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Management of Banana Xanthomonas Wilt: Evidence from Impact of Adoption of Cultural Control Practices in Uganda

Enoch M. Kikulwe [1,*], Joseph Lule Kyanjo [2], Edward Kato [3], Reuben T. Ssali [4], Rockefeller Erima [4], Samuel Mpiira [4], Walter Ocimati [1], William Tinzaara [1], Jerome Kubiriba [4], Elisabetta Gotor [5], Dietmar Stoian [6] and Eldad Karamura [1]

1. Bioversity International, P.O. Box 24384, Kampala, Uganda; w.ocimati@cgiar.org (W.O.); w.tinzaara@cgiar.org (W.T.); e.karamura@cgiar.org (E.K.)
2. Department of Agribusiness and Natural Resource Economics, School of Agricultural Sciences, Makerere University, P.O. Box 7062, Kampala, Uganda; jlule04@gmail.com
3. International Food Policy Research Institute, 1201 I St NW Eye Street, NW, Washington, DC 20005, USA; E.Kato@cgiar.org
4. National Agricultural Laboratories Research Institute, P.O. Box 7084, Kampala, Uganda; rtendo@gmail.com (R.T.S.); erimarf2013@gmail.com (R.E.); smpiira@gmail.com (S.M.); jkubiriba2012@gmail.com (J.K.)
5. Bioversity International, Via dei Tre Denari, 472/a, 00054 Maccarese RM, Italy; e.gotor@cgiar.org
6. Bioversity International, Parc Scientifique Agropolis II, CEDEX 5, 34397 Montpellier, France; d.stoian@cgiar.org

* Correspondence: e.kikulwe@cgiar.org

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Abstract: Banana Xanthomonas Wilt (BXW) is an important emerging and non-curable infectious plant pathogen in sub-Saharan Africa that can cause up to 100% yield loss, negatively impacting sustainable access to food and income to more than 100 million banana farmers. This study disentangles adopters into partial and full adopters to investigate the factors that are relevant to sustain the adoption process of BXW control practices and quantifies the impact of adopting the practices. Data from a randomly selected sample of 1200 banana farmers in Uganda where the disease is endemic was used. A multinomial logit model was used to determine the factors affecting adoption of control practices and augmented inverse probability weighting was employed to estimate the impacts of adoption on banana productivity and sales. Results show that training a woman farmer and having diverse sources of information about BXW control practices increased adoption of the control practices and reduced the disease incidences. Farmers who adopted all the recommended control practices achieved significantly the highest values of banana production and sales. We conclude that improving information access through farmers' preferred communication channels, having women-inclusive trainings, and a combination of cultural practices are effective ways for sustaining adoption of the control practices.

Keywords: Banana Xanthomonas Wilt; cultural practices; augmented inverse probability weighting; distributional impacts

1. Introduction

Emerging infectious diseases caused by plant pathogens can develop into pandemics across regions and have the potential to cause serious socio-economic disasters. Banana Xanthomonas Wilt (BXW) is one of the four most important emerging infectious diseases in developing countries that threaten the food security and income of smallholder banana farmers in sub-Saharan Africa (SSA) [1]. Yet, SSA produces one-third of bananas in the world and the crop provides more than 25% of food energy requirements for more than 100 million people [1,2].

BXW has no cure, all banana cultivars grown in the region are susceptible, and no source of resistance has been identified [3]. Further, trans-boundary transmission of the disease has been reported. For example, since its outbreak in Uganda in 2001, the disease spread to DR Congo (2001), Rwanda (2002), Tanzania, Kenya (2005), and Burundi (2010) [4]. Unlike other banana diseases, the impact of BXW on bananas is extreme and rapid [2]. When plants/plantations are attacked by the BXW-causing bacteria, *Xanthomonas campestris pv. musacearum*, there are drastic declines in yield, sales, consumption, and household incomes [5,6]. Nkuba et al. [7] valued losses caused by the disease at USD 10.2 million and USD 2.95 million in Tanzania and Rwanda, respectively.

With no curative treatment, disease management has focused on cultural methods that reduce the initial inoculum and subsequent spread of the pathogen between host plants [8]. These practices (abbreviated as ABCC) include; avoid introduction of the disease by use of clean planting materials (A), timely removal of male buds with forked sticks (B) to prevent infections mediated by insect vectors, cutting down diseased plants/mats (C) to reduce disease inoculum load in infected fields and, disinfecting cutting tools (C) with sodium hypochlorite solution or fire to prevent vector mediated infections [9]. This is backed up by awareness campaigns to educate farmers on BXW symptoms, mechanisms of spread and control, and to mobilize them to collectively manage the disease [3,6,10]. However, these management options have only produced partial success and the disease has continued to spread into previously disease-free areas and to resurge in areas where it had been controlled [11]. Further, there is a strong possibility of BXW resurgence because of low levels of adoption of control practices [12], the long incubation period of the disease in banana mats, and high latent infection levels in fields [13,14]. This is also exacerbated by the fact that once control strategies are withdrawn, even with less than 1% infection level, the disease rapidly increases to endemic level [15]. Preventing resurgence of the disease and its spread to new areas is therefore critical and it strongly depends on sustained adoption of the control practices that keep the disease incidence to manageable levels. This paper assesses adoption of BXW control technologies to empirically establish determinants that are relevant to sustain the adoption process of BXW control practices.

Tinzaara et al. [11] point to poor understanding of factors influencing BXW spread as one of the major challenges to sustainable management of the disease. Given that farmers receive information about BXW control from different sources which can be conflicting, it is critical to assess farmers' perceptions on effectiveness of information channels as sources of BXW control information. The channels that are perceived to be effective can be used as the appropriate pathways to continuously sensitize farmers about new research findings on the epidemiology and control of the disease. We also assess the perceived effectiveness of the control strategies because they influence adoption of the control practices [12].

