The Roles of Formal and Informal Delivery Approaches in Achieving Fast and Sustained Adoption of Biofortified Crops: Learnings from the Iron Bean Delivery Approaches in Rwanda

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Abstract

Biofortification is the process of breeding improved varieties of key staple crops to deliver higher levels of vitamins and minerals. The aim of biofortification is to reduce micronutrient malnutrition, also known as hidden hunger, through the staple crops that rural poor households produce and consume the most. Scaling up of production and consumption of biofortified staples is expected to reduce micronutrient deficiencies, especially among vulnerable populations in Africa and Asia. In order to inform cost-effective scaling up approaches, it is important to learn from the efforts undertaken to date to deliver the planting material of biofortified crops. One such example is the delivery of iron bean varieties in Rwanda. Since their first introduction in this country in 2010, these varieties have seen widespread adoption. At the same time, several households have disadopted the varieties either permanently or temporarily at some point after their initial adoption. In this paper, we use duration models and nationally representative data on rural households' iron bean adoption history to understand household adoption, disadoption and readoption behavior. We find that initial iron bean adoption is driven largely by "supply push", i.e., seed delivery, as well as access to extension and adoption of iron bean varieties by others in the locality. We find disadoption to be driven mainly by bean decision-maker characteristics; households with female bean decision makers, and those with more educated and more experienced bean decision makers are significantly less likely to disadopt iron bean varieties. Significant determinants of readoption pertain to farmers' access to district markets and variety-specific characteristics. These findings can help inform development of sustainable and cost-effective scaling up approaches for iron beans in Rwanda, as well as for similar biofortified crops elsewhere.

1. Introduction

Agricultural technologies have the potential to improve the productivity of farmers throughout the world. Biofortified staple crops, which are developed using conventional plant breeding methods to deliver high levels of micronutrients, can also directly address micronutrient deficiency, or “hidden hunger,” thereby improving productivity and incomes for generations to come (Alderman et al., 2006). An example of biofortification is the introduction and dissemination of iron bean varieties in Rwanda, designed to reduce iron deficiency in the country. Iron deficiency is a common cause of anemia (Petry et al. 2016), and can result in impaired cognitive and motor development as well as fatigue and low productivity. In Rwanda, 38% of children under 5 and 17% of women of child-bearing age suffer from anemia (WHO 2015).

Nutrition research has proven the efficacy of iron beans in two different populations. In Mexico, primary school children showed improvements in iron status after consuming biofortified iron beans for 3.5 months (Haas 2014). In Rwanda, iron-deficient university women showed a significant increase in hemoglobin, ferritin, and total body iron after consuming biofortified beans for 4.5 months (Haas et al. 2016). Haas et al. (2016) also measured physical and cognitive performance as functional outcomes. Luna et al. (2015) showed that improvements in iron status were accompanied by a reduction in time spent in sedentary activity and Wenger et al. (2015) showed that improvements in iron status were accompanied by improvements on cognitive tasks related to attention and memory.

Iron beans are well-suited to address iron deficiency in Rwanda. Unlike industrially fortified processed foods, which most effectively address micronutrient deficiency in urban populations, biofortification reaches rural producer households more efficiently (Bouis and Saltzman 2017). Rwanda is a densely populated but predominantly rural country, where nearly 90% of the labor force works in agriculture (FAO 2015) and the vast majority of farmers grow beans (Asare-Marfo et al. 2016a). It also has the highest per-capita bean consumption of any country in the world (CIAT 2004). For these reasons, and its high rate of anemia, Rwanda was identified as the top-priority country for the introduction of iron beans (Asare-Marfo et al. 2013).

Given the suitability of Rwanda for the introduction of biofortified iron beans, after over a decade long collaboration between the national agricultural research and extension system

(NARES) of Rwanda, the Rwanda Agricultural Board (RAB), HarvestPlus, the global leader in the technology and policy of biofortification (Harvest Plus 2017) and the International Centre for Tropical Agricultural (CIAT), ten iron bean varieties were officially released for planting in Rwanda in two waves: four varieties released in 2010 and six in 2012.

Biofortification requires a one-time investment in plant breeding, after which the varieties can be disseminated, and once adopted, used for years by farmers (Bouis and Saltzman 2017). It can thus be a cost-effective approach to fight hidden hunger, especially if many households grow the varieties. Half a million farmers grew an iron bean variety for at least one cropping season between 2012 and 2015, with most initial adoption occurring in 2015 (Asare-Marfo et al. 2016a). Disadoption also occurred; only about half of households who adopted iron beans have grown the variety every season since they first adopted (Asare-Marfo et al. 2016a). Other households have either disadopted permanently or have grown the variety intermittently. The major driving factors behind these patterns of adoption are unknown, although formal and informal delivery of iron beans have played significant roles. The formal approaches used to disseminate iron bean seeds include direct sales through contracted agrodealers as well as through direct sales by HarvestPlus employees in the local markets and other delivery approaches managed by HarvestPlus. Informal dissemination consists of households giving away and selling iron bean grain from their harvest. Both types of networks are important; 41% of iron bean growers reported obtaining their first seeds from local markets and 23% from neighbors or friends (Asare-Marfo et al. 2016a).

This study uses duration models to examine the role of formal and informal delivery approaches in determining fast (i.e. taking place after few seasons of iron bean dissemination) and sustained (i.e. more continuous) iron bean adoption in Rwanda. Duration models estimate the time between two events occurring and have been used in the economics literature since Lancaster (1972). More recently, they have been used in the adoption literature to examine adoption timing of different agricultural technologies (Burton et al 2003; Abdulai and Huffman 2005; Matuschke and Qaim 2008; Finger and El Benni 2011; Odendo et al. 2011; Genius et al. 2013; Nazli and Smale 2016). In this study, duration models are used to explain the time between iron bean dissemination and adoption, between adoption and disadoption, and between disadoption and subsequent readoption. Variables related to formal and informal delivery approaches are included as covariates in the duration models in order to estimate their impact on the timing of adoption, disadoption and readoption.

Most studies consider adoption as static, i.e. whether a household does or does not use the technology in one period. This view fails to consider when the household first adopted and if it sustains its use of the technology. Using duration models to examine adoption timing (Burton et al 2003; Abdulai and Huffman 2005; Matuschke and Qaim 2008; Finger and El Benni 2011; Odendo et al. 2011; Genius et al. 2013; Nazli and Smale 2016) acknowledges that the adoption decision occurs over time, and that different factors affect adoption timing. Disadoption of agricultural technology is less commonly examined (Neill and Lee 2001; Hassen 2004; Wendland and Sills 2008; Tiller et al. 2010; An and Butler 2012; Gilligan et al. 2016) with only a handful of studies conducted in developing countries (Neill and Lee 2001; Hassen 2004; Wendland and Sills 2008; Gilligan et al. 2016). While discontinued use may not be the final decision, as households can readopt once again, or use the technology intermittently, studies of readoption or adoption cycling of agricultural technology are scant. Researchers have used duration models to study the cycling in and out of other types of states, such as poverty in China and Europe (Callens and Croux 2009; You 2011).

This study fills a gap in the adoption literature by determining the factors that affect adoption, disadoption, and readoption timing of iron bean varieties. These dimensions of adoption are important for technologies that need to be adopted over long periods to have a significant impact, such as iron beans. It identifies determinants of both faster and sustained adoption, which are necessary for the benefits of biofortification to be fully realized. Not only are agricultural technologies more profitable the faster they are adopted (Batz et al. 2003), it is also crucial for iron-deficient populations to access the varieties as quickly as possible. Improving childhood nutrition at early ages leads to higher levels of education and future income levels (Alderman et al. 2006).

This study determines the most efficient ways to disseminate biofortified seed to a wide population so the benefits of biofortification can be realized. Findings from this study can inform future dissemination and scaling up efforts for biofortified crops, which can be designed to target households who are more likely to adopt varieties quickly and continuously. This will result in faster take-up of the technologies, more sustained adoption, and potentially lower dissemination costs.

The next section of this paper provides background information on Rwanda geography and agriculture, as well as formal iron bean delivery approaches. Section 3 explains the theoretical model of farmer decision making over time. This is followed by a detailed description of the data in Section 4. Subsequently, Section 5 explains the empirical models which link the theoretical models to the data. Section 6 provides results. Finally, the last section concludes the paper with policy implications and suggestions for future research.

