Estimating the impact of climbing bean adoption on bean productivity in Rwanda: Endogenous Switching Regression.

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Invited paper presented at the 5th International Conference of the African Association of Agricultural Economists, September 23-26, 2016, Addis Ababa, Ethiopia

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Abstract

This paper investigates the determinants of the decision to switch from cultivating bush to high yielding climbing beans and estimates the causal impact of adoption of climbing beans on productivity based a nationally representative sample of bean producing households. An endogenous switching regression model is used to account for the endogenous nature of adoption and accurately quantify the differences in productivity between climbing and bush bean technologies. Adoption of climbing bean varieties substantially increased over the past 15 years. Elevation, rainfall, and cropping systems are important determinants of adoption of climbing beans. Adoption of climbing beans increases productivity by 21 percent among adopters compared to 48 percent for non-adopters.

Keyword: Rwanda, climbing bean, adoption, and productivity effects

1. Introduction and motivation

Sub-Saharan Africa urgently needs improvements in agricultural productivity, as landholdings shrink due to population growth. This is particularly true for Rwanda where agriculture remains the primary source of livelihoods, levels of malnutrition and poverty are high, and populations continue to grow rapidly. Bean *(Phaseolus vulgaris* L.) is a food security crop for Rwanda, produced mainly on small-scale farms, with low inputs. It is a primary source of dietary protein among poor households and the second most important source of calories. Annual per capita bean consumption is about 40 kg (Graf, et al., 1991, Kalyebara and Buruchara, 2008, Blair, et al., 2010).

In the mid-1980's, declining bean productivity, caused by expansion into marginal areas, and slow dissemination of new varieties, led to bean production deficits, raising concerns about national food security (Graf, et al., 1991). This prompted researchers at the International Center for Tropical Agriculture (CIAT) and Rwanda Agriculture Board (RAB) --formerly Institute des Sciences Agronomiques du Rwanda (ISAR)-- to intensify research on climbing beans.

Climbing beans have the potential to produce an additional 100 pods per plant per season compared to bush beans, equivalent to 3.5 to 5 tons per hectare. In addition, climbing bean varieties create favorable micro-niches, which reduce fungal pathogen development that negatively affect bush bean productivity (Musoni, et al., 2001) and fixes more nitrogen to soil (Beebe, et al., 2012).

Since 1984, promotion of climbing bean cultivation in Rwanda has included breeding and selecting varieties suitable to the specific agro-ecological conditions of the low, medium, and high altitude zones (Graf, et al., 1991). Over 90 improved bean varieties have been released in Rwanda since the mid-1980s; two-thirds of which are semi-climbers or climbers (PABRA database[1]).

[1] Available at http://database.pabra-africa.org/

Dissemination revolved around development of an efficient seed system and teaching about alternative staking options to eliminate staking constraints (Graf, et al., 1991).

Despite significant research investment, evidence on adoption of climbing bean varieties is scanty and rigorous assessment of their impact on farm productivity is lacking. Most adoption and impact studies were conducted decades ago and rely on field trial data. They thus do not reflect the conditions under which typical farmers operate, focus on the distinction between improved and local varieties as opposed to bush and climbing, or fail to control for the endogenous nature of the adoption decision (Sperling and Muyaneza, 1995, Johnson, et al., 2003, Kalyebara and Buruchara, 2008). Using a nationally representative sample[2], Sperling and Muyaneza (1995) report that over 40 percent of bean-producing households cultivated improved climbing bean varieties in 1993. Higher adoption rates were reported in the North and regions with extensive bean research and dissemination activities. The authors estimate that between 10 to 20 percent of total bean area was planted with improved climbing bean varieties in 1993.

Johnson, et al. (2003) investigate the adoption and impact of CIAT-related bean varieties[3] released before 1999 and reported adoption of 16 percent of the area planted to beans for Rwanda. The yield gain of improved varieties, estimated through experimental data, was about 900 kg/ha, which is partially due to a shift from bush to climbing beans. Based on a nationwide survey of 383 farm households conducted in 2004, Kalyebara and Buruchara (2008) estimate the yield difference between local and improved varieties of 10-30 percent.

Climbing beans are more complex to manage than bush beans. This management complexity along with other factors may lead to selectivity bias, invalidating a naïve yield

[2] The study might not be indeed nationally representative since some regions had to be excluded with the start of civil war.
[3] CIAT-related varieties include varieties from CIAT gene banks, crosses made in CIAT or in NARS using CIAT genetic materials, and varieties transferred through the CIAT-supported networks.

comparison between climbing beans and bush beans. Climbing beans require relatively more fertile soils and staking, which may complicate planting or harvesting (Graf, et al., 1991). Farmers with better managerial abilities are more likely to overcome these complexities and adopt climbing beans. Selectivity bias can also arise if land allocation to bush vs. climbing bean is influenced by exposure to erosion, floods, or soil pathogens. These factors have a larger impact on bush than climbing beans (Musoni et al., 2001). If climbing beans are cultivated by farmers or on plots that systematically differ from those cultivated with bush beans, observed productivity differences cannot be attributed to the bean variety alone unless endogeneity is addressed.

Larochelle, et al. (2015) used a nationally representative sample of bean producers to estimate the impact of improved bean varieties in Rwanda and Uganda while controlling for selection. The authors used an instrumental variable (IV) method to estimate the causal effects of adoption on yield and food security. They found an average yield gain of 62 and 65 percent for adopters of improved bean varieties in Rwanda and Uganda, respectively; adopting households also had higher dietary diversity scores. Like previous studies, this study did not differentiate between climbing and bush beans, as the focus was on improved versus unimproved beans.

The objectives of this study are: i) to estimate the uptake of climbing bean varieties at the national-level, ii) identify factors influencing adoption, and iii) estimate yield gains of climbing over bush beans varieties. Our study contributes to the knowledge on climbing beans in Rwanda in three ways. First, it updates existing information on adoption of climbing bean varieties using a nationally representative survey of bean producers. Second, none of the previous studies of beans in Rwanda have focused on factors affecting adoption of climbing bean varieties using an econometric approach. Such findings are crucial to inform policies to promote adoption of climbing beans. Information on facilitators of climbing bean adoption and evidence on its impact on crop productivity will be required to inform future efforts in the region.