Reducing impacts of plant emerging infectious diseases like BXW requires approaches that integrate research and long-term commitments from the scientific and political communities [16]. Since BXW outbreak, collaborations from local, international research Institutes, universities, and stakeholders from government and non-government organizations contributed to the generation and promotion of technologies for effective control of the disease. However, to the best of our knowledge, there is no empirical evidence on the impact of level of adoption of the control practices that were developed and promoted on farmers' welfare. This paper provides the evidence on the impact of adoption of these control technologies on banana farmers' productivity and income.

The contribution of this paper is in three major directions: First, unlike the only study on adoption of BXW control technologies by Jogo et al. [12] that simply measured adoption dichotomously, adopter vs. non-adopter (an adopter was defined as a farmer who was found applying at least any one of the three recommended practices (destroying infected plants, removal of male buds with forked stick, and disinfecting farm tools) and a non-adopter otherwise), we disentangle adopters into partial and full adopters. Among partial adopters, some farmers may adopt any one or any two practices. This is because not all farmers have the capacity to apply all the control measures as recommended due to limitations such as cost, labor, time, and tradition [17,18]. Therefore, a dichotomous categorization of farmers as adopters or non-adopters conceals important differences between farmers who adopt one practice, two practices, or all the three recommended control practices (BXW control package). These differences need to be considered clearly to establish factors that are relevant to sustain the adoption process. Secondly, we extend to agricultural technology adoption literature, the use of a doubly robust estimator, augmented inverse probability weighting (AIPW) developed by Robins et al. [19] to control for selection bias and improve statistical precision in establishing impacts of adoption on farmers' welfare. Thirdly, we contribute to the limited body of multivalued treatment effects by estimating impact of adoption level of different control technologies in banana production in Uganda. In so doing, distributional impacts of technology adoption levels are assessed across different farmer domains.

2. Materials and Methods

2.1. Estimating Adoption Determinants

Farmers' utility maximization framework was used to model farmers' decisions to adopt BXW control practices. Following Asfaw et al. [20] and Ghimire et al. [21], let us assume a farmer's adoption decision is based on an underlying utility function, and the farmer makes a choice to adopt BXW control practices based on maximization of expected utility. The farmer has a choice not to adopt any practice $(j = 0)$; to adopt any one practice $(j = 1)$;. any two practices ($j = 2$); or all the three practices $(j = 3)$. With a farmer faced with four choices, the underlying utility function (U_{ij}). can be represented as:

$$U_{ij} = \beta_j X_i + \varepsilon_{ij} \tag{1}$$

where $j = 0, 1, 2, 3$; $i = 1, 2, \ldots, n$; U_{ij} is the utility farmer i derives from choosing choice j; X_i is a vector of explanatory variables that influence farmers' utility; β_j is a vector of parameters; and ε_{ij} is the error term. Following random utility theory, a farmer will choose a choice j such that $U_{i3} > U_{i2} > U_{i1} > U_{i0}$. Since adoption of BXW control practices involves a farmer's choice of non-adoption, adoption of any one, adoption of any two, and adoption of all three practices, a multinomial logit model was adopted for the study following Hassan et al. [22] and assumption of independent irrelevant alternatives. The model is expressed as:

$$P\left(y = \frac{j}{x}\right) = \frac{exp(x\beta_j)}{\left(1 + \sum_{k=1}^{j} exp(x\beta_k)\right)}, j = 0, 1, 2, 3 \tag{2}$$

where y denotes a random variable taking on the values 0, 1, 2, and 3; and x denotes a set of conditioning variables. The response probabilities $p(y = j)$ in this study are:

$p(y = 0)$, probability that a farmer does not adopt any practice;
$p(y = 1)$, is the probability that a farmer adopts any one practice;
$p(y = 2)$, is the probability that a farmer adopts any two practices;
$p(y = 3)$, probability that a farmer adopts all three practices.

Parameter estimates provided in Equation (2) only provide the direction of the effect of the independent variables on the dependent variable, but not the magnitude of change or probabilities. To obtain the marginal effects of the explanatory variables, Equation (2) is differentiated with respect to the explanatory variables [23] as:

$$\delta_j = \frac{\partial p_j}{\partial x_i} = p_j \left[\beta_j - \sum_{k=0}^{j} p_k \beta_k \right] = p_j \left(\beta_j - \overline{\beta} \right). \tag{3}$$

The empirical model estimated was specified as:

$$P(y = j) = \alpha + \beta_1 x_1 + \ldots + \beta_n x_n \tag{4}$$

where β's are the estimated parameters and x's are explanatory variables described in Table 1.

Table 1. Descriptive statistics of the dependent and explanatory variables by Banana Xanthomonas Wilt (BXW) adoption level.

