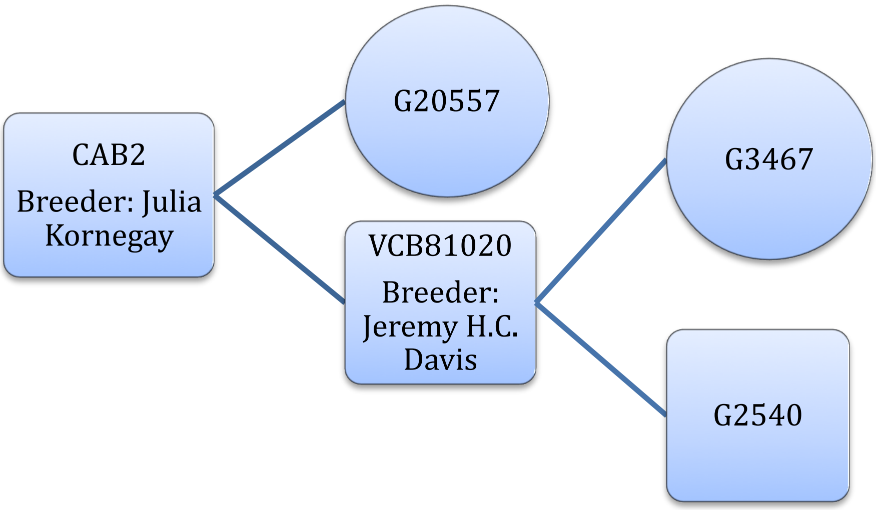


Figure 6. **Yield from the production of dry beans in Rwanda,** (1961-2017)**.** Source: FAOSTAT data on crops production

10 Annex: pedigrees of iron-biofortified varieties

CAB 2



Characteristics of CAB2

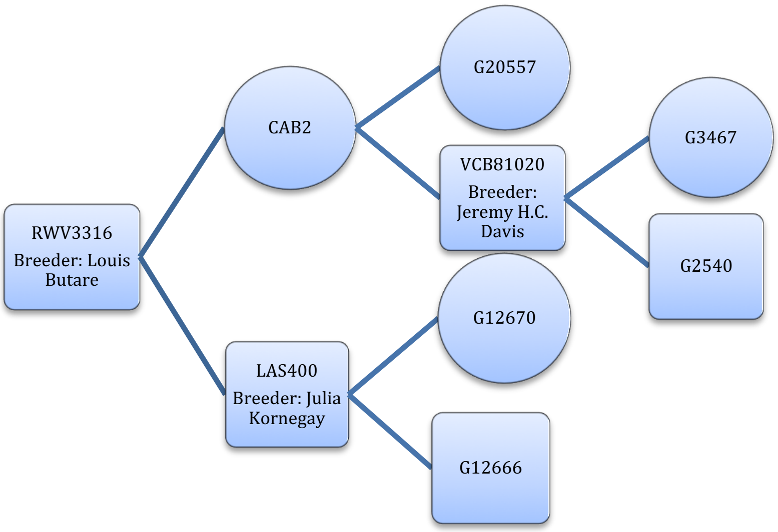
Color	Growth habit	Yield potential	Adaptation	Iron Content	Maturity
White	Climber	3t/ha	High altitude	76 ppm	115 days

Information on the varieties coming from the genebank

	G20557	G3467	G2540
Genus	Phaseolus	Phaseolus	Phaseolus
Species	Vulgaris	Vulgaris	Vulgaris
100 seed weight	31.3	37	21
Growth habit	Bush-indeterminate	Climbing	Climbing
Use	Dry bean	Dry bean	Dry bean

Country	Kenya	Mexico	Congo
Altitude		1575	
Type of material	Bred-line	Landrace	Landrace
Core collection	No	No	No
Seed color	Cream, purple	Cream, black	White
Seed shape	Elongated	Rounded	Rounded
Seed brightness	Intermediate	Intermediate	Intermediate
BCMV reaction	Resistant	Susceptible	Susceptible
Epoasca reaction	Susceptible	Susceptible	Susceptible
Protein	T	S	S