Third, this paper provides rigorous evidence of the impact of adoption of climbing beans on farm productivity using an instrumental variable approach to control for selection bias. Bean productivity is estimated at the plot-level, which enables us to include, in addition to village- and household-level characteristics, plot-specific characteristics, improving the precision of the estimates. Actual and counterfactual yields among adopters of the technology are predicted and contrasted, which provides our measure of the yield gains from adoption for adopters.

Next section presents the data used in the analysis and selected descriptive statistics, followed by the analytical framework describing how unbiased treatment effects are estimated in section 3. The empirical estimation strategies are also discussed in this section. The econometric results are presented and discussed in section 4. The paper ends with conclusions and recommendations.

2. Survey design and data

2.1 Sources of data

Data were obtained through a nationally representative households survey conducted from March to August 2011 by RAB in collaboration with CIAT, Virginia Tech, and the International Potato Center (CIP) as part of a project entitled Diffusion and Impact of Improved Varieties in Africa (DIIVA). A multi-stage sampling procedure was employed to select villages and respondents. The first stage consisted of stratifying the sample based on the country's ten major agro-ecological zones. Bean production occurs in all the zones, broadly categorized into three major elevation areas: : high-, medium-, and low-elevation. The high elevation area (>1700 masl) accounts for 40 percent of land area under bean cultivation, while the mid-elevation (1400-1700 masl) and low elevation (800-1400 masl) areas contribute about 30 percent of the bean land area each.

In the second stage of sampling, the 14,942 agricultural villages were assigned to the ten agro-ecological zones and eighty villages randomly selected based on weighted probabilities. In the final step, 18 households were random selected from each village, giving a total sample size of 1440 households. Approximately 90 percent of surveyed households grew beans in the study season, leading to a sample of 1296 bean-producing households. The household survey gathered information at household and plot levels. Through community surveys information on village level variables that could explain bean varietal adoption independent of their effect on productivity was elicited.

2.2 Descriptive statistics

Overall, 50.6 percent of sampled bean-producing households cultivate bush beans, 42.7 percent grow climbing beans only, and 8.0 percent cultivate both bush and climbing beans--thus defined as partial adopters. About 42 percent of the land under bean production is allocated to climbing bean varieties (table 1). Although adoption of climbing beans is relatively higher in the high altitude areas, reaching 86.1 percent, diffusion into low- and mid-elevation as has occurred. About 25 percent of farmers in these areas grow climbing beans.

The majority of farmers reside in remote areas served by poor road infrastructure and where access to institutional services and markets is low. Extension agents are found, on average, 4.6 km from the village center, and bean growers average about 19km from the nearest urban center. Climbing bean growers are located in areas with greater population pressure on land (about 285 vs. 224 people/0.8km^2), which could provide incentives to adopt climbing beans. Climbing bean adoption rate is low in villages susceptible to droughts, where only 25.1 percent of households are full adopters and 7.6 percent partial adopters.

Adopters and non-adopters of climbing beans have similar household socio-economic characteristics but differences emerge for partial-adopters. On average, bean-producing households have 4.7 members, 34 percent of whom are children younger than 15 years of age and members older than 65 years old (table 1). Household heads, the majority of whom are males (74%), average 45 years old, and have low levels of education. Livestock, a key household asset, average 1.86 TE[4], but higher for growers of climbing than for non-growers (1.93 vs. 1.69 TE) and highest among households that grow both types of beans (2.58 TE). Land cropped per household is about 0.9 ha, leading to very small scale bean production, about 0.35 ha (table 1). Bush and climbing bean growers have similar amount of land under cultivation while households growing both type of beans have larger cultivated area (1.1 ha). On average, each household cultivates about 1.56 bean plot, with mean plot size of 0.23 ha. Households cultivating both types of beans have significantly more plots under bean cultivation (2.5 plots) than those cultivating only climbing or bush beans.

3. Conceptual framework and estimation strategy

3.1 Adoption of climbing bean and its impact on productivity

The majority of bean producers in Rwanda derive their livelihoods from farming in an economic environment characterized by land scarcity, low off-farm employment opportunities, and high risk of crop failure. The mountainous terrain limits development of quality road networks

[4] Measure of livestock equivalent are computed based on the following conversion factors: cattle=1, sheep, goat and pigs=0.4, and, poultry=0.08.

resulting in high transportation costs, which impedes some households from participating in input or output markets. In such a situation, the demand for climbing bean technology can be modeled from the perspective of a non-separable household model, where the decision to grow climbing bean varieties is driven by expected utility maximization over consumption goods and leisure given household constraints, resource endowments, and market conditions (de Janvry, et al., 1991).

Assume that T_{1ij}^* denotes the expected utility derived from the cultivation of climbing bean varieties and T_{0ij}^* the expected utility associated with the production of bush bean varieties by farmer *i* on plot *j*[5]. Farmer *i* is assumed to compare the two expected utilities and select the alternative that leads to the highest expected utility. The difference between the expected utilities, i.e. $T_{ij}^* = T_{1ij}^* - T_{0ij}^*$, reveals the choice made by farmer *i* on plot *j*. The expected utility derived from cultivating climbing beans (T_{1ij}^*) is unobservable but based on random utility theory can be represented by a binary indicator T_{ij}. T_{ij} is equal to 1 when $T_{ij}^* > 0$ and is equal to zero for $T_{ij}^* \le 0$, indicating non-adoption (i.e. farmer *i* cultivates bush beans on plot *j*). This adoption decision can be represented as:

$$T_{ij}^* = \gamma Z_{ij} + \mu_{ij}, \; T_{ij} = 1 \text{ if } T_{ij}^* > 0 \tag{1}$$

Z_{ij} is a vector of all observable variables hypothesized to influence the choice between bush and climbing beans and γ is a vector of coefficients to be estimated. μ_{ij} is a random error term assumed to have zero mean and constant variance.