Variable	All Sample	Non-Adopters	Use Any One Practice	Use Any Two Practices	Use BXW Control Package	F/Chi2 Value
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	
Explanatory Variables						
Gender (1 = Male-headed)	0.78 (0.41)	0.76 (0.43)	0.70 (0.46)	0.81 (0.39)	0.87 (0.34)	7.87 ***
Age of household head (in years)	53.03 (15.26)	55.01 (14.42)	53.56 (15.29)	51.39 (14.71)	52.82 (16.43)	2.46 *
Household size	6.32 (2.93)	6.29 (3.42)	6.33 (2.86)	6.35 (2.82)	6.29 (2.56)	0.03
Education level of HHD (years)	5.94 (3.64)	5.75 (3.67)	5.76 (3.79)	6.26 (3.47)	5.94 (3.61)	1.45
Total land (in acres)	5.87 (12.08)	7.59 (20.66)	4.95 (6.74)	5.73 (8.35)	5.89 (12.34)	1.90
Received training on BXW (Yes = 1)	0.55 (0.49)	0.48 (0.50)	0.43 (0.49)	0.59 (0.49)	0.69 (0.46)	15.19 ***
BXW trainee (woman = 1)	0.19 (0.39)	0.18 (0.39)	0.11 (0.31)	0.19 (0.39)	0.31 (0.46)	10.93 ***
Number of trainings in past 5 years	2.24 (6.01)	1.40 (2.80)	1.13 (2.75)	3.01 (8.27)	3.38 (7.14)	9.76 ***
Farming objective (Subsistence = 1)	0.33 (0.47)	0.19 (0.39)	0.33 (0.47)	0.37 (0.48)	0.41 (0.49)	8.68 ***
Regions (%)						
Central	25.56	12.06	28.88	35.13	19.67	108.23 ***
South-western	37.55	34.17	28.26	33.23	58.58	
Mid-Western	22.68	34.67	28.57	17.41	11.72	
Eastern	14.22	19.10	14.29	14.24	10.04	
BXW Control Package						
Timely removal of male buds (yes = 1)	0.45 (0.50)	0.00 (0.00)	0.14 (0.35)	0.66 (0.47)	1.00 (0.00)	514.52 ***
Cutting down diseased plants/mats (yes = 1)	0.57 (0.50)	0.00 (0.00)	0.40 (0.49)	0.78 (0.42)	1.00 (0.00)	356.20 ***
Disinfecting cutting tools (yes = 1)	0.55 (0.50)	0.00 (0.00)	0.47 (0.50)	0.59 (0.49)	1.00 (0.00)	222.08 ***
Dependent Variables						
Annual value of Matoke (US$/acre)	195.59 (437.42)	124.21 (445.43)	138.17 (287.56)	225.82 (464.84)	292.41 (531.31)	8.18 ***
Annual value of all bananas (US$/acre)	230.11 (973.07)	121.05 (423.36)	244.09 (1616.71)	229.57 (478.77)	302.78 (532.49)	1.30
Annual matoke sales (US$/acre)	93.98 (243.98)	58.86 (250.21)	66.66 (136.42)	106.11 (217.71)	144.00 (352.42)	6.42 ***
Number of observations	1076					

Note: Values in parentheses are standard deviations (SD). 1 US$ = 3550 Uganda Shillings by 2015; ***, and * represent statistical significance at 1%, and 10%, respectively.

2.2. Estimating the Impact of Adopting BXW Control Practices

We established the impact of BXW control package adoption on smallholder banana productivity and incomes. Generally, impact assessment involves estimating the mean effect of adopting a technology (such as the BXW control package), which requires comparison of the outcome variable for the same group of farmers with and without treatment. Consider an outcome to be value of banana production (Y). The impact of adopting a BXW control package could be measured by taking the difference of the mean value of banana production of all farmers who adopted BXW control practices and the mean value of banana production they would obtain had they not adopted the technology (counterfactuals), which is referred to as the average treatment effect (ATE). However, the counterfactual is not observed because a household cannot be in the treated and the control groups at the same time. Use of a plausible control group of non-adopters helps to overcome this dilemma by comparing the outcomes of non-adopters with those of adopters.

The commonly used estimators of average treatment effects can be categorized into parametric estimators (like OLS and probit model), inverse probability weighting estimators, and matching estimators [24]. However, methods based on a propensity score are now widely used to estimate treatment effects [25]. Austin and Mamdani [26] describe four methods of using the propensity score. They include covariate adjustment using the propensity score, stratification on the propensity score, propensity score matching, and inverse probability of treatment weighting using the propensity score. Matching and weighting are among the common ways of using the propensity score to balance the treatment and control groups. Propensity score matching and/or weighting helps to reduce selection bias by balancing the observed distribution of covariates across the treated and control groups. As a result, for a control group to be considered a plausible counterfactual, no systematic differences in the distribution and overlap of covariates should be observed between the treatment and the control group after matching or weighting.

Matching estimators based on propensity score include nearest neighbor matching (NNM), radius matching, kernel matching (KM), and stratification matching [27]. NNM and KM are among the most commonly applied matching estimators and have been applied by authors such as References [28–30] to estimate average treatment effects.

Besides matching, weighting the observations using the propensity score also creates balance between treated and control units in the weighted sample [31]. Weighting methods develop plausible counterfactuals by assigning the inverse of the estimated propensity score to treated individuals whereas non-treated individuals receive a weight equal to the inverse of 1 minus the estimated propensity score [25]. Among the commonly used weighting estimators is the inverse probability weighted (IPW) estimator that models the probability of treatment without any assumptions about the functional forms of the outcome model. However, the estimator becomes extremely unstable as the overlap assumption gets close to being violated and sensitive to misspecification of the propensity score model. Doubly robust approaches are therefore used to improve the efficiency of IPW estimators because they use both the outcome regression model and the propensity score model to derive an estimator that remains consistent if either of the two models is correctly specified [32]. Among the doubly robust estimators is the augmented inverse-probability-weighted (AIPW) estimator developed by Robins et al. [19]. In this study, we use the less applied but theoretically more appealing AIPW to establish impact of adoption of BXW control practices on banana farmers' productivity and incomes.