2. Background Information on Iron Bean Release and Dissemination

2.1. Rwanda Geography and Agriculture

Rwanda is a small, mountainous country with high population density in East Africa. Most of the population is rural and works in agriculture. Most of Rwanda has two growing seasons per year: Season A, which runs from September to February (NISR 2015) and Season B, which runs from March to June (NISR 2015). Rwanda has ten distinct agro-ecological zones, which are explained in more detail in section 5.3.2. Administratively, from largest unit to smallest, Rwanda is separated into five provinces, 30 districts, 416 sectors, 2,148 cells, and 14,837 villages (National Institute of Statistics Rwanda 2017).

Beans are widely grown and considered staple foods throughout the country (USAID 2011). Households grow several bean varieties, some bush and some climbing bean types. Climbing beans grow up right and require the use of stakes to achieve their high yield potential, while bush beans grow lower to the ground. Climbing beans are particularly popular at higher altitudes, such as in the northern part of the country, where the climate is colder and rainfalls are more abundant.

2.2. Iron Bean Release and Formal Dissemination

Of the ten iron bean varieties released in Rwanda, eight are climbing bean varieties and two are bush bean varieties. The varieties have different agronomic and consumption characteristics to accommodate diverse agro-ecological conditions and consumer preferences. Names and characteristics of the ten iron bean varieties are given in table 14 in the appendix.

Formal dissemination of iron bean varieties began in season 2012B and intensified over the next six growing seasons. Iron bean seed is first grown by contracted seed multipliers, who multiply iron bean foundation seed to produce certified seed. Seed multiplication began in 2012A and is located primarily in the Eastern province, where land is more available. The certified seed is then distributed to farmers through agrodealers, direct marketing in local markets, and through individualized delivery approaches called payback and seed swap. Agrodealers began selling iron bean seed in 2012B. They are authorized to market certified iron bean seed in seed packs ranging from 1 to 50 kgs. Contracts with agrodealers began in the Eastern province but are now heavily concentrated in Kigali, where agrodealer shops are more prevalent. Direct marketing, which also began in 2012B, reaches households in local markets, where they can purchase iron bean seed. Harvestplus and partners worked with individual farmers and cooperatives in payback, in which farmers were given iron bean seed for free in exchange for part of their harvested grain. Payback operated from 2013A to 2014B, after which it was replaced by seed swap. Seed swap is similar, except that farmers trade their local bean varieties for iron bean varieties at the start of the growing season.

To further promote iron bean awareness, a song about iron bean varieties was produced and released on November 6, 2014 (HarvestPlus 2014). The song was played on many radio channels and also in concerts. The music video accompanying this song can be found at: https://www.youtube.com/watch?v=fo6449Rd3I0.

3. Theoretical Framework of Adoption Timing

When examining the adoption decision, it is necessary to consider not only whether a household adopts, but when it adopts. A household will adopt when the benefit of adopting is greater than that of not adopting, and the benefit of adopting at that point in time is greater than the benefit of waiting to adopt after more information is obtained (Abdulai and Huffman 2005).

Microeconomic theory can explain why some households adopt earlier than others (Abdulai and Huffman, 2005; Fuglie 2001). Following the theory proposed by Jensen (1982), we assume that households are profit-maximizers but have asymmetric information about the technology. Differences in information and beliefs about the profitability of the technology explain why farmers adopt the technology at different times. Adoption is therefore a problem of decision making under uncertainty, where agents can learn about the technology, reducing their uncertainty. When a technology is first introduced, households do not know if it will be profitable, and thus wait to adopt until more information is gathered. At each time period, households make the trade-off between the expected net return of adopting and the discounted expected value of the next piece of information. In addition, they may be limited by constraints such as lack of cash or credit to purchase the new technology, or the technology may be unavailable.

The modeling approach here follows that of Karshenas and Stoneman (1993) and Abdulai and Huffman (2005). The time T net present value of adopting at time t is defined as:

$$R_{it} = -P_t + \int_t^{\infty} g(.) \exp[-r(T-t)]\, dT \tag{3}$$

Where R_{it} is the net present value of adoption for household *i* at time *t*, P_t is the price of the technology paid by the household, *g(.)* represents the per-period benefits of the technology, which depend on household characteristics, technology characteristics, knowledge about the technology, and how early the household adopts relative to other farmers. Finally, *r* is the real discount rate. The earlier the household adopts, the higher will be the total benefit. In order for adoption to occur at time t, R_i must be greater than the benefits of the traditional methods (the profitability condition), benefits must be maximized at time t (the arbitrage condition), and the technology must be available. The profitability condition identifies who will adopt and the arbitrage condition identifies the time period adoption will occur. The arbitrage condition is given by:

$$y_i(t) = \frac{d[R_{it}\exp(-rt)]}{dt} \le 0 \tag{4}$$

Where y_i is the discounted net real present value of the technology. Its stochastic form is:

$$y_i(t) + \mu_i \le 0 \tag{5}$$

Where μ_i is an error term assumed to be independent of y_i and invariant across households over time. The probability of adoption in the time interval $[t, t+h]$ for farmer i who has not already adopted is given by $\lambda_i(t)$, the hazard rate:

$$\lambda_i(t) = \text{prob}[\, y_i(t) + \mu_i \leq 0] = V[y_i(t)] \tag{6}$$

Households maximize profits by readjusting decisions regarding which varieties and other technologies to use each season. After adopting, households decide whether or not to continue growing the variety the next season, and so on, assuming that planting material remains available. Households gain more information about the performance of the variety when grown under their specific conditions. Households incorporate this additional information when updating the decision to grow the variety the following season. This theoretical framework can therefore also be applied to the decision to discontinue growing, and readopting the variety.

4. Data

4.1. Study Data

The data used in this study are nationally representative of bean producers in Rwanda and were collected in two stages. The first stage occurred in May and June 2015, at the beginning of the 2015B cropping season, and consisted of a listing exercise and listing community survey. These surveys provided information about iron bean adoption patterns within villages over time. A subset of households interviewed in stage one were reinterviewed in stage two to obtain detailed information about household characteristics and iron bean adoption. The second stage included the main household survey and main community survey and was implemented in September 2015, at the end of the same cropping season.

For the listing exercise, 120 representative villages were selected with assistance from the National Institute of Statistics of Rwanda and all households in the selected villages were interviewed, totaling 19,575 households[1]. The survey asked households if they had ever grown an iron bean variety and if so, they were asked follow up questions including year first adopted, source of original planting material, bean color and type (bush vs. climber), and adoption

[1] More information on sampling methodology is available in Asare-Marfo et al. 2016a

history[2]. This survey also collected GPS coordinates of all households interviewed. The listing community survey asked village leaders about iron bean adoption and popular bean varieties in the village.

The main household survey was administered to a subsample of 12 households per village[3]. In total, 1,397 households were interviewed[4]. When possible, six iron bean adopters and six non-adopters were selected randomly in each village. In villages with fewer than six iron bean adopters, all adopters were sampled and non-adopters were randomly selected to obtain a total of 12 households. The main household survey interviewed the main bean decision maker about household composition, bean farming decision making, asset ownership and housing characteristics. It also collected detailed information on season 2015B bean cultivation and on iron bean varietal adoption history. The main community survey interviewed village leaders on village characteristics, services and amenities related to education, health and market access, extension, crop prices, adoption of iron beans, and the presence of formal iron bean delivery approaches in the village.

4.2. Additional Data

We use HarvestPlus data on formal iron bean dissemination collected for each cropping season and delivery approach to estimate farmer proximity to delivery approaches. Using household geolocations and those for agrodealers and seed multipliers, we compute the distance from households to these delivery approaches. For direct marketing, payback and seed swap, geographic coordinates are not available and we use dummy variables to indicate the administrative units where the delivery took place. Additional spatial variables, created by combining household geographical coordinates and various GIS datasets, are included in the analysis.

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[2] Survey enumerators showed seed samples of all iron bean varieties to farmers to facilitate variety identification.
[3] One of the 120 villages sampled in the listing exercise did not have any bean growers. Households from the remaining 119 villages were resampled for the main household survey.
[4] One household had to be dropped due to missing observations, so the sample for this study is 1,396.

5. Empirical Models

5.1. Duration Modeling of Decision Making

The conceptual framework above explains that households will adopt at different times. In this framework, the probability of adopting in any given period, given that the household has not already done so, is represented by the hazard rate. Hazard rates are modeled empirically using duration models. Duration models focus on the conditional probability of an event occurring given that it has not already occurred, and not on the unconditional probability of a specific event happening (Kiefer 1988). Duration models analyze the time it takes for households to transition between two states. Table 1 provides descriptions of the different states and units of analysis for the adoption, disadoption and readoption models.