Given that climbing bean technology is newer than bush bean, knowledge of its relative advantages, management practices, and expected costs is expected to reduce uncertainty, and favor

[5]We address partial adoption at the household-level by measuring adoption at the plot-level as binary variable. The empirical data indicate that climbing and bush beans are rarely grown in the same plot.

adoption for risk-averse farmers (Feder, et al., 1985, Foster and Rosenzweig, 2010, Barham, et al., 2014). Innovations in research for both types of beans (e.g multiple constraint resistant varieties) also mean that the relative benefits of climbing bean are non-static —and revisions in previous adoption decisions are made as new information is gained. Characteristics expected to lower the cost of learning, facilitate access to new information or directly influencing attitudes towards risk include wealth, landholding, education, gender, family size, and age, access to agriculture extension services, and social learning (Feder, et al., 1985, Foster and Rosenzweig, 2010, Aldana, et al., 2012, Genius, et al., 2014, Matuschke and Qaim, 2009).

Previous studies show that climbing beans perform better at high altitude and under consistent rainfall conditions than bush beans, which means that growing climbing bean could reduce the risk of crop failure under these conditions (Musoni, et al., 2001, Koundouri, et al., 2006). Following literature, we expect adoption decisions to depend on factors such as soil quality (Bellon and Taylor, 1993, Wollni, et al., 2010). Variety choice is also influenced by market factors such as distance to input and output collection centers, and market centers (Minten, et al., 2013).

In order to determine the yield gain of climbing over bush beans, we employ an ESR model to deal with the issue of endogeneity of adoption of climbing beans and to correctly identify the effect of adoption on yield. The ESR makes use of IVs but relaxes the assumption underlying most conventional IV methods that technology adoption results in an intercept shift only. A flexible model is clearly more relevant for climbing bean technology given its complexity, more extensive input requirements, and the likely different inputs response between the two bean types.

3.2 Endogenous switching regression model

An ESR is a two-stage estimation approach, where in the first stage, the decision of whether or not to adopt climbing beans is estimated. From this equation, which is also referred to as the selection equation, the Inverse Mills Ratio (IMR) is computed and included in the second stage equations to control for selectivity bias. Conditional on the technology adoption decision being observed in the first stage, outcomes in the second stage are estimated as two separate regimes:

Regime 1: $Y_{1ij} = \beta_1 X_{1ij} + \epsilon_{1ij}$ if $T_{ij}=1$ (2.a)

Regime 2: $Y_{2ij} = \beta_2 X_{2ij} + \epsilon_{2ij}$ if $T_{ij}=0$ (2.b)

Y_{1ij} and Y_{2ij} define bean productivity of plot *j* for farmer *i* in the adopting (1) and non-adopting (2) regimes. X_{1ij} and X_{2ij} are vectors of variables explaining bean productivity in the respective regimes. Betas are vectors of coefficients to be estimated that are specific to the climbing and bush bean regimes. Vectors ϵ_{1ij} and ϵ_{2ij} are the respective error terms, which together with the error terms μ_{ij} in equation 1 are assumed to have trivariate normal distribution with zero mean and the following covariance matrix:

$$\Omega = \begin{bmatrix} \sigma_\mu^2 & \sigma_{1\mu} & \sigma_{2\mu} \\ \sigma_{1\mu} & \sigma_1^2 & \cdot \\ \sigma_{2\mu} & \cdot & \sigma_2^2 \end{bmatrix} \quad (3)$$

Where σ_μ^2 is the variance of the error term in the adoption equation (1) and is assumed to be equal to 1; σ_1^2 and σ_2^2 are the variances of the error terms in the climbing (2a) and bush (2b) bean productivity functions; and $\sigma_{1\mu}$ ($\sigma_{2\mu}$) represents the covariance of the error terms between the adoption equation μ_{ij} and climbing (bush) bean productivity function ϵ_{1ij} (ϵ_{2ij}). The dots (.) signify unidentified covariance between ϵ_{1ij} and ϵ_{2ij} given that Y_{1ij} and Y_{2ij} are in two separate regimes and are never observed simultaneously (Maddala, 1983). Since the error terms of the selection equation are correlated with those of the productivity functions, the expected values of ϵ_{1ij} and ϵ_{2ij} are non-zero and computed as follow:

$$E(\varepsilon_{1ij} \mid T_{ij}=1) = \sigma_{1\mu}\frac{\phi(Z_{ij}\gamma)}{\Phi(Z_{ij}\gamma)} = \sigma_{1\mu}\lambda_{1ij} \qquad (4.a)$$

$$E(\varepsilon_{2ij} \mid T_{ij}=0) = -\sigma_{2\mu}\frac{\phi(Z_{ij}\gamma)}{1-\Phi(Z_{ij}\gamma)} = \sigma_{2\mu}\lambda_{2ij} \qquad (4.b)$$

Where $\phi(.)$ is the standard normal probability density function, and $\Phi(.)$, the standard normal cumulative density function. $\lambda_{1ij} = \frac{\phi(Z_{ij}\gamma)}{\Phi(Z_{ij}\gamma)}$ and $\lambda_{2ij} = \frac{\phi(Z_{ij}\gamma)}{1-\Phi(Z_{ij}\gamma)}$ are the respective IMRs computed from the first stage and added in the second stage equations to control for selection bias. When the estimated $\hat{\sigma}_{1\mu}$ and $\hat{\sigma}_{2\mu}$ are statistically significant, the error terms between the adoption equation and productivity functions are correlated and the null of no selection bias is rejected (Di Falco, et al., 2011).

Full-information maximum likelihood (FIML) method which does not require cumbersome adjustments of the residuals for the standard errors to be consistent (Lokshin and Sajaia, 2004) is used. The log likelihood function is:

$$\ln L_i = \sum_{i,j=1}^{N} T_{ij}\left[\ln\phi\left(\frac{\varepsilon_{1ij}}{\sigma_1}\right) - \ln\sigma_1 + \ln\Phi(\theta_{1ij})\right] + (1-T_{ij})\left[\ln\phi\left(\frac{\varepsilon_{2ij}}{\sigma_2}\right) - \ln\sigma_2 + \ln(1-\Phi(\theta_{2ij}))\right] \qquad (5)$$

Where $\theta_{kij} = \frac{\left(Z_{ij}\alpha + \rho_k\varepsilon_{kij}/\sigma_k\right)}{\sqrt{1-\rho_k^2}}, k=1,2$ and ρ_k denotes the correlation coefficient between the error term μ_{ij} of the selection equation (1) and the error term ϵ_{kij} of regime specific outcome equations (2.a-b) (Lokshin and Sajaia, 2004, Di Falco, et al., 2011).