Because observational data treatment assignment may be related to the covariates that also affect the outcome of interest, covariates must be balanced by matching or weighting so that systematic differences in the distribution and overlap of covariates between the treatment and the control group are removed for proper estimation of treatment effects [33]. We employ the standardized differences and variance ratios tests to check the extent of covariate balancing between the matching estimators (NNM and KM) and the robust AIPW estimator. The test is based on the fact that a perfectly balanced covariate has a standardized difference of zero and variance ratio of one [34].

In impact evaluation literature, although authors [35–37] have expanded estimation of treatment effects from binary to multivalued treatments, limited focus has been given to multivalued treatment assignments, despite the fact that many empirical application treatments are multivalued in nature [37]. This study estimated treatment effects under a multivalued treatment effects framework, following References [38–40]. The treatments included non-adoption; adoption of any one practice; adoption of any two practices; and adoption of three practices.

The *teffects aipw* command in Stata 14 was used to estimate the average treatment effects of the level of adoption of BXW control practice on annual value of matoke production per acre, annual value of matoke sales per acre, and annual value of all banana production per acre. One of the assumptions required to use the treatment effects estimators is the overlap assumption, which states that everyone has a positive probability of receiving each treatment level. The *pstolerance* command in Stata was used to evaluate violation of the overlap assumption. Violation of the overlap assumption occurs if the predicted probabilities are close to 0 or 1 [41]. For the probability to be close to 0 to violate the overlap assumption, Stata uses a default value of 1×10^{-5} as the tolerance level. We used this tolerance level and found that there were no predicted probabilities that violated the overlap assumption. We further tested violation at 0.001 tolerance level and results confirmed no violation of the overlap assumption.

Specifically, a multinomial logit regression (Equation (5)) was used to predict treatment status (level of adoption of disease control technologies) as a function of various covariates. The covariates for the treatment model included; gender, age, age squared, subsistence level of production, information sources on BXW control, off-farm income access, regional dummies, and dummy of if a woman was trained in BXW management.

$$p(y = j) = \alpha + \beta_1\, age + \beta_2\, age^2 + \beta_3\, gender + \beta_4\, subsistence + \beta_5\, information\_source + \beta_6\, offfarm\_income + \beta_7\, woman\_trained + \beta_8\, regions + \varepsilon_i \quad (5)$$

where $p(y = j)$ is the probability of not adopting, adopting any one practice, adopting any two practices, and adopting all three practices. A linear regression model (Equation (6)) was then used to estimate the impact of adoption level of BXW control practices on the outcome variable, Y_i. Outcome variables considered were annual value of matoke production per acre, annual value of matoke sales per acre, and annual value of all banana production per acre. Covariates that were included in the outcome model were land owned, gender, age, subsistence level of production, and regional dummies.

$$Y_i = \alpha + \beta_1 gender + \beta_2 age + \beta_3 subsistence + \beta_4 acreage + \beta_5 regions \ldots \varepsilon_j \quad (6)$$

2.3. Data Collection Methods and Data Sources

Data comes from Uganda, a country where the disease was reported in 2001, continued to spread to all major banana growing regions, and even currently continues to spread into new areas and resurge in areas where it had been managed [2,11,42]. Data were collected from four purposively selected major banana-growing and consuming regions (i.e., eastern, central, mid-western, and south-western) between December 2015 and March 2016. From each region, three districts were randomly selected, totaling 12 districts (Kamuli, Kumi, and Mbale districts from eastern; Kayunga, Kiboga, and Luwero from central; Bushenyi, Rukungiri, and Ntungamo from south-western; and Kabarole, Masindi, and Mubende districts from mid-western region). Two major banana-producing sub-counties were purposively selected per district and from each sub-county one parish was randomly selected. At the parish level, three villages were randomly, totaling to 72 villages for the sample. Seventeen households were randomly selected from each village using a village listing provided by the local council authorities. In so doing, a total of 1224 households were interviewed. However, due to missing data, some responses were dropped.

A pre-tested questionnaire was used to collect data on: Socio-demographic characteristics of the farmer; farmer's objective of growing bananas; farmer training on BXW management; farmer competence in detection of BXW spread mechanisms and BXW control practices; farmer perceptions on effectiveness of the recommended control strategies and dissemination channels; status of BXW at farmer level; control options the farmer is using to manage BXW disease; number BXW trainings received; number of years since BXW peak; number of years since BXW outbreak; and banana production and sales at the current BXW incidence level.

3. Results

3.1. Summary Statistics

Table 1 shows descriptive statistics of respondents disaggregated by the adoption level of BXW control practices. About half of the respondents had received training on BXW control practices with a significantly higher percentage (69%) of BXW control package adopters reporting to have received training on BXW control. On average, farmers received two trainings on BXW in the past five years, but BXW control package adopters received significantly more trainings in the previous five years compared to partial adopters. A significantly larger percentage of households adopted three practices when a woman was trained in BXW control.

A total of 33% of the farmers produced bananas at a subsistence level, of which 41% were using all the three practices in the BXW control package. Among the three BXW control practices, significantly more households practiced cutting down diseased plants/mats, followed by disinfection of tools. Use of timely removal of male buds with a forked stick was the least adopted practice (Table 1). Significant differences were also observed in terms of adoption level of BXW control practices and regions. The eastern region had the highest percentage of farmers who did not adopt any practice whereas south-western Uganda had the highest percentage of farmers who adopted all three practices.

There were significant differences between all outcome variables and level of adoption of control practices. Results show that non-adopters obtained the least value of production and value of sales and the value was highest among the BXW control package users. The results imply that adoption of BXW control practices reduced the disease incidence, and consequently, increased banana yields and sales.