Table 1: Model states

Model	State 1 Beginning	State 2 Beginning	Units of Analysis Included in Model
Adoption	2012B: First season of widespread iron bean dissemination	Season of first adoption of an iron bean variety	All households
Disadoption	Season of first adoption of an iron bean variety	Season of first disadoption of the same iron bean variety	Households who have adopted an iron bean variety
Readoption	Season of first disadoption of an iron bean variety	Season of first readoption of the same iron bean variety	Households who have disadopted an iron bean variety

The adoption model examines timing from the beginning of intensive iron bean dissemination in 2012B to adoption[5]. Adoption is defined as the first time the household grows any iron bean variety. Households that adopted prior to 2012B cannot be included in this analysis, since they already transitioned to state 2 before 2012B. We use two alternative approaches to examine early (pre-2012B) adoption. First, logit and probit models analyze determinants of early adoption, where the dependent variable equals one for those who adopted

[5] State one begins in 2012B because variables pertaining to delivery approaches are not available before this time period.

prior to 2012B, which corresponds to 3.5% of bean producing households, and zero otherwise; second, the baseline hazard model without covariates is estimated to examine the overall time-pattern of adoption from pre-2010 to 2015B. The disadoption model estimates the time between the first season a household grows an iron bean variety to the first season it discontinues its use. This model only includes households who have grown at least one iron bean variety. Finally, the readoption model estimates the time between the first season a household disadopts a variety and the first season it readopts it. This model only includes households who have disadopted at least one iron bean variety.

The exit time, T, is the time it takes to transition from state one to state two. The exit time has a cumulative distribution function $F(t) = \Pr(T \leq t)$, where *t* is a specific time period, and a conditional probability density function $f(t) = \Pr(T = t \mid T \geq t)$. The hazard rate can be represented by these two functions. The hazard rate represents the probability that a household adopts in the next time interval, given that it has not yet adopted. The hazard rate h(t) is thus:

$$h(t) = \lim_{h \to 0} \frac{F(t+h) - F(t)}{h} \times \frac{1}{1 - F(t)} = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{S(t)} \qquad (7)$$

Since we are interested in identifying the factors that affect adoption timing, we specify a Cox proportional hazard model. This model analyzes the impact of covariates on the hazard rate, meaning how they affect the probability of adopting in each time period. The proportional hazard rate for household *i* is:

$$h_i(t, X_{it}, \beta) = h_0(t) * \exp(X_{it}\beta) \qquad (11)$$

where h_0 is the baseline hazard function, X_{it} is a vector of explanatory variables that shift the hazard rate multiplicitavely, and β is the vector of parameters to be estimated. The baseline hazard function models the time dependence of adoption, estimating how adoption changes over time without the effect of covariates. The hazard time of household *i* is therefore a function of the baseline hazard and covariates (Matushcke and Qaim 2008). Adoption, disadoption, and readoption are each modeled separately, have their own hazard function, estimated coefficients, and beginning and end states.

5.2. Estimation

Household adoption, disadoption and readoption are modeled using discrete time duration analysis because households make farming decisions at the beginning of each growing season. Discrete duration data is set up in household-period format (Jenkins 2008). Each household has several observations; one per growing season between state one and state two (see table 1). The data includes a sequence variable, called t_i, that measures the passage of time and captures the time dependence of adoption. For each model, $t_i = 1$ at the start of state one, and increases by one unit for each cropping season that passes until stage two is reached. In the adoption model, the dependent variable is initially set to zero, and will change to one the cropping season the household transitions to state two, i.e. first adopts. For households who never adopt, the dependent variable is equal to zero for all seasons. For example, in the adoption model, $t_i = 1$ corresponds to season 2012B. If we assume that the household adopts in 2015B, then it will have seven observations. The dependent variable takes a value of zero for all observations from $t_i = 1$ to $t_i = 6$; for $t_i = 7$ the dependent variable equals 1.

Discrete duration models are estimated through maximum likelihood techniques, typically logit or complementary log-log models (Jenkins 2008). The complementary log-log model is used for estimation in this paper. It is the discrete-time analog to the continuous-time proportional hazard model, meaning that the exponentiated model coefficients can be interpreted as hazard rates (Jenkins 2008).

The baseline hazard function can have different functional forms, representing different forms of time dependence of adoption. For the adoption model, we use the three most common functional forms: log time, a cubic polynomial function of time, and season-specific dummy variables (Jenkins 2008). For the disadoption and readoption models, using season-specific dummy variables is not a feasible approach because for some seasons there is no transition to state two. For instance, a household grew a variety for 11 seasons before disadopting, but none disadopted after eight, nine, or 10 seasons; therefore, the time dummies that correspond to t = 10 and t = 11 are dropped. In situations such as these, Carter and Signorino (2010) recommend not using time dummy variables; the log time and cubic polynomial functions are therefore used. The most appropriate functional form is chosen based on Akaike Information Criteria (AIC). Standard errors are robust to heteroskedasticity and are clustered at the village level.

5.3. Model Variables and Descriptive Statistics

5.3.1. Definitions and Descriptive Statistics of Adoption Patterns

We consider a household to be an adopter if it has ever grown an iron bean variety in at least one season, a disadopter if it has discontinued use of the variety, and a readopter if it grows a variety again after disadopting. Table 2 shows the percentage of households in each category.

Table 2: Percentage of adopters, disadopters, and readopters

Decisions	All households %	Adopters %	Disadopters %
Adoption	29.41		
Disadoption	17.07	59.46	
Readoption	3.57	13.07	23.14
Number of observations	1,396	577	266

Note: 70.59% of households never adopted iron beans. Every disadopter is also an adopter and every readopter is also an adopter and a disadopter.

Among bean producers in Rwanda, about 29% are adopters, 17% disadopters, and 4% readopters. Most adopters (about 60%) are also disadopters, and 13% are also readopters. About 23% of disadopters are also readopters, meaning that most disadopters disadopt permanently.

Iron bean adoption is not even among varieties. Table 3 shows iron bean adoption by variety. Over half of adopted iron bean varieties are RWR2245. The second most popular variety is MAC44.

Table 3: Iron bean adoption by variety

Variety	Adoption of iron bean varieties %
RWR2245	52.44
MAC44	17.49
RWV3316	8.17
RWV3317	5.11
RWV1129	3.96
RWR2154	1.76
CAB2	2.98
RWV2887	1.83
MAC42	2.84
RWV3006	3.41
Number of observations	691

Prior to 2013A, less than 2% of the population grew an iron bean each season (table 4). Adoption began to increase steadily after 2012B, which is when most iron bean dissemination began. The significant increase after 2013A could be attributed to the emergence of the payback. Regressions investigate the contributors to increased adoption over time.

Table 4: Iron bean adoption by season

Season[6]	Bean growing households that grew an iron bean %
2010A	1.09
2010B	1.18
2011A	1.09
2011B	1.43
2012A	1.79
2012B	1.92
2013A	3.56
2013B	5.77
2014A	6.59
2014B	10.35
2015A	10.51
2015B	16.69
Number of observations	1,396

About 57% of iron bean varieties have been disadopted (table 5). Disadoption occurs most frequently after one season; 44.46% of varieties are grown for only one cropping season while 8.77% of disadoption occurrs after the variety has been grown for two seasons. Only a small percentage of varieties are disadopted after being grown for more than two seasons.

[6] .8317% of the sample grew an iron bean prior to 2010A, but we do not have data on which seasons these households grew the varieties prior to 2010A.

Table 5: Iron bean disadoption and timing of disadoption by season, conditional on adoption

Disadoption of iron beans	Iron beans grown by households %
No	43.48
Yes	56.63
Number of seasons the variety was grown before disadoption	
1 Season	44.46
2 Seasons	8.77
3 Seasons	1.87
4 Seasons	.65
5 Seasons	.59
6 Seasons	.10
7 Seasons	.02
11 Seasons	.17
Number of observations	691

Most iron bean varieties are never readopted once disadopted (table 6). When readopted, they are most often readopted after only one season of discontinued use. A very small percentage of disadopted varieties are readopted after more than one season of discontinued use. In sum, if a household disadopts or readopts an iron bean variety, it typically does so quickly, usually in the following season. In general, the more time that passes, the less likely it is that a household will disadopt or readopt.