3.3 Average treatment and heterogeneity effects

The average treatment effect on the treated (ATT) and untreated (ATU) is estimated by comparing the conditional expected productivity values under the actual and counterfactual scenarios for adopters (i.e. climbing bean plots) and non-adopters (i.e. bush bean plots) similar to Kassie, et al. (2008), Di Falco, et al. (2011) among others. The formulations for both treatment effects are represented by equations 6.a-d (table 2). Equations 6.a and 6.b are the expected values under the actual scenarios while equations 6.c and 6.d correspond to those under the counterfactual scenarios, i.e. assuming climbing (bush) bean plots were to be planted with bush (climbing) beans. The ATT_{ij} is the average yield gain on plot j associated with cultivating climbing beans—computed as the difference between equation 6.a and 6.c as:

$$ATT_{ij} = E(Y_{1ij} \mid T_{ij} = 1) - E(Y_{2ij} \mid T_{ij} = 1) = X_{1ij}(b_1 - b_2) + (s_{1m} - s_{2m}) l_{1ij} \qquad (7.a)$$

Similarly, the ATU_{ij} is the yield gain on plot *j* bush bean grower *i* would obtain if she were to plant climbing beans. The yield gain of cultivating climbing beans for non-adopters (ATU_{ij}) is calculated by subtracting equation 6.d from 6.b, which corresponds to equation 7.b:

$$ATU_{ij} = E(Y_{1ij} \mid T_{ij} = 0) - E(Y_{2ij} \mid T_{ij} = 0) = X_{2ij}(b_1 - b_2) + (s_{1m} - s_{2m}) l_{2Sij} \qquad (7.b)$$

From the ESR framework we also calculate the base heterogeneity effects for adopters and non-adopters. The base heterogeneity for plots under climbing beans cultivation (adopters), BH_{1ij}, is computed as the difference between equations 6.a and 6.d while the base heterogeneity for plots planted with bush beans (non-adopters), BH_{2ij}, is the difference between equation 6.b and 6.c. The heterogeneity effect in both cases measures the possibility that plots could still differ in productivity regardless of whether they are planted to climbing or bush bean because of unobservable characteristics such as the land quality attributes or farmer skills. Finally, we calculate ATT_{ij}-ATU_{ij}, as the difference between equations 7.a and 7.b and test whether non-adopters would obtain higher, lower, or similar yield as adopters if they were to switch to climbing beans.

3.5 Empirical estimation

Bean productivity is expressed as a function of inputs (X_{ij}), plot specific characteristics (P_{ij}), and household characteristics (HH_i); and estimated assuming a Cobb-Douglas specification in each regime:

$$\text{Regime 1: } \ln(Y_{1ij}) = b_{10} + b_{11}(\ln X_{1ij}) + b_{12}(\ln P_{1ij}) + b_{13}(\ln HH_{1i}) + e_{1ij} \qquad (8.a)$$

$$\text{Regime 2: } \ln(Y_{2ij}) = b_{20} + b_{21}(\ln X_{2ij}) + b_{22}(\ln P_{2ij}) + b_{23}(\ln HH_{2i}) + e_{2ij} \qquad (8.b)$$

The $b's$ represent coefficients to be estimated while e_{1ij} and e_{2ij} are respective error terms defined in equations 2 (a-b).

Inputs used in bean production are labor, organic fertilizers (manure and compost)[6], chemical fertilizers, pesticides, seeding rate and new improved bean variety. Labor devoted to bean cultivation is mainly provided by family members, and is statistically higher for climbing bean than bush bean (table 3). Plots cultivated with climbing beans received on average 8080 kg/ha of organic fertilizers while organic fertilizer application averages 5190 kg/ha for bush beans. These application rates are below the recommended rates of 20-30 ton/ha of organic manure (RAB, 2012). Since chemical fertilizer and pesticide application is uncommon in the production of both bean types, these inputs enter the productivity functions as dummy variables. Fourteen percent of climbing bean plots received chemical fertilizer applications compared to only 5% of bush bean plots. The significant difference in organic and chemical fertilizer applications is evidence that

[6] Observations with zero values for organic fertilizer application were handled as suggested in Battese (1997) to avoid dropping these observations or creating bias by assuming that log(0)=0.

farmers are aware of the greater fertilizer requirement of climbing beans. Most farmers do not follow the recommended seeding rate, as it exceeds 80 kg/ha on about 28 percent of the plots and is below 60kg/ha on about 30 percent of the plots (table 3). Compared to bush bean plots, seeding rate is more likely to exceed the recommended rates for climbing bean because the latter is prevalently planted on smaller mono cropped plots. About one percent of the bean plots received pesticide application with no difference between climbing and bush bean types. Plot characteristics included in the productivity functions are soil fertility, soil pH, elevation, average monthly rainfall, distance between plot and residence, and plot management practices such as type of cropping systems and bean varietal diversity. Intercropping and variety diversity may abate yield losses (Kwikiriza, et al., 2011). Bean varietal diversity indicates whether one bean variety, two bean varieties, or three or more bean varieties were planted in plot *j*. Household characteristics include the age, gender, education of the household head.

The new improved varieties is potentially endogenous in the productivity of bean. A control function approach (CF) for non-linear models (Smith and Blundell, 1986) was used to test and control for possible endogeneity of new improved varieties, measured as the proportion of seed planted. The CF method discussed in Wooldridge (2002) and used in other studies (e.g. Mason and Smale 2013; Kassie et al. 2014; Mathenge et al. 2014; and Smale and Mason 2014) entails taking generalized residuals[7] from a reduced form Tobit model of new improved variety in the first stage and include it as an additional regressor in the productivity estimation. Statistical significance of the coefficients for the generalized residuals provides evidence of endogeneity of improved seed. Standard errors in the second stage are corrected by bootstrapping both productivity and adoption equations.

[7] Generalized residuals were computed following a formula described in Cameron and Trivedi (2005: p 544).