RWV 3316



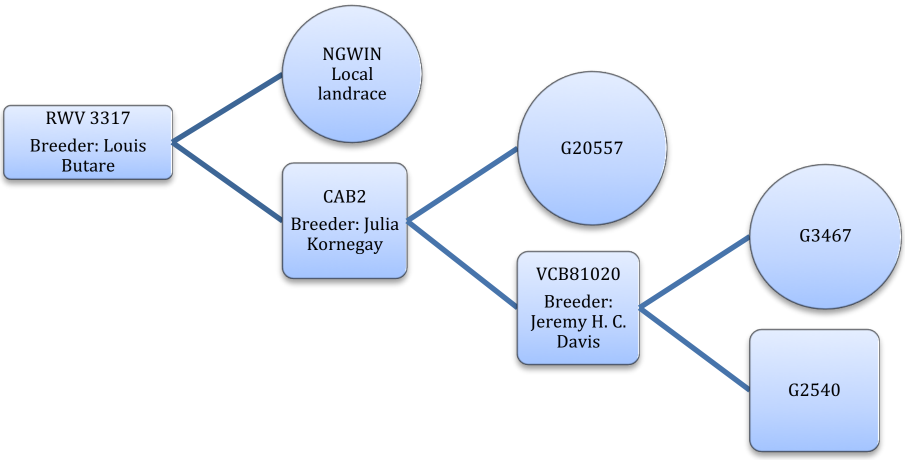
Characteristics of RWV 3316

Color	Growth habit	Yield potential	Adaptation	Iron Content	Maturity
Red	Climber	4t/ha	High altitude	92 ppm	110 days

Information on the varieties coming from the genebank

	G20557	G3467	G2540	G12670	G12666
Genus	Phaseolus	Phaseolus	Phaseolus	Phaseolus	Phaseolus
Species	Vulgaris	Vulgaris	Vulgaris	Vulgaris	Vulgaris
100 seed	31.3	37	21	85	43.3
Growth habit	Bush-	Climbing	Climbing	Climbing	Climbing
Use	Dry bean	Dry bean	Dry bean	Dry bean	Dry bean
Country	Kenya	Mexico	Congo	Colombia	Colombia
Altitude		1575			2000
Type of	Bred-line	Landrace	Landrace	Landarace	Landrace
Core	No	No	No	No	No
Seed	Cream, purple	Cream, black	White	Red	Cream, red
Seed	Elongated	Rounded	Rounded	Rounded	Elongated
Seed	Intermediate	Intermediate	Intermediate	Intermediate	Opaque
BCMV	Resistant	Susceptible	Susceptible	Susceptible	Susceptible
Epoasca	Susceptible	Susceptible	Susceptible	Susceptible	Susceptible
Protein	T	S	S	C	C

RWV 3317



Characteristics of RWV 3317

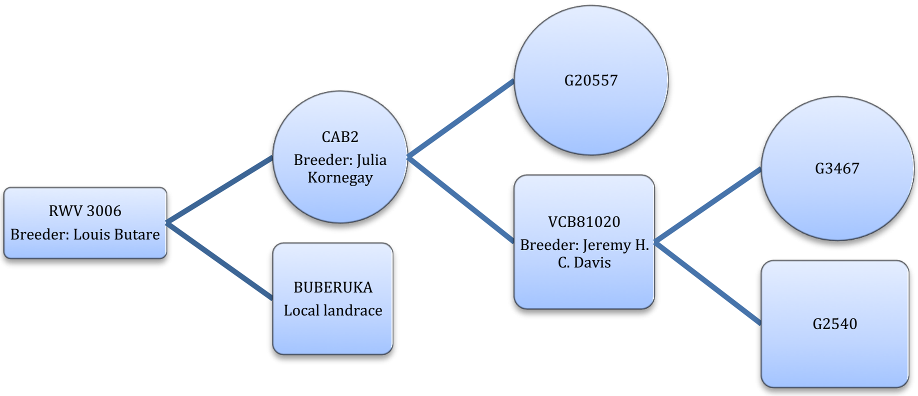
Color	Growth habit	Yield potential	Adaptation	Iron Content	Maturity
Red	Climber	4t/ha	High altitude	74 ppm	110 days