Table 6: Iron bean readoption and timing of readoption by season, conditional on disadoption

Readoption of iron beans	Iron beans disadopted by households %
No	80.90
Yes	19.10
Number of seasons the variety was discontinued before readoption	
1 Season	16.39
2 Seasons	.82
3 Seasons	.46
4 Seasons	.94
7 Seasons	.49
Number of observations	308

5.3.2. Variable Descriptions

Factors expected to influence the timing of adoption, disadoption, and readoption decisions relate to proximity to iron bean dissemination, household demographics and assets, access to markets and information, agroecological zone, and experiences growing iron beans.

These are represented by the X vector in equation (11). Table 7 provides names and descriptions of all covariates, and indicates whether they are time-varying.

Table 7: Variable names and descriptions for covariates of adoption, disadoption, and readoption models

Variable Category	Variable Name	Variable Description	Time Varying
Dissemination	direct markets	Number of direct marketing approaches in the sector	Yes
Dissemination	payback	Someone in the village participated in payback	Yes
Dissemination	seed swap	Someone in the village participated in seed swap	Yes
Dissemination	agrodealers	Distance to nearest agribusiness, in meters	Yes
Dissemination	multipliers	Distance to nearest seed multiplier, in meters	Yes
Dissemination	adoption rate	Previous-season village adoption rate of iron beans	Yes
Dissemination	heard song	Respondent has heard iron bean song	Yes
Demographic	gender	Gender of main bean decision maker, 1= female	No
Demographic	education	Education level of main bean decision maker 0 = no schooling 1 = some primary education 2 = some secondary education or more	No
Demographic	experience	Years of bean farming experience of main bean decision maker	No
Demographic	household size	Number of household members	Yes
Demographic	share 0-5	Household share age 0-5	Yes
Demographic	share 6-14	Household share age 6-14	Yes
Demographic	share women	Household share of women of child-bearing ag, 15-49	Yes
Asset	wealth quint[7]	Wealth index quintile 1 2 3 4 5	No
Asset	ag. equipment	Count of agricultural equipment (range 0-5)	No
Asset	TLU[8]	Tropical livestock unit	No
Asset	cultivated land	Land cultivated in 2015B, in meters squared	No
Asset	member in farmer association	Household is in a farmer association	Yes[9]

[7] A wealth index was created using polychoric principal components analysis (pca) to capture household wealth. It includes housing characteristics, access to water, and household assets.

[8] The tropical livestock unit (TLU) variable reflects livestock ownership where 1 cow = .5, 1 sheep = .1, 1 goat = .1, 1 pig = .2, 1 chicken = .01, 1 rabbit = .02.

[9] Households were asked the year in which they joined an organization and if they are still a part of that organization. If the household is no longer part of the organization, it is assumed they were only members for one year, since there is no additional information about how long they were members.

Market & Info.	city distance	Distance to nearest city of at least 50,000 people, in kilometers	No
Market & Info.	local market	% of village households who sell beans at a local market	No
Market & Info.	district market	% of village households who sell beans at a district or urban market	No
Market & Info.	road distance	Distance to nearest road[10] from household, in meters	No
Market & Info.	ext. percent	% of village households who obtain information from extension	No
Market	bean price	Bean price in 2015B (average of price in time of high and low availability)	No
Agroecological	zone	Agro-ecological zone 1: Le Mayaga et Bugessera peripheriques 2: Le Plaine de Bugarama 3: Le Plateau Central 4: Le arriere pays de Cyangugu 5: Le bord du lac Kivu 6: Le cones et hautes plaines volcaniques 7: Le crete Zaire-Nil 8: Le cretes at plateau bordant les savanes 9: Les hautes terres de Burebuka 10: Les savanes de L'Estet du Bugesera Central	No
Experience	iron awareness	Farmer was aware that this was an iron bean variety when they first saw or heard about it	No
Experience	recycled	Original planting material came from recycled grain of another farmer	No
Experience	variety	Iron bean variety grown	No

Dissemination variables relate to both formal and informal iron bean delivery approaches. Proximity to formal approaches is captured by distance from the household to the nearest agrodealer and seed multiplier in each season, the number of direct marketing approaches in the household's sector each season, and variables indicating whether any household in the village has ever participated in payback or seed swap. While seed multipliers are not a delivery approach that disseminates iron bean seed to growers directly, households may still gain information about and access to the varieties by being in close proximity to multipliers. Finally, a variable capturing whether the household has heard the iron bean promotional song is included in this category because it increases awareness of iron beans. Informal dissemination is captured by the

[10] Refers to classified national and district roads (Rwanda Transport Authority 2008)

previous-season iron bean adoption rate, which is the total number of adopters in the village in the previous season divided by the total village population. Squared terms for distance to agrodealers, distance to seed multipliers, and iron bean adoption rate are included as well to determine whether these variables affect adoption at a decreasing rate.

It is expected that each of these variables will lead to faster iron bean adoption because they will make iron bean seeds more readily available, thus reducing the costs of obtaining them, and will provide households with greater information regarding iron beans. According to our conceptual framework, households with greater access to information about the varieties are expected to adopt sooner, since the benefit of waiting for more information falls, all else held equal. The expectation that access to information about the varieties promotes adoption is consistent with the literature (Feder et al. 1985; Minshi 2004; Matuschke and Qaim 2009; Foster and Rosenzweig 2010; Conley and Udry 2010; Wollni and Andersson 2014).

Household demographic characteristics include the gender, education level and bean farming experience of the main bean decision maker, as well as the household size, percentage of the household that is under 5, percentage that is 6-15, and percentage that is women of child-bearing age. It is expected that households whose main bean decision maker has more education will adopt more quickly (Feder et al. 1985; Odendo et al. 2005; Abdulai and Huffman 2005; Matuschke and Qaim 2008; Wendland and Sills 2008; Foster and Rosenzweig 2010). More educated farmers may have a better ability to assess and process information about iron bean varieties, allowing them to make better farming decisions. A similar effect is expected for households whose main bean decision maker has more experience growing beans. The expected effect of gender is ambiguous. Male farmers may have greater access to resources that are difficult to measure, but because women in Rwanda often perform the majority of bean-farming activities (Asare-Marfo et al. 2016b), female farmers may have more knowledge relevant to bean variety selection. The shares of women of childbearing age, young and older children are included because these populations are more likely to benefit from higher iron consumption. These households may therefore value the iron content of iron beans more highly and be more likely to adopt.

Household assets include a wealth index that enters the model in quintiles, livestock ownership measured in tropical livestock units, ownership of agricultural equipment, land cultivated in 2015B, and whether the household is or has been a member of a farmer association. It is expected that farmers with greater wealth, agricultural assets, livestock, agricultural equipment, and cultivated land will adopt faster than others (Feder et al. 1985; Foster and Rosenzweig 2010; Nazli and Smale 2016). Better-off farmers are likely to have a greater ability to bear risk, as well as greater access to resources and information, allowing them to adopt more quickly. In addition, households with members involved in a farm organization, which is considered a social asset, are expected to be more likely to adopt that variety due to knowledge spillovers.

Market and information variables include the average price of beans in the village in 2015B, the percentage of households in the village who access extension, and variables related to market access (distance to roads and cities of 50,000 inhabitants, and the percentage of village households who sell in local and district markets). Bean prices and extension access are obtained from the community survey and measured at the village level to avoid endogeneity of these variables. High bean prices may promote adoption, particularly for households who sell beans. Greater market access and access to extension are positively correlated with adoption in the literature (Feder et al. 1985; Foster and Rosenzweig 2010; Minten et al. 2013; Wollni and Andersson 2014). Market opportunities can make it easier for households to obtain information about the varieties, and obtain iron bean planting material. The percentage of households in a village who sell in local markets and district markets are used as a proxy for market orientation. Access to district markets may provide households with more significant sales opportunities than local markets, so these are included separately. Distance from the household to a main road and the nearest city of at least 50,000 inhabitants are included to control for proximity to markets and services. Living closer to a main road may reduce the time needed to reach the markets. Also, agrodealers may visit households near main roads more frequently than those who live remotely.

Agro-ecological zone is included to control for agricultural potential and suitability of iron bean varieties. Zones vary by soil type, altitude, terrain, and rainfall. Le cones et hates plaines volcaniques (zone 6), Le crete Zaire-Nil (zone 7), and Les hates terres de Burebuka (zone 9) are mountainous regions. The remaining zones are primarily flat or hilly. Despite these differences, beans are a staple food in every zone (USAID 2011). Households who live in zones where iron beans perform well may have faster rates of adoption due to greater productivity and thus profitability of the beans. Favorable growing conditions are associated with technology adoption (Feder et al. 1985; Foster and Rosenzweig 2010). Different varieties may see faster adoption in different zones, depending on how different varieties perform under different agro-ecological conditions and the popularity of climbing vs. bush bean, although our model would not capture this differentiation.