For the ESR model to be identified, it is important that IVs that directly affect adoption of climbing bean but not productivity are included alongside those automatically generated by the non-linearity of the selection model of adoption. Previous occurrence of droughts that caused bean yield loss, and population density are included as IVs. Since climbing beans require reliable level of soil moisture, they are expected to be less adopted in areas vulnerable to such abiotic stresses (Musoni, et al., 2001). We use village-level occurrence of droughts in the five years prior to the survey as a measure of drought vulnerability to avoid possible correlation with productivity in the period studied. High population density results in land shortage that might favor adoption of labor- and capital-using technologies, but could also reduce transaction costs that positively influence access to technology. We expect no direct effect of population density on yield.

Several tests were conducted to assess the validity of IVs[8], adjusting for potential heteroskedasticity. The Hansen J statistic, a test for over-identification of all instruments, indicates that our instruments are valid as the null hypothesis is not rejected (p-value =0.432). The Kleibergen-Paap rk LM and Kleibergen-Paap rk Wald statistics test of the null hypothesis that the excluded instruments are only weakly correlated with the endogenous regressor, are strongly rejected suggesting that the model is well-identified and weak-inference bias should not be an issue. Last, a falsification test conducted following Di Falco, et al.(2011) provided no evidence that the IVs affect the productivity of bush bean plots, i.e. the non-adopters[9].

[8] The tests for the validity of the instruments, at the exception of the falsification test, are conducted using the Stata user written command "Ivreg2".

[9] Test results show p-values for IV as 0.273 for population density and 0.614 for the dummy for seed loss due to drought in previous five years.

Another important issue when estimating production function using plot-level survey data is the possible endogeneity of inputs. The C statistic test of exogeneity for labor, organic fertilizer, improved seed [10] and all the instrumental variables could not be rejected in all cases[11].

4. Results

4.1 Determinants of adopting climbing beans

The marginal effects on the probability of adopting climbing beans are provided in table 4 along with standard errors clustered at the household-level. The IVs are highly significant in explaining the decision to grow climbing beans. A ten-unit increase in population density increases the probability that a plot will be allocated to climbing beans by 2 percentage point (table 4). Village-level occurrence of droughts in the five years prior to the survey reduces the likelihood of adopting climbing beans by 68 percentage points, because climbing beans require reliable rainfall to achieve their high yield potential (Musoni, et al., 2001). Besides the IVs, the most important variable associated with the adoption of climbing beans is elevation, which confirms earlier findings that climbing beans are most suited for high elevation and cool temperature areas (Musoni, et al., 2001). High elevation areas tend to be associated with longer rainfall periods, which constrain postharvest drying of bush bean varieties--harvested over a relatively short period--, thereby favoring the choice of climbing beans at high altitude (Graf, et al., 1991).

Plot specific characteristics such as soil fertility and pH are also important determinants of climbing bean growing. The probability of adopting climbing bean is higher on plots with average

[10] Improved variety seed is exogenous when generalized residuals are included. Labour used in bean production is spread across the growing period, and can easily be adjusted in response to production shocks such as severe weather changes or disease outbreak that is also expected to affect plot productivity, while organic manure application rate could be correlated with managerial ability of the farmer.
[11] Test results are excluded to keep the paper length short but can be made available by authors on request.

soil fertility and those with higher soil pH (table 4), which might be an indication that production environment differs according to the bean type grown. However, climbing beans are less frequently planted as a multiple cropping systems because of their crawling growth habits that interferes with the performance of other crops (table 4). Table 4 also shows that climbing bean plots are less likely to be cultivated with three or more varieties simultaneously and that adoption rate of new improved varieties among climbing bean growers is lower relative to that observed among bush bean growers. This suggests that climbing bean growers are more constrained in terms of accessing new bean varieties, which could be linked with the complexity of staking that makes it even lesser attractive for private to engage in multiplication of new climbing bean variety seed.

Similarly, increase in the distance between the plot and homestead, significantly reduces the probability of cultivating climbing beans, perhaps because the efficiency losses due to unproductive labor effort (i.e. walking) might be greater for climbing beans(Larochelle and Alwang, 2013) (table 4) because of their longer vegetative cycle and need for staking. Consistent with findings of Sperling and Muyaneza (1995), our study reveals no influence of household demographics on adoption of climbing beans, implying that its taking up is biased by neither gender nor education status.

4.2 Determinants of bean yield

The second stage of the ESR provides the estimated coefficients for the productivity functions in the climbing and bush bean regime, which are reported in table 5. The null hypothesis that $\hat{s}_{1m}=\hat{s}_{2m}=0$ could not be rejected, which implies that important unobserved factors that would make climbing bean adoption endogenous in bean productivity function (the outcome) is controlled for by included observed variables.

Consistent with the economic theory, all inputs have a positive and significant impact on productivity of beans. However, the yield response to input use differs between the two bean types for some inputs. A one-percent increase in organic fertilizer application leads to a yield gain of 0.13 percent for climbing beans compared to 0.06 percent for bush beans (table 5), which is consistent with the notion that climbing beans are more responsive to fertilizer application than bush beans[12]. Similarly, bean productivity is sensitive to chemical fertilizer application, which increases yields for climbing bean by 18 percent. Results further indicate that the application of pesticide increases yield by about 41 and 45.6 percent for climbing and bush beans respectively. This suggests that pesticide is an underutilized. Growing improved varieties increases bean productivity for both climbing and bush types by a significant magnitude. For example, bean plots cultivated with only (100 percent) new improved variety seed produce 39 percent higher yields for climbing bean and 31 percent higher for bush beans. The yield advantage is significant at 10 percent in each case. As alluded to in previous sections, bean seeding rate in Rwanda greatly varies across farms and has a significant effect on crop productivity. Among 28 percent of plots with far below the recommended rates, the average yield is about 66 percent lower than that obtained by farmers within the recommended seeding rate[13] and much lower as compared to yield from plots with seeding rate higher than 80 kg/ha.