3.2. Farmers' Perceptions on Effectiveness of BXW Control Practices

Farmers' evaluation of the effectiveness of the control practices in controlling BXW showed that more than 80% of the farmers perceived the practices to be very effective at controlling BXW (Figure 1). This presents a great potential for intensifying adoption since farmers' perception significantly influences their adoption decisions [12].

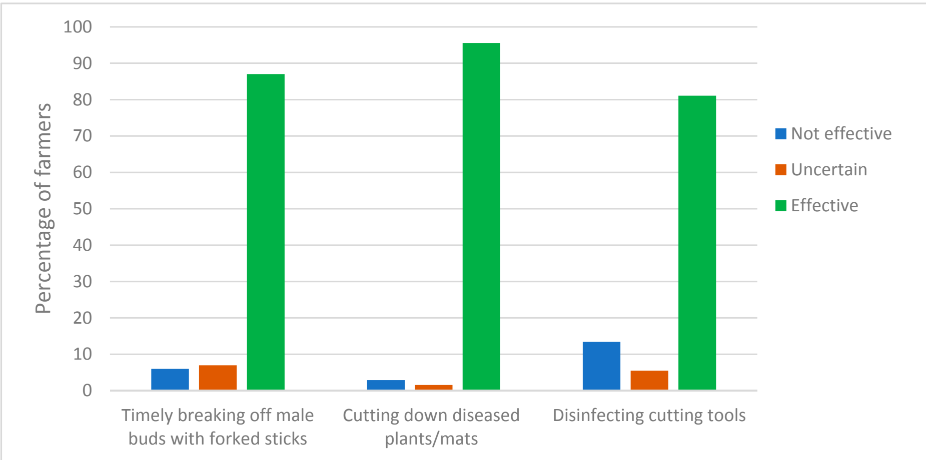

Figure 1. Farmers' perceptions on effectiveness of the BXW control practices. (Source: Survey data).

There were mixed perceptions on the effectiveness of the different sources of information on BXW control (Figure 2). Farmer-to-farmer information exchange, radio talk shows, and exchange visits were perceived to be more effective, whereas short message service (SMS), posters/leaflets, and billboards/posts were perceived as less effective. These results are in line with the earlier study by Tunio et al. [43], which also reported that farmer-to-farmer exchange and radio are the most effective information sources regarding diffusion of recommended technologies among rice growing farmers in Pakistan.

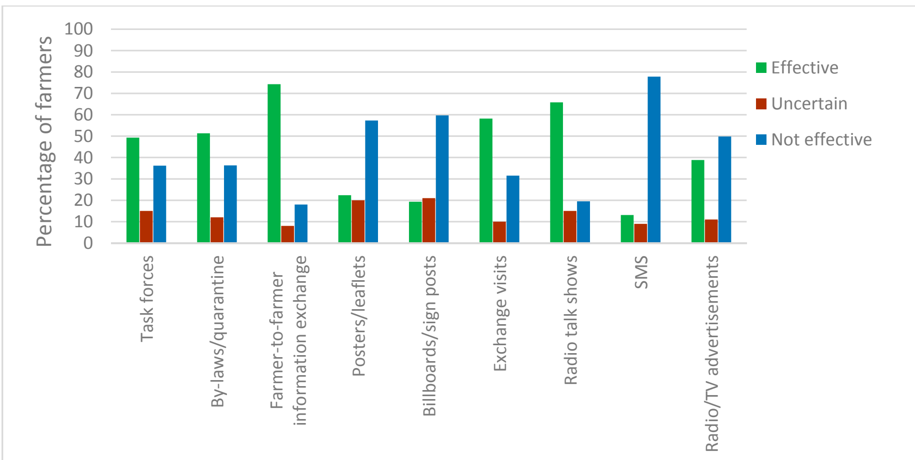

Figure 2. Farmers' perceptions of effectiveness of information sources for BXW control practices. (Source: Survey data).

3.3. Determinants of Adoption of BXW Control Practices

Results of the multinomial logit model show that subsistence farmers are more likely to adopt all the control practices and less likely not to adopt any practice compared to semi-commercial farmers (Table 2).

Table 2. Determinants of adoption of BXW control practices.

Independent Variables	Marginal Effects for the Multinomial Logit Model			
	No Adoption	Use Any One Practice	Use Any Two Practices	Use BXW Control Package
Male-headed HH vs. female	0.015 (0.030)	−0.063 * (0.036)	−0.008 (0.040)	0.055 (0.039)
Age of HHD	0.002 *** (0.001)	0.000 (0.001)	−0.002 ** (0.001)	0.000 (0.001)
Education of HHD (years)	−0.002 (0.003)	−0.003 (0.004)	0.004 (0.004)	0.001 (0.003)
Household size	0.001 (0.004)	0.003 (0.005)	−0.006 (0.005)	0.003 (0.004)
Subsistence (Yes = 1)	−0.154 *** (0.027)	−0.036 (0.029)	0.069 ** (0.029)	0.121 *** (0.026)
S-western vs. central	0.128 *** (0.027)	−0.079 ** (0.036)	−0.194 *** (0.037)	0.145 *** (0.034)
Mid-west vs. central	0.169 *** (0.031)	0.060 (0.042)	−0.171 *** (0.041)	−0.058 * (0.032)
Eastern vs. central	0.102 *** (0.032)	−0.023 (0.046)	−0.076 (0.050)	−0.004 (0.040)
Banana land (acres)	0.005 * (0.003)	−0.008 (0.008)	0.002 (0.005)	0.002 (0.004)
BXW training	0.041 (0.033)	0.018 (0.040)	−0.038 (0.039)	−0.021 (0.036)
Number of trainings in past 5 years	−0.006 (0.004)	−0.011 * (0.006)	0.011 *** (0.003)	0.006 ** (0.002)
HH with Woman trained vs. HH with no woman trained	0.010 (0.032)	−0.083 ** (0.041)	−0.016 (0.037)	0.088 *** (0.030)
Farmer-to-farmer exchange (Yes = 1)	−0.095 *** (0.025)	0.154 *** (0.033)	0.014 (0.034)	−0.072 ** (0.031)
Radio source (Yes = 1)	−0.123 *** (0.023)	0.011 (0.029)	0.087 *** (0.029)	0.025 (0.026)
Exchange visits (Yes = 1)	0.004 (0.025)	−0.092 *** (0.030)	0.030 (0.031)	0.059 ** (0.028)
Off-farm income access (Yes = 1)	0.091 *** (0.022)	−0.023 (0.029)	−0.036 (0.029)	−0.032 (0.026)