The models examining household behavior after iron bean adoption include the variables described above and additional variables related to a household's experience growing the varieties, as has been done in the literature on disadoption (Wendland and Sills 2008). Additional variables included in the disadoption and readoption models are: household awareness that the variety was high in iron when it first heard of the variety, whether the original planting material was obtained from another farmer's recycled grain, and a categorical variable differentiating between the ten iron bean varieties. Awareness of high iron content may make households more inclined to continue growing the variety since these households are aware of an additional benefit of the variety that other households would not be aware of[11]. The expected effect of using recycled grain as planting material is ambiguous, but relates to its impact on profitability of the variety. Certified seed from formal dissemination may be of higher quality and provide higher yield than second-generation seed. Alternatively, households may be more likely to receive grain from friends of varieties that are well-suited to their particular growing conditions, and they can benefit from greater knowledge about the variety. In this case, households who first grew iron beans from recycled grain would be less likely to disadopt iron bean varieties. Certain iron bean varieties may be disadopted or readopted more frequently than others; this could be true if a farmer did not achieve the expected yield. Alternatively, some varieties may be more available through formal or informal delivery approaches, facilitating readoption.

Households with more knowledge of the benefits of iron beans or who value high iron content will be less likely to disadopt the varieties; this may be true of female adopters and adopters with more education, access to extension, and households with larger shares of women and children. Education, bean farming experience, and extension may also improve management practices, allowing households to achieve higher yields more quickly. This expectation is

[11] Awareness of a variety's iron content could influence initial adoption as well, but since this information is available only for households that had heard of each iron bean variety, it cannot be included in the model that includes non-adopters.

consistent with results found in the literature (Wendland and Sills 2008; Hassen 2004). It is expected that proximity to formal and informal dissemination is likely to make households less likely to disadopt iron beans, as these will make it easier for households to obtain the seeds season after season; this is consistent with the findings of Gilligan et al. (2012). Households with greater market access should have greater incentive to sustain adoption assuming iron bean varieties are easily marketable. Finally, agro-ecological variables are expected to have an effect, as they will likely influence the yields of the varieties. If households obtain good yields from iron beans, they are more likely to continue to grow the varieties than if they obtain poor yields. Disadoption is thus expected in regions where iron beans are less suitable; however, some varieties will be better suited to certain regions than others, so regressions at the variety level would capture this effect more clearly.

5.3.3. Descriptive Statistics

Descriptive statistics of covariates show some systematic differences between adopters and disadopters (table 8). For time-varying variables, the statistics are calculated from 2015B data.

Table 8: Descriptive statistics for covariates of adoption, disadoption, and readoption models

Variable Category	Variable Name	Mean (SD) adopters	Mean (SD) non-adopters	P-value that means are equal
Dissemination	direct markets	.08 (.48)	.075 (.48)	.951
Dissemination	payback	.13 (.34)	.071 (.26)	.005
Dissemination	seed swap	.03 (.18)	.042 (.20)	.513
Dissemination	agrodealers	18,590.24 (12014.11)	19,160.86 (10564.28)	.463
Dissemination	multipliers	16,905.32 (14923.39)	21,909.69 (20142.09)	.0000
Dissemination	adoption rate	21.20 (14.65)	11.910 (9.42)	.0000
Dissemination	heard song	.47 (.50)	.415 (.49)	.123
Demographic	gender	.63 (.48)	.629 (.48)	.985
Demographic	education			
	no schooling	.23 (.42)	.359 (.48)	.000
	some level of primary	.66 (.47)	.583 (.49)	.017
	some secondary education or more	.10 (.30)	.057 (.23)	.026
Demographic	experience	25.71 (15.07)	27.902 (16.86)	.063
Demographic	household size	5.08 (2.02)	4.742 (2.03)	.014
Demographic	share 0-5	.15 (.16)	.163 (.18)	.426
Demographic	share 6-14	.25 (.20)	.226 (.20)	.070
Demographic	share women	.25 (.15)	.241 (.16)	.367
Assset	wealth quint			
	1	.16 (.37)	.217 (.41)	.050
	2	.16 (.37)	.218 (.41)	.034
	3	.18 (.38)	.212 (.41)	.156
	4	.25 (.43)	.180 (.38)	.029
	5	.26 (.44)	.174 (.38)	.004
Asset	ag. equipment	1.34 (.79)	1.193 (.77)	.015
Asset	TLU	.50 (.74)	.412 (.96)	.267
Asset	cultivated land	5681.25 (8344.16)	4301.89 (7294.62)	.016
Asset	member in farmer association	.19 (.39)	.148 (.36)	.150
Market	city distance	37.96 (22.38)	36.59 (19.73)	.388
Market	local market	42.92 (37.35)	42.764 (34.65)	.952
Market	district market	4.70 (14.24)	6.564 (17.12)	.060
Market	road distance	1470.70 (1315.53)	1329.133 (1363.22)	.181
	ext. percent	.68 (.26)	.637 (.28)	.032
Market	bean price	346.88 (71.48)	366.553 (75.64)	.000
Agroecological	zone			
	1	.11 (.31)	.07 (.26)	.064

	2	.02 (.13)	.03 (.17)	.108
	3	.35 (.48)	.33 (.47)	.555
	4	.01 (.10)	.02 (.15)	.033
	5	.03 (.16)	.04 (.19)	.274
	6	.02 (.12)	.05 (.21)	.003
	7	.06 (.24)	.12 (.33)	.001
	8	.18 (.39)	.10 (.30)	.000
	9	.05 (.22)	.14 (.35)	.000
	10	.19 (.39)	.11 (.31)	.010
Experience	iron awareness	.25 (.43)	n/a	n/a
Experience	recycled	.33 (.47)	n/a	n/a
Experience	variety	descriptive stats shown in table 3		
Number of obs.		577	819	

Note: Values for time-varying variables are given for 2015B. For adoption rate, this refers to the 2015A village adoption rate (because values are lagged one season). The statistics for iron awareness and recycled refer to the first iron bean varieties grown by households.

On average, households have less than one direct marketing approach in the sector in which they live, with no statistically significant difference between adopters and non-adopters. Approximately 13% of adopters and 7% of non-adopters live in villages where payback took place; these figures are 3% and 4% for seed swap, respectively. The difference between iron bean adopters and non-adopters is statistically significant for payback but not seed swap. Households live over 15 km on average from agribusinesses and seed multipliers; adopters live closer than non-adopters to seed multipliers but not to agribusinesses. The average iron bean village adoption rate was almost twice as high in 2015A for adopters as non-adopters; 21% and 12% respectively. Finally, over 40% of households have heard the iron bean song, with no significant difference between adopters and non-adopters.

Most bean decision makers are women with some level of primary education, and have on average 26 years of bean farming experience. The decision makers of adopters are less likely to have no education and more likely to have at least some secondary education than those of non-adopters. Adopters have slightly larger household sizes than non-adopters, but both groups have about five members on average. Household composition does not vary significantly between adopters and non-adopters. Iron bean adopters are more likely to be in the top two wealth quintiles and less likely to be in the bottom two compared to non-adopters. Adopters own more agricultural equipment and cultivate more land on average than non-adopters. Livestock ownership and farm organization membership do not vary significantly between adopters and non-adopters.

Households live almost 40 km away from cities of 50,000 people on average, and less than 1.5 km from roads, with no differences between adopters and non-adopters. About 43% of households sell in local markets compared to less than 10% in district markets. On average, adopters live in villages where a smaller percentage of households sell in district markets. About two-thirds of households access extension; adopters live in villages with slightly more access to extension than non-adopters. The bean price ranges between 340 and 370 RWF (about $.45); iron bean adopters live in villages with lower bean prices on average than non-adopters. Finally, the most populous zone is Le Plataeu Central (zone 3), and the population of adopters vs. non-adopters varies in several of the zones. Le cretes at plateau bordant les savanes (zone 8) and les savanes de L'Estete du Bugesera Central (zone 10) have higher shares of adopters than non-adopters, while Le arriere pays de Cyangugu (zone 4), Le cones et hautes plaines volcaniques (zone 6), Le crete Zaire-Nil (zone 7), and Les hautes terres de Burebuka (zone 9) have larger shares of non-adopters.