Information on the varieties coming from the genebank

	G20557	G3467	G2540
Genus	Phaseolus	Phaseolus	Phaseolus
Species	Vulgaris	Vulgaris	Vulgaris
100 seed weight	31.3	37	21
Growth habit	Bush-indeterminate	Climbing	Climbing
Use	Dry bean	Dry bean	Dry bean
Country	Kenya	Mexico	Congo
Altitude		1575	
Type of material	Bred-line	Landrace	Landrace
Core collection	No	No	No
Seed color	Cream, purple	Cream, black	White
Seed shape	Elongated	Rounded	Rounded
Seed brightness	Intermediate	Intermediate	Intermediate
BCMV reaction	Resistant	Susceptible	Susceptible

Epoasca reaction	Susceptible	Susceptible	Susceptible
Protein	T	S	S

RWV 3006



Characteristics of RWV 3006

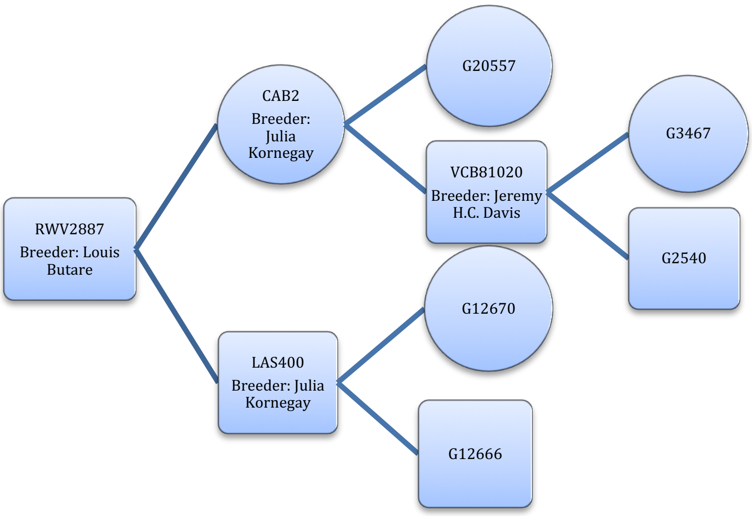
Color	Growth habit	Yield potential	Adaptation	Iron Content	Maturity
White	Climber	4t/ha	Mid to low altitude	76 ppm	110 days

Information on the varieties coming from the genebank

	G20557	G3467	G2540
Genus	Phaseolus	Phaseolus	Phaseolus
Species	Vulgaris	Vulgaris	Vulgaris
100 seed weight	31.3	37	21
Growth habit	Bush-indeterminate	Climbing	Climbing
Use	Dry bean	Dry bean	Dry bean
Country	Kenya	Mexico	Congo
Altitude		1575	
Type of material	Bred-line	Landrace	Landrace
Core collection	No	No	No
Seed color	Cream, purple	Cream, black	White
Seed shape	Elongated	Rounded	Rounded

Seed brightness	Intermediate	Intermediate	Intermediate
BCMV reaction	Resistant	Susceptible	Susceptible
Epoasca reaction	Susceptible	Susceptible	Susceptible
Protein	T	S	S

RWV 2887



Characteristics of RWV 2887

Color	Growth habit	Yield potential	Adaptation	Iron Content	Maturity
Dark red	Climber	4t/ha	Mid to high altitude	85 ppm	110 days