Plot characteristics that significantly influence bean productivity are soil fertility, rainfall, type of cropping system, and varietal diversity. Bean productivity is negatively affected by a decrease in soil fertility and positively influenced by rainfall amounts, with the latter showing a coefficient with larger magnitude and hence important determinant (table 5). For one percent

[12] The result could also be partially explained by the type of soil climbing beans are grown. The adoption model shows that climbing beans are planted in less fertile soil than bush beans but in soil that are more responsive to fertilizer application.

[13] Recommended seeding rate for bean is about 60 kg/ha for climbing bean and 70kg/ha for bush (RAB, 2012)

increase in the amount of rainfall above average, bean productivity increases by about 5.5 percent for climbing bean and 3.6 percent for bush (table 5). Yield for bean planted under intercropping systems is also higher compared to sole cropping, perhaps because benefits associated with the interaction between crops that abates yield loss due to disease and pest spread. The yield advantage could also be linked to better phosphorous (P) acquisition under intercropped systems as reported in Wang et al. (2014) from cereal/legume intercropping experiments in China. Consistent with the findings reported in Di Falco, et al. (2007) and Kwikiriza, et al. (2011), plot-level bean varietal diversity significantly increases the productivity of beans.

Surprisingly, bean productivity responsiveness to household demographics is specific to the bean type. Notably, an increase in the age of the household head reduces bush bean productivity by 0.17 percent, while education of the households head increases it. Bush bean productivity is on average 20.5 percent higher among households headed by individuals with primary level of education compared to those with none.

4.3 Yield effect of adopting climbing beans

The average yield gain associated with switching from bush to climbing beans, the average treatment effect, is computed for adopters and non-adopters by predicting bean productivity under actual and counterfactual scenarios based on equations presented in table 2.

The predicted output per hectare for climbing bean plots is 1472.6 kg compared 1368 kg for bush bean plots (table 6). This compares closely with the respective observed average yield 1323 kg/ha (1096 kg/ha) for climbing (bush) bean plots (table 3). A naïve comparison between predicted yields suggests a yield gain of about 8 percent for adopters. However, this method does not take into account selectivity issues. To do so, counterfactual yields must be estimated for adopters and non-adopters. Adopters of climbing beans would produce 1214.2 kg/ha if they had not switched to climbing beans (i.e. had planted bush beans), which is 21.3 percent less than under the actual scenario, and thus our measure of the average treatment effect on adopters. Adopters obtain an additional 258 kg/ha from climbing bean cultivation compared to the situation where they had not adopted. Under the counterfactual scenario, bush bean growers would produce 2014kg/ha; this is if they were to switch to climbing beans. This represents an additional output of 646 kg per hectare or an average yield gain of 47.3 percent. Our results confirm earlier findings from on farm experiments of the superior yielding properties of climbing bean varieties over bush bean varieties.

The transitional heterogeneity is negative implying that on average, the yield gains from adopting climbing bean is higher among farmers who have not yet adopted relative to those who have adopted. This is similar to the findings in Di Falco, et al. (2011) and Suri (2011). The base heterogeneity is negative under both scenarios. In the first scenario, adopters and non-adopters grow climbing beans while in the second scenario both groups grow bush beans. In either case, the actual adopters of climbing beans would obtain lower yield than would the current bush bean growers, which is represented by the negative base heterogeneity of 542 kg in the climbing bean scenario and of 153.8 kg in the bush bean scenario. This means that there is some source of unobserved heterogeneity that makes adopters of climbing beans on average worst off than producers of bush beans, such as cultivation on more marginal and degraded land.

4.4 Robustness check

To test the robustness of our results, we re-estimate the models on a subsample of 104 households that grow both bush and climbing beans, which includes 259 plots. We did this using an ordinary least squares regression and including a dummy for climbing bean as one of the regressors in the productivity function, with standards errors clustered at household-level. The average yield for climbing beans among households that grow both is about 23 percent higher than that of bush bean. The coefficient is significant at the 5 percent level and consistent with the results obtained from ESR[14].

5. Conclusion and discussion

Over the years, climbing bean production in Rwanda has received increasing attention. The major interest in climbing bean lies in its high yielding potential and hence suitability to intensify bean production on land scarce areas. This study updates the adoption rate, estimates the determinants of adoption, and the yield gain associated with switching from bush to climbing beans using a nationally representative sample of Rwandan bean producers. An endogenous switching regression model was employed to account for the possibility of selection bias and obtain unbiased impact of adoption on yield.

Study findings indicate that diffusion of climbing bean in terms of farmers and area occupied has increased four to five folds since 1985. However, geographical distribution remains highly variable, with the adoption concentrated in high elevation areas, and areas less prone to drought conditions. Adoption is also highly influenced by population pressure, which stresses their role in mitigating land scarcity constraint and support the idea of scaling up the technology to other areas in East and Southern Africa where high population is causing land fragmentation, over-cultivation, and diminishing landholdings. This is evidence that promotion of climbing bean has made it possible for land constrained households to extend the bean production to more marginal lands characterized by flooding that would otherwise not be cultivated with bush beans. However,

[14] Results from this analysis is excluded to keep the length of paper short but can be made available from the authors on request

this also exposes bean to higher risks of climate variability, and poor soil characteristics. Thus further research should continue to be supported to address new emerging and increases in existing constraints that affect climbing beans in new environments.

Adoption of climbing beans significantly increases bean productivity in Rwanda, which is of great importance to achieve food security and poverty reduction in a country where small landholdings pose a big challenge. This study reveals positive average yield gains for both adopters and non-adopters. However, the yield impact, which average 21 percent for adopters is far way below the potential yield advantage demonstrated through field experiments. This is because, on average, farmers underutilize inputs, including low seeding rates linked to poor access to staking materials and low soil fertility. Moreover, growers of climbing beans are concentrated in regions where the climate is most suited for this technology but thus systematically differ from bush bean producers in terms of their productive capacities. The former cultivate more marginal lands and would be worst off with bush bean technology in their current physical environment. On the other hand, farmers currently growing bush beans may be hesitant to switch to climbing beans due to barriers such as less access to staking materials, high opportunity cost of adoption related to learning new crop management practices, and greater input requirements. Bush bean growers would on average obtained 48 percent more yield if they were to switch from bush to climbing bean growing.