About 25% of adopting households knew that the first iron bean variety they grew was high in iron when they first heard of it. About a third of adopting households obtained the initial planting material for their first iron bean variety from a recycled source.

6. Results

6.1. Adoption

6.1.1. Early Adopter Logit Results

To examine early (pre-2012B) adoption, we estimate logit and probit models where the dependent variable is adopting an iron bean variety prior to 2012B. Variables on household demographics, assets, market and information access, and agroecological zones are controlled for. The logit model has better model fit based on AIC, so logit model results are presented below in Table 9.

Table 9: Logit model results examining early (pre-2012B) adopters, n = 1396

		Wald chi2 (3) =	127.410	
		Prob > chi2 =	0.000	
		Pseudo R2 =	0.234	
Log pseudolikelihood =	-187282.450			
adopt early	Odds Ratio	Robust Std. Err.	P>|z|	Sig. Level
gender (1=female)	2.091	0.599	0.010	**
education (base = no education)				
some primary education	1.991	0.956	0.151	
some secondary education or more	4.084	2.803	0.040	**
bean experience (years)	1.019	0.015	0.185	
household size	0.972	0.100	0.779	
share 0-5	7.002	9.537	0.153	
share 6-15	8.331	10.422	0.090	*
share women	1.569	2.281	0.757	
wealth quintile (base = 1)				
2	0.203	0.161	0.044	**
3	1.148	0.849	0.852	
4	1.721	1.027	0.363	
5	3.376	1.954	0.036	**
ag. equipment (qty)	1.799	0.293	0.000	***
TLU	0.931	0.102	0.513	
cultivated land (m^2)	1.000	0.000	0.037	**
member in farmer association	0.629	0.359	0.416	
city distance (km)	1.000	0.000	0.883	
district market (%)	1.014	0.010	0.165	
local market (%)	1.002	0.004	0.664	
road distance (m)	1.000	0.000	0.154	
ext. percent	0.594	0.423	0.464	
bean price (RWF)	1.001	0.002	0.561	
zone				
1	5.176	3.301	0.010	**
2	0.701	0.650	0.702	
6	0.394	0.421	0.384	
7	0.184	0.212	0.142	
8	6.884	5.087	0.009	***
9	1.194	1.005	0.833	
10	2.563	2.710	0.374	
_cons	0.000	0.001	0.000	

Note: ***, **, * denote significance at 1%, 5%, 10% respectively. Zone 3 is the base zone because it is the most populated. Zones 2, 4, and 5 are combined into one category because zone 4 perfectly predicts non-adoption. These zones are all in the same Livelihood Zone as classified by USAID (2011).

Households that have a bean decision maker who is female and has at least some secondary education are over two and four times more likely to be early adopters than households with a bean decision maker who is male and has no education, respectively. Households in the second wealth quintile are less likely to be early adopters and households in the richest quintile are more likely to be early adopters than those in the lowest wealth quintile. Households with more land and more agricultural equipment are also more likely to be early adopters. Finally, households in Le Mayaga et Bugesera peripheriques (zone 1) and Le crete et plateau bordant les savanes (zone 8) are over five and six times more likely to be early adopters than households in Le Plateau Central (zone 3), the most populous zone. Both of these zones are flat, lowland zones that cover the area surrounding Kigali. Early adopters may have obtained early access to varieties by living near trial plots or other early forms of dissemination. Early adopters are geographically clustered; 68% are located in the Eastern province and over half of early adopters live in only four districts (Bugesera, Kirehe, Muhanga, and Nyagatare, which collectively make up only 17% of bean growers), which supports this theory.

6.1.2. Baseline Hazard Model

We examine adoption timing from pre-2010 to 2015B using a baseline hazard duration model with no covariates other than time dependence variables. Out of the functional forms for the baseline model that we tested, we determine that time dummy variables are the most appropriate way to capture time dependence based on AIC. Table 10 gives the maximum likelihood results for the cloglog baseline hazard model, with the hazard function modeled as a piece-wise function using season dummy variables.

Table 10: Complementary log-log results for baseline hazard model, n = 16660

adopt	Coef.	Hazard Rate	Robust Std. Err.	P>t	Sig. Level
pre-2010	-4.785	0.008	0.341	0	***
2010A	-5.383	0.005	0.378	0	***
2010B	-5.968	0.003	0.718	0	***
2011A	-5.771	0.003	0.624	0	***
2011B	-5.016	0.007	0.437	0	***
2012A	-4.528	0.011	0.306	0	***
2012B	-4.949	0.007	0.344	0	***
2013A	-3.932	0.020	0.239	0	***
2013B	-3.408	0.033	0.216	0	***
2014A	-3.304	0.037	0.188	0	***
2014B	-2.863	0.057	0.195	0	***
2015A	-2.828	0.059	0.164	0	***
2015B	-2.307	0.100	0.125	0	***

Note: ***, **, * denote significance at 1%, 5%, 10% respectively. Standard errors and p values, and significance levels all correspondent to coefficient estimates. Hazard rates are also presented due to their more natural interpretation.

As seasons pass, the parameter estimates and hazard rates increase in almost every season, indicating an increasing adoption trend over time. The hazard rate in the baseline model is the probability that a household will adopt, given that it has not already adopted. From pre-2010 to 2011B, the hazard rate fluctuates and remains under 1%, meaning a probability of adoption of less than 1%. There are then large increases from 2011B to 2012A, followed by a drop from 2012A to 2012B, and another large increase from 2012B to 2013A. The hazard rate almost doubles from 2015A to 2015B, reaching a probability of adoption of about 10% for households that have not yet adopted.

6.1.3. Covariate Results

In order to understand what drives the changes in probability over time, covariates must enter the model. Table 11 shows the results of the initial adoption model with covariates, described in Setion 5.1. A negative coefficient on a covariate (and hazard rate less than 1) means that the variable has a negative effect on adoption while a positive coefficient (and hazard rate greater than 1) means that the variable has a positive effect on adoption.

Table 11: Complementary log-log results for adoption model, n = 8451

adopt	Coef.	Hazard Rate	Robust Std. Err.	P>t	Sig. Level
2012B	-6.077	0.002	0.783	0.000	***
2013A	-5.062	0.006	0.627	0.000	***
2013B	-4.837	0.008	0.582	0.000	***
2014A	-4.840	0.008	0.601	0.000	***
2014B	-4.465	0.012	0.517	0.000	***
2015A	-4.598	0.010	0.553	0.000	***
2015B	-4.151	0.016	0.576	0.000	***
direct markets (# in sector)	0.206	1.228	0.042	0.000	***
payback (1 = in village)	0.499	1.648	0.251	0.046	**
seed swap (1 = in village)	-0.521	0.594	0.485	0.283	
agrodealers (m)	0.000	1.000	0.000	0.311	
$agrodealers^2$ (m)	0.000	1.000	0.000	0.644	
multipliers (m)	0.000	1.000	0.000	0.088	*
$multipliers^2$ (m)	0.000	1.000	0.000	0.081	*
adoption rate	0.097	1.101	0.012	0.000	***
adoption $rate^2$	-0.001	0.999	0.000	0.000	***
heard song	0.006	1.006	0.175	0.974	
gender (1 = female)	0.117	1.125	0.154	0.446	
education (base = no education)					
some primary education	0.276	1.318	0.168	0.101	
some secondary education or more	0.385	1.470	0.264	0.144	
experience (years)	-0.005	0.995	0.005	0.339	
household size	0.045	1.046	0.043	0.291	
share 0-5	-0.485	0.616	0.438	0.268	
share 6-15	0.003	1.003	0.503	0.995	
share women	-0.282	0.755	0.362	0.436	
wealth quint (base = 1)					
2	0.123	1.131	0.239	0.608	
3	0.010	1.010	0.213	0.962	
4	0.403	1.496	0.191	0.035	**
5	0.307	1.359	0.237	0.195	
ag. equipment	0.217	1.242	0.130	0.094	*
TLU	-0.034	0.967	0.078	0.669	
cultivated land (m^2)	0.000	1.000	0.000	0.658	
member in farmer association	0.115	1.122	0.165	0.488	
city distance (km)	-0.004	0.996	0.005	0.420	
district market (%)	-0.012	0.988	0.005	0.026	**
local market (%)	-0.001	0.999	0.002	0.702	
road distance (m)	0.000	1.000	0.000	0.179	
ext. percent	0.868	2.383	0.263	0.001	***
bean price (RWF)	-0.001	0.999	0.001	0.204	
zone (base = 3)					
1	-0.058	0.944	0.274	0.832	
2	-1.435	0.238	0.519	0.006	***
4	-0.777	0.460	0.473	0.100	
5	-0.758	0.469	0.352	0.031	**
6	-0.977	0.376	0.364	0.007	***

7	-0.812	0.444	0.291	0.005	***
8	-0.319	0.727	0.299	0.285	
9	-1.036	0.355	0.331	0.002	***
10	0.140	1.151	0.369	0.704	

Note: ***, **, * denote significance at 1%, 5%, 10% respectively. Standard errors and p values, and significance levels all correspondent to coefficient estimates. Hazard rates are also presented due to their more natural interpretation.