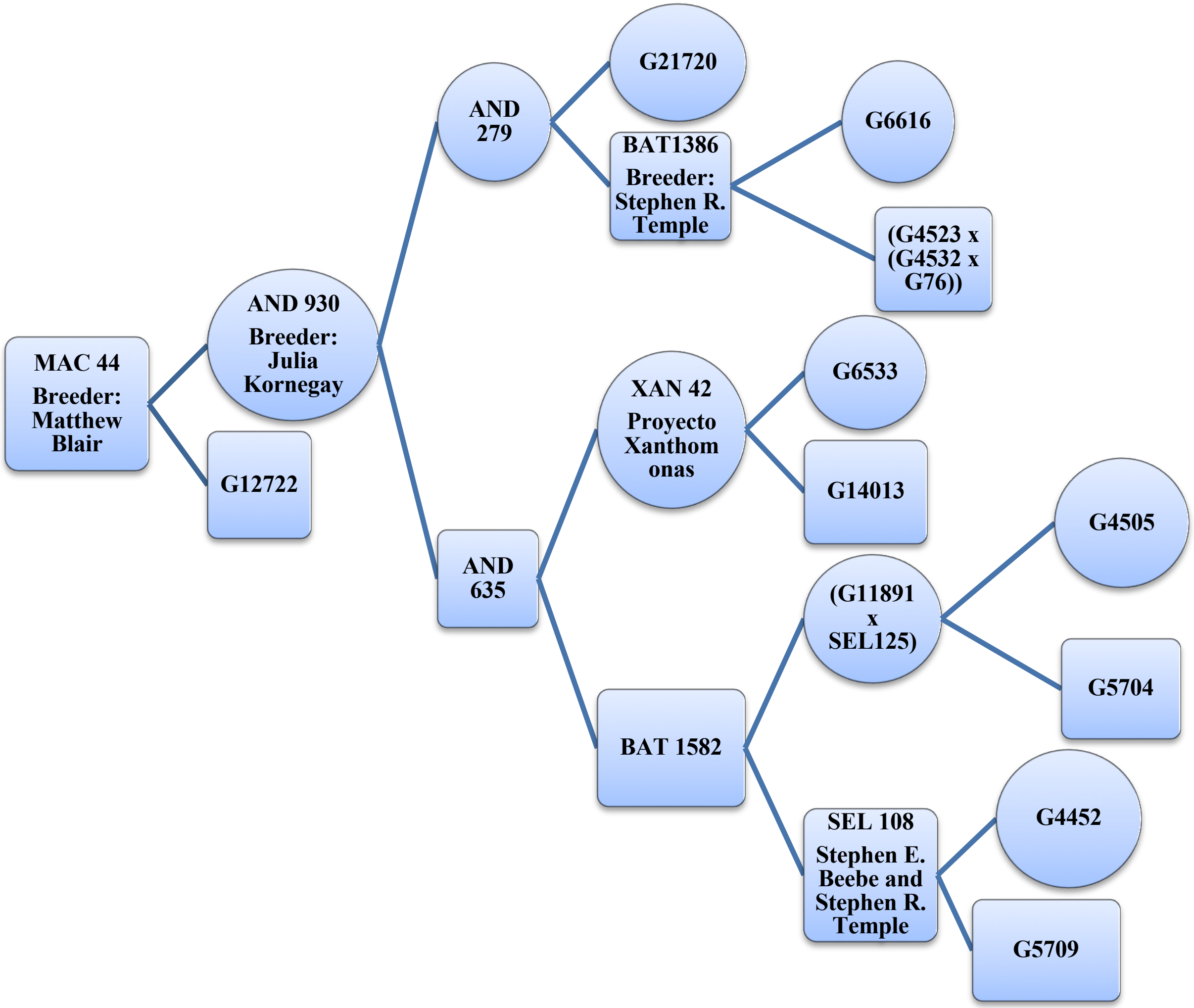
Information on the varieties coming from the genebank

	G20557	G3467	G2540	G12670	G12666
Genus	Phaseolus	Phaseolus	Phaseolus	Phaseolus	Phaseolus
Species	Vulgaris	Vulgaris	Vulgaris	Vulgaris	Vulgaris
100 seed	31.3	37	21	85	43.3
Growth habit	Bush-	Climbing	Climbing	Climbing	Climbing
Use	Dry bean	Dry bean	Dry bean	Dry bean	Dry bean
Country	Kenya	Mexico	Congo	Colombia	Colombia
Altitude		1575			2000
Type of	Bred-line	Landrace	Landrace	Landrace	Landrace
Core	No	No	No	No	No
Seed	Cream, purple	Cream, black	White	Red	Cream, red
Seed	Elongated	Rounded	Rounded	Rounded	Elongated
Seed	Intermediate	Intermediate	Intermediate	Intermediate	Opaque

BCMV	Resistant	Susceptible	Susceptible	Susceptible	Susceptible
Epoasca	Susceptible	Susceptible	Susceptible	Susceptible	Susceptible
Protein	T	S	S	C	C

MAC 44 – MAC 42*

*MAC 44 and MAC 42 have the same pedigree but differ in their genealogy.