Note: Values in parentheses are standard errors. ***, **, and * represent statistical significance at 1%, 5%, and 10%, respectively.

Similarly, the more trainings on BXW control received, the more likely a farmer adopts any two or three of the recommended control practices. Besides, training a woman farmer (in both female- and male-headed households) on BXW management practices increases the likelihood of using all three practices by about 9 percentage points compared to training a male farmer.

Information sources about BXW control technologies showed significant influence on farmers' decisions to adopt. Farmers who accessed information from fellow farmers were more likely to use one control practices; those who accessed information from radio were more likely to adopt two control practices, whereas farmers who accessed information through exchange visits were more likely to adopt all the control practices.

Access to off-farm work increased the probability of not adopting any BXW control practices by 9 percentage points, which is in line with other authors indicating that working off farm may take away productive labor from the farm that can be essential in adoption of BXW control practices [44].

Results further show that regional differences significantly influenced adoption of the control practices. In southwestern region, the probability of adopting all three practices was 14 percentage points higher than in central Uganda. Farmers in mid-western Uganda were more likely not to adopt any of the control practices by 17 percentage points and less likely to adopt all three practices by 6 percentage points compared to those in central Uganda. There was a 10-percentage-point likelihood of not adopting any control practice by farmers in eastern Uganda compared to farmers in the central region.

3.4. Impact of Levels of Adoption of BXW Control Practices on Farmers' Welfare

To show robustness of results, we present standardized differences and variance ratios as diagnostic statistics that check covariate balance between the different estimators after estimating treatment effects (Table A1). It can be seen from Table A1 that both matching estimators and AIPW estimator provide good covariate balance. However, for the AIPW estimator, overall, standardized differences are closer to zero and the variances ratios are closer to one than matching estimators. Based on these results, we conclude that the AIPW is superior in establishing covariate balance than matching estimators and therefore interpretation of impact estimates is based on the results of AIPW estimator.

Using AIPW estimator, results in Table 3 show that impacts of adopting BXW practices on all outcome variables increases with increase in number of practices adopted. For instance, the annual value of all banana production increased by US$139 and US$187 when a farmer adopted any two and all practices, respectively, compared to when the farmer did not adopt any control practice. Significant differences also occurred in value of matoke production for the different levels of adoption, with full-package adopters having the highest production compared to partial adopters. Similarly, the value of matoke sales significantly increased with increase in number of BXW control practices adopted.

Table 3. Impact of adoption of BXW control practices on farmers' livelihoods.

Outcome Variables	Adoption Level	AIPW Estimator
Annual value of Matoke production (USD)	Any one practice vs. no adoption	23.00 (30.67)
	Any two practices vs. no adoption	131.10 *** (37.90)
	BXW control package vs. no adoption	174.68 *** (40.78)
Annual value of matoke sales (USD)	Any one practice. vs. no adoption	14.52 (13.89)
	Any two practices vs. no adoption	60.50 *** (17.19)
	BXW control package vs. no adoption	92.46 *** (21.57)
Annual value of all banana production (USD)	Any one practice vs. no adoption	134.92 (87.63)
	Any two practices vs. no adoption	138.71 *** (37.26)
	BXW control package vs. no adoption	186.87 *** (39.86)
Observations		1036

Note: Values in parentheses are robust standard errors. 1 US$ = 3550 Uganda Shillings by 2015; ***represent statistical significance at 1%.

3.4.1. Distributional Impacts of Adoption Level of BXW Control Practices by Farm Size

Farm size was categorized into small farms (1 acre and below), medium farms (1.001 to 5 acres), and large farms (more than 5 acres). The estimated ATE for each adoption level per outcome variable is the average value that small, medium, or large farms get when they move from non-adoption to adoption of any one, any two, or all three practices (Table 4). For example, farmers with medium and large farms significantly increase their value of all banana production by 207% and 159%, respectively, per acre per year when they adopt all three practices.

Table 4. Impact of adoption level of BXW control practices by farm size.