This study's findings are important for the design of strategies for increasing bean productivity in Rwanda. More specifically, the positive and significant influence of pesticide application in explaining variations in bean yield for climbing and bush bean plots is a signal of the existing environmental stresses that could be addressed with better adapted varieties and complementary management practices. Some well adapted varieties might already be available in the stock of newly released varieties and this study provides information that can help target their dissemination. The prior information that climbing bean exhibits better resistance to fungal foliar and root disease and have higher potential to recover from the effects of flood underscores its potential as a strategy for adaptation to climate change and re-enforces the suggestion for continued support. However, there is need for interventions to develop seed systems specific for climbing bean and accelerate diffusion of new varieties if this strategy is going to be effective. In the context degraded soils, additional efforts should be devoted to interventions on fertility management to increase access to good agricultural practices and unleash the yield potential of climbing beans as well as that of bush beans in Rwanda. Options to improve soil fertility include the promotion of livestock-crop integrated system, especially with climbing beans, which produce significant quantities of biomass to serve as livestock feed. Climbing beans also seem to be more responsive to manure relative to bush beans, which makes this integrated agricultural system very attractive for addressing Rwanda agriculture challenges.

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Tables:

Table 1: Summary statistics of village, household, and bean production characteristics

	Climbing bean growers only		Bush bean growers only		Climbing and bush bean growers		Full sample	
Village and household characteristics	Mean	SD.	Mean	SD	Mean	SD	Mean	SD.
Extension agent in village (1=yes)[2,3]	0.37	0.48	0.40	0.49	0.61	0.49	0.40	0.49
Distance to nearest urban center (km)[1]	18.13	9.64	19.32	9.55	18.10	10.18	18.72	9.65
Population density (ind./0.8km^2)[1,3]	284.53	107.21	223.84	98.16	273.81	117.50	253.71	107.80
Drought 10 years prior survey (1=yes)[1,2,3]	0.37	0.48	0.85	0.35	0.60	0.49	0.63	0.48
HH size	4.62	1.91	4.66	2.01	5.05	2.12	4.67	1.98
Dependency ratio (dep/HH size)	0.34	0.23	0.34	0.24	0.36	0.22	0.34	0.23
Age of HH head	45.21	14.06	44.07	13.65	45.52	13.24	44.67	13.80
Gender of HH head (1=male)	0.75	0.43	0.72	0.45	0.78	0.41	0.74	0.44
Formal years of schooling of HH head[3]	3.96	2.98	3.79	3.08	4.53	2.92	3.93	3.03
Livestock equivalent[1,2,3]	1.93	1.99	1.69	2.08	2.58	2.30	1.86	2.07
Land cropped (ha)	0.87	1.28	0.93	1.20	1.14	2.00	0.92	1.31
Bean production characteristics								
Number of bean plots per HH[2,3]	1.52	0.80	1.43	0.76	2.51	0.98	1.56	0.85
Total bean area (ha)	0.33	0.62	0.36	0.52	0.44	0.79	0.35	0.59
Share of bean area in total area (%)[1]	0.42	0.31	0.46	0.33	0.42	0.34	0.44	0.32
Bean plot area (ha)[1,3]	0.21	0.46	0.25	0.35	0.17	0.39	0.23	0.40
Number of observations (%)	552 (42.66)		639 (49.38)		103 (7.96)		1294	

Note: 1, 2, and 3-- means are statistically different at the 5 percent level between: 1) Climbing and bush bean growers, 2) Climbing and climbing-bush bean growers, and 3) Bush and climbing-bush bean growers.

Table 2: Conditional expectations and treatment effects for adopters and non-adopters of climbing bean

	Adopters (Climbing bean growers)	***Non-adopters (Bush bean growers)***	***Treatment Effect***
Plots planted with climbing beans	*6.a)* $E(Y_{1ij} \mid T_{ij}=1)=\beta_1 X_{1ij}+\sigma_{1u}\lambda_{1ij}$	*6.c)* $E(Y_{2ij} \mid T_{ij}=1)=\beta_2 X_{1ij}+\sigma_{2u}\lambda_{1ij}$	*6.a) – 6.c)=ATT*
Plots planted with bush beans	*6.d)* $E(Y_{1ij} \mid T_{ij}=0)=\beta_1 X_{2ij}+\sigma_{1u}\lambda_{2ij}$	*6.b)* $E(Y_{2ij} \mid T_{ij}=0)=\beta_2 X_{2ij}+\sigma_{2u}\lambda_{2ij}$	*6.d) – 6.b) =ATU*
Heterogeneity effect	*6.a-6.d =* BH_1	*6.c-6.b=* BH_2	*ATT-ATU =TH*

Table 3: Descriptive statistics for variables included in the productivity functions, by bean types, Rwanda, 2011

	Climbing bean plots		Bush bean plots		Full sample	
	Mean	SD.	Mean	SD	Mean	SD
Yield (kg/ha) ***	1323.42	1547.57	1095.81	1230.15	1205.61	1396.61
Labor (Man-days/ha)	502.56	566.71	363.47	521.42	429.96	547.83
Organic fertilizer (kg/ha) ***	8080.2	18858.8	5190.63	15218.9	6584.51	17128.39
Chemical fertilizer (1=yes) ***	0.14	0.34	0.05	0.22	0.09	0.29
Pesticide application (1=yes)	0.02	0.13	0.01	0.09	0.01	0.11
Proportion of seed that is improved***	0.17	0.36	0.32	0.45	0.25	0.42
Soil Fertility						
Good	0.39	0.49	0.41	0.49	0.4	0.49
Medium	0.5	0.5	0.49	0.5	0.49	0.5
Poor	0.1	0.3	0.1	0.3	0.1	0.3
Seeding rate below 60kg/ha)***	0.26	0.44	0.32	0.47	0.29	0.46
Seeding rate above 80kg/ha***	0.25	0.43	0.31	0.46	0.28	0.45
Seeding rate within 60 to 80kg/ha (recommended)***	0.49	0.50	0.37	0.48	0.43	0.49
Extension at village level located in the village***	0.36	0.48	0.46	0.50	0.41	0.49
Extension outside village in a distance of <2 hours walk***	0.14	0.35	0.11	0.32	0.13	0.33
Extension outside village in distance of 2 to 4 hours walk**	0.49	0.50	0.42	0.49	0.46	0.50
Soil pH (ideal=1) ***	0.24	0.42	0.18	0.38	0.21	0.4
Elevation (m) ***	1846.39	249.87	1543.06	211.62	1689.38	276.14
Monthly average rainfall (2004-8) ***	16.02	0.6	15.86	0.8	15.94	0.71
Distance home to plot (min. walk)	17.29	28.51	16.8	21.75	17.04	25.24
No. of varieties per plot						
1 variety***	0.88	0.33	0.81	0.39	0.85	0.36
2 varieties***	0.09	0.29	0.13	0.34	0.11	0.31
3&+ varieties***	0.03	0.17	0.06	0.23	0.04	0.2
Plot intercropped (1=yes) ***	0.28	0.45	0.65	0.48	0.47	0.5
Age of HH head	45.36	13.72	44.16	13.16	44.74	13.44
Gender of HH head (1=male)	0.78	0.42	0.74	0.44	0.76	0.43
Education of HH head						
None	0.24	0.43	0.29	0.45	0.26	0.44
Primary	0.71	0.45	0.67	0.47	0.69	0.46
Secondary	0.05	0.21	0.04	0.2	0.05	0.21
Observations	943		1016		1959	