Characteristics of MAC 42

Color	Growth habit	Yield potential	Adaptation	Iron Content	Maturity
Sugar	Climber	4t/ha	Mid to high altitude	91 ppm	85 days

Characteristics of MAC 44

Color	Growth habit	Yield potential	Adaptation	Iron Content	Maturity
Red mottled	Climber	4t/ha	Mid to low altitude	78 ppm	84 days

Genealogy of MAC 42

(- CMC (F2)-CMC-CMC-C07-CMC-3 W-(M)W-(M)W)

Genealogy of MAC 44

(- CMC (F2)-CMC-CMC-C25-CMC-3 W-(M)W-(M)W)

Reading the genealogy

MC stands for "Massal composition". Massal selection refers to the traditional method of selecting suitable reproductive material from the best plants.

C, W, Z are letters used to show CIAT's station where the reproduction of the beans was conducted.

C stands for CIAT's station of Palmira

W stands for CIAT station of Darien

Z stands for CIAT stations of Popayan.

M means that breeders did not select the material from the best plans but used all the material coming from a certain plot.

C represents the gamete. This is used when breeders conduct individual selection. The number next to C, corresponds to the number of the plant that is chosen in the breeding process.

Example for MAC44

The breeding program that led to MAC44 lasted nine generations. From the first until the fourth generation, breeders, working in Palmira, chose the plants through a Massal Selection. In the fifth generation, breeders selected only one of the plants, the number 25, and used about five-six pods to take out the seeds used to plant the sixth generation. In the sixth generation, breeders did one more time a Massal Selection, while in the seventh they selected pods only from the third plant. Finally, in the last two generations, which took place in Darien, breeders used all the material coming from a certain plot, without doing any selection. This is because after a certain amount of generations, the traits (normally the color) that breeders are wishing to have is already reached and stabilized and there is almost no risk of segregation.

Information on the varieties coming from the genebank

	G12722	**G21720**	**G6616**	**G4523**	**G76**	**G6533**	**G14013**	**G11891**	**G4505**	**G5704**
Genus	Phaseolus	Phaseolus	Phaseolus	Phaseolus	Phaseolus	Phaseolus	Phaseolus	Phaseolus	Phaseolus	Phaseolus
Species	Vulgaris	Vulgaris	Vulgaris	Vulgaris	Vulgaris	Vulgaris	Vulgaris	Vulgaris	Vulgaris	Vulgaris
100 seed weight	60	39	38.3	43.6	49	40	44	40	30	33
Growth habit	Climbing	Bush	Bush	Bush	Bush	Postrate-intermediate	Bush	Bush	Bush	Bush
Use	Dry bean	Dry bean	Snap bean	Dry bean	Dry bean	Dry bean	Dry bean	Dry bean	Snap bean	Dry bean
Country	Colombia	Colombia	Dominican Republic	Colombia	United States	Brazil	Colombia	Mexico	United States	Peru
Altitude	2000					500				
Type of material	Commercial-variety	Commercial variety		Commercial variety	Commercial variety	Landrace	Bred-line	Bred-line		Commercial variety
Core collection	No		NO	NO	YES	NO	NO	NO	NO	NO
Seed color	Cream, red	Red, cream	Red, cream	Red, cream	Pink	Pink, red	Pink, red	Yellow	Brown, cream	Yellow
Seed shape	Rounded	Elongated	Rounded	Rounded	Kidney	Rounded	Elongated	Rounded	Elongated	Rounded
Seed brightness	Intermediate	Intermediate	Opaque	Intermediate	Intermediate	Opaque	Opaque	Intermediate	Intermediate	Intermediate
BCMV reaction	Susceptible	Susceptible	Variable	Susceptible	Resistant	Susceptible	Resistant	Susceptible	Resistant	Susceptible
Epoasca reaction	Susceptible	Resistant	Susceptible	Susceptible	Susceptible	Intermediate	Susceptible	Susceptible	Susceptible	Susceptible
Protein	T	T	T	T	T	T	T	T	T	T