		Annual Value of Matoke Production (USD) Per Acre		Annual Value of Matoke Sales (USD) Per Acre		Annual Value of All Banana Production (USD) Per Acre	
		Coefficient	**%**	**Coefficient**	**%**	**Coefficient**	**%**
Small Farms							
ATE	Any one practice	−87.31 (116.02)	−34.9	−35.14 (64.55)	−32.6	−105.00 (106.32)	−37.1
	Any two practices	281.78 (190.03)	112.6	158.22 (127.31)	147.0	286.99 (180.06)	101.4
	BXW control package	8.82 (201.81)	3.5	21.83 (78.45)	20.3	−59.65 (246.68)	−21.1
POM	No adoption	250.34 ** (106.62)		107.65 * (61.87)		283.01 *** (96.29)	
Medium Farms							
ATE	Any one practice	19.84 (40.49)	19.5	20.52 (14.66)	51.2	144.43 (120.82)	150.1
	Any two practices	120.87 ** (47.44)	118.6	64.36 *** (17.05)	160.5	137.87 *** (44.44)	143.3
	BXW control package	178.13 *** (54.84)	174.7	105.27 *** (28.99)	262.5	199.94 *** (52.26)	207.9
POM	No adoption	101.93 *** (35.87)		40.11 *** (10.73)		96.19 *** (30.81)	
Large Farms							
ATE	Any one practice	30.53 (56.73)	20.9	11.32 (31.98)	13.9	141.93 (118.96)	110.5
	Any two practices	121.34 ** (60.86)	83.1	38.95 (31.69)	47.9	111.71 ** (55.60)	86.9
	BXW control package	192.55 *** (64.69)	131.8	96.69 ** (45.38)	118.9	204.43 *** (62.42)	159.1
POM	No adoption	146.08 *** (45.39)		81.29 *** (27.07)		128.48 *** (39.95)	

Note: Numbers in parentheses are robust standard errors. 1 USD = 3550 Uganda Shillings by 2015; ***, **, and * represent statistical significance at 1%, 5%, and 10%, respectively.

Small farms do not receive significant benefits from adoption of any level of the control practices compared to non-adoption. For medium farms, the impact of adoption level was significant for all the outcome variables when at least two are adopted but benefits were highest when three practices are adopted. This category increased its value of matoke production, matoke sales, and all banana production by 175%, 263%, and 208%, respectively, when all the three practices are adopted (Table 4). For large farms, the impact of the level of adoption increased for all outcome variables when three practices were adopted. The adoption of all three practices increased the value of matoke production, sales and all banana production by 132%, 119%, and 159%, respectively.

3.4.2. Distributional Impacts of Adoption Level of BXW Control Practices by Participation in Extension Training

The potential outcome means (POM) and average treatment effects (ATE) for trained farmers were higher than that of untrained farmers for all outcome variables and levels of adoption (Table 5). These results confirm the role of extension training in improving farmers' welfare. Farmers trained in BXW management obtain on average 176% more value of matoke production when they adopt all three practices compared to 113% for those who were not trained but adopted the three practices (Table 5). This can be attributed to the latter's failure to correctly apply the disease control practices. There were large positive and significant benefits (216%) for trained farmers in terms of value of all banana production when they move from non-adoption to adoption of all three practices compared to that (101%) for non-trained farmers.

Table 5. Impact of adoption level of BXW control practices by participation in training.

		Value of Matoke Production (USD)		Value of Matoke Sales (USD)		Value of All Banana Production (USD)	
		Coefficient	%	Coefficient	%	Coefficient	%
Trained in BXW Management							
ATE	Any one practice	26.35 (40.65)	20.3	22.72 (20.91)	36.1	43.17 (37.18)	35.9
	Any two practices	203.57 *** (57.62)	157.2	86.44 *** (26.70)	137.3	232.18 *** (55.80)	193.2
	BXW control package	228.48 *** (56.35)	176.4	109.60 *** (34.29)	174.0	259.25 *** (53.56)	215.7
POM	No adoption	129.50 *** (34.47)		62.97 *** (16.78)		120.19 *** (29.72)	
Not Trained in BXW Management							
ATE	Any one practice	7.36 (50.24)	6.5	−3.44 (19.39)	−7.3	215.40 (169.74)	188.1
	Any two practice	27.42 (50.71)	24.1	19.68 (19.81)	41.9	3.79 (49.89)	3.3
	BXW control package	128.46 ** (64.68)	112.8	94.46 *** (29.74)	201.2	116.03 * (63.04)	101.3
POM	No adoption	113.91 ** (45.19)		46.94 *** (16.89)		114.52 ** (45.33)	

Note: Numbers in parentheses are robust standard errors. 1 US$ = 3550 Uganda Shillings by 2015; ***, **, and * represent statistical significance at 1%, 5%, and 10%, respectively.

4. Discussion

This study shows high positive perceptions of effectiveness of BXW control practices by farmers. This presents a great potential for intensifying adoption of the control practices since farmers' perception significantly influences their adoption decisions [12]. In cases where some farmers still perceive the control practices to be ineffective, it may be attributed to incorrect application of the practices. It is therefore vital to continuously empower them with the required knowledge through their preferred communication channels, including farmer-to-farmer information exchange, radio talk shows, and exchange visits. The results on perceived effectiveness of information dissemination sources support results from Tunio et al. [43] that farmer-to-farmer exchange and radio are the most effective information sources regarding diffusion of recommended technologies among rice growing farmers in Pakistan.

Results show positive and significant effects of banana production level, training a woman, use of different information sources, and regional differences on farmers' adoption decisions. Higher adoption likelihood by subsistence farmers could be due to the centrality of the crop to their livelihoods, or the relative ease of adopting the practices on their smaller acreage. The positive effect of training women can be attributed to the fact that they are more engaged in day-to-day management of banana plantations, and therefore, their participation in training increases the probability of adoption.

The positive influence of exchange visits can be attributed to the fact that farmers are practically exposed to the control practices. Exchange visits allow for the explanation of complex issues related to the epidemiology of the disease and control practices. Exchange visits are a highly effective way of motivating farmers, enhancing adoption of improved practices, and opening up communication channels among farmers [45]. The results of significant and positive influence by farmer-to-farmer exchange are in line with Langyintuo & Mekuria [46] who also reported significant contribution of farmer-to-farmer interaction in technology adoption among Mozambican farmers. Our findings also align with those previously reported by Ouma et al. [47] who showed positive and significant effect of radio as a preferred source of information on adoption.