Note: ***, **, * denotes that average between climbing and bush bean plots are statistically different at 1, 5, and 10 percent level.

Table 4: Marginal effects on the probability of adopting climbing bean, Rwanda, 2011

	ME	Std. Errors.
Proportion of seed that is improved	-0.365***	0.071
Generalized residual imp roved seed	0.928***	0.254
Pesticide application (1=yes)	-0.077	0.099
Organic fertilizer (kg/ha)	0.015*	0.008
Labor (man-days/ha)	0.026**	0.011
dummy correction zero organic fertilizer	0.106	0.072
Intercropped (1=yes)	-0.087***	0.021
Chemical fertilizer application (1=yes)	0.001	0.034
Soil fertility (Base = good)		
Medium	0.056***	0.022
Poor	0.042	0.032
Bean varietal diversity (Base = 1 variety)		
2 varieties	-0.045	0.028
3 or more varieties	-0.095**	0.047
Bean seeding rate (base below 60kg/ha)		
Within 60 to 80kg/ha (recommended)	0.004	0.033
Above 80kg/ha	-0.102***	0.031
Dist. from dwelling to plot (min. walk)	-0.029***	0.007
Elevation (m)	0.991***	0.099
Avg. monthly rainfall between 2004-8	0.277	0.318
Education of HH head (Base=none)		
Primary	0.019	0.028
Secondary	-0.061	0.052
Age of HH head	0.011	0.034
Gender of HH head (1=male)	0.036	0.024
Soil pH (1=ideal)	0.190***	0.040
Extension at village level (base=located in village)		
Outside village within distance of <2 hours walk	-0.008	0.032
Outside village within distance of 2 to 4 hours walk	0.037	0.051
Population density(ind./0.8km^2)	0.001***	0.000
Drought at village-level in last 10 years	-0.156***	0.023
Observations	1,959	

Note: *** p<0.01, ** p<0.05, * p<0.1. ME= Marginal effects. HH= Household.

[1]Standard errors are clustered at the household-level.

Table 5: Productivity function of climbing and bush beans, Rwanda, 2011

	Climbing bean		Bush bean	
Variable	Coef.	SE.	Coef.	S. E.
Proportion of seed that is new improved	0.392*	0.213	0.308*	0.178
Generalized residual improved seed	-0.932	0.739	-0.866	0.661
Pesticide application (1=yes)	0.414***	0.162	0.456	0.292
Organic fertilizer (kg/ha)	0.132***	0.028	0.066***	0.025
Labor (man-days/ha)	0.542***	0.031	0.578***	0.029
Dummy correction zero organic fert	1.190***	0.253	0.448**	0.208
Intercropped (1=yes)	0.192**	0.095	0.060	0.058
Chemical fertilizer application (1=yes)	0.183**	0.083	-0.249	0.175
Soil fertility (Base = good)				
Medium	-0.113*	0.066	-0.106**	0.055
Poor	-0.150	0.096	-0.242**	0.101
Varieties diversity (base=one variety)				
2 varieties	0.060	0.099	0.277***	0.070
3 or more varieties	0.335***	0.136	0.273**	0.115
Seeding rate (base=below 60kg/ha)				
Recommended rate 60-80kg/ha	0.597***	0.089	0.661**	0.090
Recommended rate of 80kg/ha	0.835***	0.086	0.923***	0.082
Dist. from dwelling to plot (min. walk)	0.000	0.022	-0.006***	0.021
Elevation (m)	-0.906	0.703	-0.371	0.283
Avg. monthly rainfall between 2004-8	5.549***	1.049	3.640***	0.775
Education of HH head (Base=none)				
Primary	0.116	0.079	0.206***	0.072
Secondary	0.198	0.130	0.061	0.131
Age of HH head	-0.001	0.100	-0.189**	0.096
Gender of HH head (1=male)	0.023	0.078	0.084	0.059
Soil pH (1=ideal)	0.071	0.113	0.106	0.076
Extension (base=in village				
within 2 hours walk	-0.147**	0.077	-0.051	0.082
distance of 2 to 4 hours walk	-0.174	0.115	0.095	0.116
Constant	-6.758	6.912	-4.718*	2.665
Sigma	0.7021	0.043	0.714	0.030
Rho	-0.237	0.3295	0.123	0.117
Observations	943		1,016	

Note: *** p<0.01, ** p<0.05, * p<0.1. S.E. Standard errors. HH= Household.

[1]Standard errors are clustered at the household-level.

Table 6: Average predicted bean yield (kg/ha), and treatment and heterogeneity effects

Sub-sample	Decision stage		Treatment effect	
	Climbing beans (Kg/ha)	Bush beans (Kg/ha)		
Climbing beans	1472.61	1214.15	TT=258.46	21.3%
Bush beans	2014.62	1368.00	TU=646.63	47.3%
	BH1=-542.01	BH2=-153.85	TH=-388.17	