The increasing value of the time-dummy coefficients shows that the probability of adopting increases as time passes, all else held equal. However, there is now less variation in the time dummies than there is when covariates are not in the model (see table 10), indicating that the passage of time does not explain adoption as much when other variables are included in the model.

Results show that exposure to direct marketing and payback, as well as past-season iron bean adoption rate are all determinants of adoption. An additional direct marketing approach in a household’s sector is correlated with over a 20% increase in the probability of adopting in any season. Living in a village where someone has participated in payback is correlated with an increase in the probability of adoption of more than 60% in all seasons. Distance to agrodealers and seed multipliers has no association with adoption; for seed multipliers, this is not surprising because iron bean seed is not marketed directly to households from seed multipliers. It is surprising, however, that distance to agrodealers is not correlated with adoption. Having had a seed swap in the village is also not correlated with greater probability of adoption. It is possible that seed swap began too recently prior to the survey to have sufficient time to have a significant impact on adoption. Another issue is that few villages were sampled that had experienced seed swap, which may have made it difficult to detect an impact. Households who have heard the song about iron beans are not more likely to adopt.

By one measure of market access, the percentage of farmers who sell in district markets, market access is negatively correlated with adoption. This is surprising. It is possible that households with lower levels of market access are more concerned with growing nutritious crops if they purchase little food. Other variables capturing market access (percentage of households who sell in local markets, distance to the nearest road and distance to the nearest city of 50,000 people) have not significant relationship on adoption. Access to extension, on the other hand, is positively correlated with faster adoption times; an additional percentage point of households that access extension is correlated with over a doubling of the probability of adoption in each season. Extension thus has a greater impact on adoption than proximity to delivery approaches. Bean price also has no impact on adoption, although this variable is a crude measure of actual bean prices; while bean prices change regularly in reality, this variable only captures the value in 2015B.

The number of agricultural tools that the household owns is correlated with faster adoption, but is significant at only a 10% level. Households in the fourth wealth quintile are also more likely to adopt. Other household characteristics are not correlated with adoption. This is surprising given the literature, which has found household asset characteristics to correlate with higher levels of adoption.

Finally, adoption is lower in the following agro-ecological zones than in Le Plateau Central: Le Plaine de Bugarama (zone 2), Le bord du lac Kivu (zone 5), Le cones et hates plaines volcaniques (zone 6), Le crete Zaire-Nil (zone 7), Le crete at plateau bordant les savanes (zone 8), and Les hautes terres de Burebuka (zone 9).

In sum, adoption is driven largely by access to extension, formal and informal dissemination. It is not clear whether this adoption is sustained, however, which is investigated in the next section.

6.3. Disadoption

The disadoption model examines determinants of iron bean disadoption, controlling for time dependence, and includes all households who have ever grown an iron bean variety that they did not disadopt prior to 2012B. If a household has grown more than one iron bean variety since 2012B, every variety the household has grown is included in the sample.

Table 12 displays results for the disadoption model described in Section 5.1. Time dependence is modeled using a cubic polynomial function of time, chosen based on AIC. A negative coefficient (and hazard rate less than one) indicates that the variable reduces the likelihood of disadoption. A positive coefficient (and hazard rate greater than one) means that the variable increases the likelihood of disadoption.

Table 12: Complementary log-log results for disadoption model, n = 1417

disadopt	Coef.	Hazard Rate	Robust Std. Err.	P>t	Sig. Level
t	8.383	4371.215	1.073	0	***
t_2	-2.024	0.132	0.316	0	***
t_3	0.116	1.123	0.020	0	***
direct markets (# in sector)	-0.017	0.983	0.037	0.65	
payback (1 = in village)	0.335	1.398	0.328	0.307	
seed swap (1 = in village)	-1.230	0.292	0.442	0.005	***
agrodealers (m)	0.000	1.000	0.000	0.029	**
agrodealers^2 (m)	0.000	1.000	0.000	0.015	**
multipliers (m)	0.000	1.000	0.000	0.016	**
multipliers^2 (m)	0.000	1.000	0.000	0.001	***
adoption rate	0.029	1.029	0.022	0.196	
adoption rate^2	0.000	1.000	0.000	0.319	
heard song	0.270	1.310	0.381	0.479	
gender (1 = female)	-0.481	0.618	0.171	0.005	***
education (base = no education)					
some primary education	-0.410	0.664	0.206	0.047	**
some secondary education or more	-1.084	0.338	0.429	0.012	**
experience (years)	-0.021	0.980	0.005	0	***
household size	0.069	1.072	0.057	0.221	
share 0-5	0.571	1.771	0.573	0.318	
share 6-15	0.370	1.447	0.596	0.535	
share women	0.096	1.100	0.635	0.88	
wealth quint (base = 1)					
2	-0.181	0.835	0.351	0.606	
3	-0.604	0.546	0.374	0.106	
4	-0.331	0.718	0.335	0.324	
5	-0.539	0.583	0.357	0.131	
ag. equipment (qty.)	0.201	1.223	0.134	0.133	
TLU	-0.261	0.770	0.136	0.054	*
cultivated land (m^2)	0.000	1.000	0.000	0.454	
member in farmer association	-0.359	0.699	0.197	0.069	*
city distance (km)	0.004	1.004	0.006	0.574	
district markets (%)	-0.001	0.999	0.006	0.82	
local markets (%)	-0.001	0.999	0.003	0.803	
road distance (m)	0.000	1.000	0.000	0.783	
ext. percent	0.036	1.037	0.382	0.925	
bean price (RWF)	0.000	1.000	0.002	0.877	
iron awareness	-0.116	0.890	0.189	0.539	
recycled	-0.192	0.826	0.185	0.3	
zone (base = 3)					
1	-0.435	0.647	0.329	0.186	
2	-1.088	0.337	0.674	0.107	
4	0.028	1.028	0.629	0.965	
5	-0.078	0.925	0.369	0.833	

6	0.877	2.403	0.566	0.122	
7	-0.579	0.560	0.459	0.207	
8	-0.336	0.714	0.364	0.356	
9	-0.354	0.702	0.472	0.452	
10	0.129	1.137	0.414	0.756	
variety					
MAC44	0.324	1.383	0.215	0.133	
RWV3316	-0.305	0.737	0.339	0.368	
RWV3317	0.230	1.259	0.292	0.431	
RWV1129	-1.034	0.356	0.402	0.01	**
RWR2154	-0.282	0.755	0.450	0.531	
CAB2	0.125	1.133	0.406	0.758	
RWV2887	0.471	1.602	0.402	0.241	
MAC42	-0.157	0.855	0.593	0.791	
RWV3006	0.799	2.223	0.348	0.022	**
_cons	-8.787	0.000	1.320	0	

Note: ***, **, * denote significance at 1%, 5%, 10% respectively. Standard errors and p values, and significance levels all correspondent to coefficient estimates. Hazard rates are also presented due to their more natural interpretation.

The high hazard rate on the time duration variable indicates that the probability of disadopting increases dramatically as households grow iron bean varieties for more seasons, but at a decreasing rate. Its high value could be partially due to the structure of the data: it is impossible for a household to disadopt a variety the same season that they adopt, so disadoption is never observed at t = 1. The data must be structured in this way in order to capture the effects of time-varying covariates on disadoption.

In general, disadoption is driven more by household characteristics than adoption is. Households whose bean decision maker is a female, and has more education and bean farming experience are less likely to disadopt in any time period. Households who own more livestock and have a member belonging to a farming association are also less likely to disadopt, though thess variables are only significant at the 10% level.

Having seed swap in the village makes households only about 30% as likely to disadopt a variety compared to households that have not had seed swap in their village. Other delivery channels have no effect on disadoption. Distance to agrodealers and seed multipliers have a precisely measured but very close to zero effect.

None of the market access variables are significant, nor is access to extension. Agroecological zone is also insignificant, meaning that disadoption of varieties is no more likely under different agroecological conditions.

Whether the household knew the variety was high in iron when household members first heard of it, and whether it got its initial planting material from someone else's recycled grain are not statistically significant in explaining disadoption. The variety RWV1129 is disadopted more slowly and RWV3006 is disadopted more quickly than RWR2245. Other iron bean varieties have a similar rate of disadoption as RWR2245.

6.4. Readoption

Some households grow iron bean varieties intermittently. Table 13 shows results for the readoption duration model described in Section 5.1. In this model, time dependence is modeled using a cubic polynomial function; this functional form was chosen based off of AIC.

Table 13: Complementary log-log results for readoption model, n = 768

readopt	Coef.	Hazard Rate	Robust Std. Err.	P>t	Sig. Level
t	5.094	163.075	1.588	0.001	***
t_2	-1.175	0.309	0.429	0.006	***
t_3	0.068	1.070	0.026	0.008	***
direct markets (# in sector)	0.061	1.063	0.161	0.706	
payback (1 = in village)	0.874	2.398	0.717	0.223	
agrodealers (m)	0.000	1.000	0.000	0.846	
$agrodealers^2$ (m)	0.000	1.000	0.000	0.998	
multipliers (m)	0.000	1.000	0.000	0.544	
$multipliers^2$ (m)	0.000	1.000	0.000	0.254	
adoption rate	0.003	1.003	0.049	0.951	
adoption $rate^2$	0.000	1.000	0.001	0.948	
heard song	0.407	1.503	0.392	0.299	
gender (1 = female)	-0.805	0.447	0.507	0.113	
education (base = no education)					
some primary education	-0.237	0.789	0.532	0.656	
some secondary education or more	-2.033	0.131	1.315	0.122	
experience (years)	0.013	1.013	0.024	0.577	
household size	0.083	1.086	0.166	0.619	
share 0-5	0.474	1.606	1.923	0.805	
share 6-15	-1.359	0.257	1.818	0.455	
share women	1.349	3.852	2.483	0.587	
wealth quint (base = 1)					
2	1.206	3.339	0.933	0.196	
3	0.107	1.113	0.965	0.912	
4	1.399	4.051	0.984	0.155	
5	0.333	1.395	0.958	0.728	
ag. equipment	0.249	1.282	0.383	0.516	
TLU	0.103	1.109	0.289	0.721	
cultivated land (m^2)	0.000	1.000	0.000	0.715	
member in farmer association	1.022	2.779	0.681	0.133	
city distance (km)	0.02900	1.030	0.020	0.145	
district market (%)	0.035	1.036	0.013	0.008	***
local market (%)	-0.003	0.997	0.007	0.682	
road distance (m)	0.000	1.000	0.000	0.734	
ext. percent	1.396	4.039	1.032	0.176	
bean price (RWF)	-0.002	0.998	0.004	0.550	
iron awareness	0.718	2.051	0.430	0.095	*
recycled	-0.513	0.599	0.485	0.291	
zone					
1	-0.396	0.673	0.808	0.624	
2, 4, 5	0.882	2.417	1.283	0.492	
6	-1.139	0.320	1.219	0.350	
7	1.772	5.883	1.022	0.083	*
8	1.465	4.330	0.969	0.130	
9	-1.579	0.206	1.324	0.233	
10	-1.722	0.179	1.124	0.126	

variety					
MAC44	-1.965	0.140	0.744	0.008	***
RWV3316	-1.296	0.274	1.281	0.312	
RWV3317	-3.440	0.032	1.706	0.044	
RWV1129	0.546	1.727	1.059	0.606	
RWR2154	0.901	2.463	0.645	0.163	
CAB2	0.585	1.795	1.410	0.678	
RWV2887	-0.821	0.440	1.000	0.411	
MAC42	-1.375	0.253	1.295	0.289	
RWV3006	-2.637	0.072	0.804	0.001	***
_cons	-10.612	0.000	3.265	0.001	

Note: ***, **, * denote significance at 1%, 5%, 10% respectively. Standard errors and p values, and significance levels all correspondent to coefficient estimates. Hazard rates are also presented due to their more natural interpretation. Swap and zone 2 perfectly predicted non-readoption. Swap is dropped and zone 2 is combined with zone 4 and 5, as these are in the same livelihood zone (USAID 2011)

The likelihood of readopting increases as time passes at a decreasing rate. Like in the disadoption model, the high hazard ratio of the t variable may be due to the structure of the data; readoption is never observed at t = 1 but is often observed at t = 2. Few other variables are significant in this regression. None of the delivery approaches has an effect on readoption. Female bean farmers with at least some secondary education are less likely to readopt in any time period, although these are significant only at 10%. Households who live in a village where a higher percentage of farmers sell in district markets are more likely to readopt; perhaps improved market access makes it easier to obtain seed. Households in agroecological zone 7 are less likely to readopt, but this is significant at only a 10% level. Varieties MAC44 and RWV3006 are less likely to be readopted than RWR2245.

7. Conclusions

Examining disadoption and readoption provides more insight into iron bean adoption patterns and determinants than simply looking at initial adoption alone. Initial adoption is driven primarily by direct marketing and payback, as well as the previous-season iron bean adoption rate in the village and access to extension. Disadoption, however, depends more on household characteristics; female farmers with higher levels of education and bean farming experience grow iron beans more continuously than other farmers. Integration with district markets makes households more likely to readopt, and two varieties (MAC44 and RWV3006) are less likely to be readopted than RWR2245.

The most commonly cited reason for households disadopting an iron bean is that it is low-yielding (42%), followed by seed not being available (10%) (Asare-Marfo et al. 2016b). Differences in disadoption and readoption of different varieties could thus be due to how well households like the varieties or to the availability of the varieties. Variety RWV3006 is more likely to be disadopted than RWR2245, while RWV1129 is less likely to be disadopted; MAC44 and RWV3006 are both less likely to readopted by households, given disadoption.

Overall, results indicate that some delivery approaches are highly significant in promoting adoption; direct marketing and payback increase likelihood of initial adoption while seed swap makes disadoption less likely. It is possible that an effect of seed swap on adoption would emerge after more seasons of data collection. Proximity to agrodealers and seed multipliers on the other hand, does not influence adoption. The release of the song promoting iron beans did not influence adoption patterns at all. Finally, informal iron bean dissemination and information networks represented by the previous-season iron bean adoption rate play a large role in initial adoption but no role in later adoption patterns. Results indicate that approaches to scale up dissemination should focus on direct marketing and seed swap, and that seed swap (and formerly payback) may be more successful in promoting sustained adoption than direct marketing. However, more precise data should be collected on the locations of these approaches in order to fully understand these effects.

Households with female bean decision makers are more likely to grow iron beans continuously; agencies disseminating biofortified seed may therefore wish to target these households for seed swap in the future. The role of education in determining initial adoption is not entirely clear: having some secondary education is correlated with being an early (pre-2012B) adopter, but is not otherwise correlated with initial adoption. However, education is correlated with more continuous adoption of iron beans. In order to help the households who would likely benefit the most from iron beans, efforts can be made to encourage low-education households to adopt more continuously. Finally, to reach households with higher shares of children or women of child bearing age, populations who would benefit from higher iron consumption, these households may have to be targeted directly, because there is no evidence that they are currently more likely to grow iron beans.

There are some limitations to this research based on the data that was available. It is likely that the effects of dissemination could be more precisely estimated if data on exactly when and where each delivery approach operated were available in every season. In addition, efforts were made to ensure accurate iron bean classification, but they are still largely dependent on households' ability to accurately identify varieties.

Future research could incorporate heterogeneity in results by including interaction terms in the regression. Separate models could also be run for different iron bean varieties to examine if different varieties have different determinants of adoption patterns. Duration analysis can also be modeled in more complex ways, such as by using a competing risks framework. This will be explored in future research.

Appendix

Table 14: Iron bean varieties

Variety	Bean Type	Year Released	Year Disseminated	Year of Intense Dissemination
RWR2245	Bush	2010	2011	2012
RWR2154	Bush	2010	2011	2012
MAC44	Climbing	2010	2011	2012
RWV1129	Climbing	2010	2013	2014
RWV3006	Climbing	2012	2012	2014
RWV3316	Climbing	2012	2012	2014
RWV2887	Climbing	2012	2013	2014
RWV3317	Climbing	2012	2013	2014
CAB2	Climbing	2012	2013	2014
MAC42	Climbing	2012	2013	2014

Note: This table was reproduced from Table 1 in Asare-Marfo et al. (2016a)

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