The significant influence of regional differences in adoption decisions can be attributed to the variation in the importance of banana and banana farming objectives across Uganda. Banana is more important in southwestern region where it is a semi-commercial crop, followed by the central region, mid-western region, and least in eastern region. In addition, after the disease outbreak, there were more task forces, by-laws, and ordinances developed to oversee regular surveillance and enforcement control of the disease in southwestern Uganda with active involvement of all banana stakeholders. This implied BXW control was taken as a communal activity rather than individual farmer responsibility, and hence contributed to higher levels of adoption of BXW control practices in southwestern region. These results concur with other studies that regional differences influence farmers' adoption decisions [48,49]. Based on these results, we derive three suggestions that can sustainably improve the adoption process of BXW control practices. First, trainings in BXW management need to be more women inclusive. Second, there should be more concerted efforts to continuously sensitize and train farmers especially in eastern and mid-western regions as these regions can be important sources of inoculum. Third, dissemination of BXW control messages should incorporate and strengthen farmer-to-farmer information sharing, use of radios and exchange visits to significantly achieve maximum benefits of adoption of the recommended control practices.

Our findings further show positive and significant impact of adoption of BXW control practices on banana farmers' productivity and sales. We therefore infer that adoption of these cultural control practices significantly reduced disease incidence levels, and subsequently increased banana production and sales. However, maximum benefits from the control practices accrued when they are used as a BXW control package. This finding is in line with References [2,12,15] who indicated that effective management of BXW is achieved when the practices are adopted as a package. Study findings also report gains from adoption of BXW control technologies to be lower for small-sized banana farms (whose priority crops may not be bananas) than for medium and large-sized farms. We therefore suggest that technologies that focus on reducing disease incidence levels are likely to have more benefits if targeted towards farmers that consider the crop under context as their main priority.

More positive and significant benefits of adoption of control practices were observed for farmers who participated in BXW trainings from public extension than those who did not participate in the trainings. These results are in line with Nakano et al. [50] who also reported more benefits in paddy yield for trained farmers compared to those for farmers who were not trained. This also confirms the study by Gautam et al. [51] that reported significantly higher crop yields and gross margins among trained farmers in IPM in Bangladesh than non-trained ones. The results indicate that some farmers, though not trained through public extension, access information about BXW management from other sources like fellow farmers, which helps them reduce BXW incidence and hence improve their production and income. This underscores the role of diverse information dissemination channels other than the public extension trainings in improving farmers' welfare.

5. Conclusions

Banana Xanthomonas Wilt is the major biotic threat to banana production in East and Central Africa that can cause 100% crop losses, hence threatening the incomes and food security of millions of farmers in the region. This paper contributes to the growing literature on infectious disease management by identifying preferred and appropriate pathways to disseminate the recommended control practices and factors responsible to sustain the adoption process. Differing from previous studies that dichotomously measure adoption, this study disentangled adoption into non-adopters, partial, and full adopters to reveal important differences that influence adoption decisions. Further, the study extended the use of a doubly robust and theoretically attractive estimator, AIPW, to agricultural technology adoption literature and provide efficient estimates of the impact of adoption of the disease control practices.

The study results showed that adoption of all three cultural practices—(1) timely removal of male buds with forked sticks, (2) cutting down diseased plants/mats, and (3) disinfecting cutting tools—significantly reduced the disease incidence and increased the value of banana production by USD187 and banana income by more than USD90 per acre per annum. However, accrued benefits differed by farm size, participation in training, and the number of control practices adopted, with the highest benefits accrued when all the control practices were adopted.

These findings suggest that women-inclusive trainings and farmer-preferred information dissemination pathways can sustainably increase adoption of recommended cultural control practices in countries where the disease exists or where it is expected to spread and emerge. Similarly, the smaller the banana farm size, the more likely the farmer will adopt at least one of the BXW control practice, and, if adopted as a package, the more income received per annum. This paper also confirms that the application of a combination of cultural practices focusing on (1) avoiding introduction of the disease into fields, (2) preventing insect-mediated infections and contaminated farm tools, and (3) reducing disease inoculum load in infected fields can be an effective way for controlling infectious plant pathogens such as BXW. It should, however, be noted that cropping systems, particularly in Africa, are also constrained by many other production and socioeconomic factors. Given variations in farmers' resource outlay, it is worthwhile to invest in understanding these constraints which are likely to affect farmers' adoption potential, and in turn, reduce adoption benefits.

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Appendix A

Table A1. Standardized differences for covariates balancing for each estimator (Matching estimators vs. AIPW).

	NN5				Kernel				AIPW			
	Std. Differences		Variance Ratio		Std. Differences		Variance Ratio		Std. Differences		Variance Ratio	
	Raw	Matched	Raw	Matched	Raw	Matched	Raw	Matched	Raw	Weighted	Raw	Weighted
Use any one* vs. *no adoption												
Male-headed HH (Yes = 1)	−0.05	−0.02	1.05	1.02	−0.05	−0.10	1.05	1.10	−0.03	−0.01	1.04	1.01
Age of HH head	−0.05	0.02	1.05	1.04	−0.05	0.00	1.05	1.06	−0.08	0.00	1.09	1.04
Age squared	−0.04	0.02	0.96	0.98	−0.04	0.00	0.96	0.98	−0.06	0.00	0.98	0.97
Subsistence (Yes = 1)	0.30	0.15	1.34	1.18	0.30	0.08	1.34	1.06	0.31	0.02	1.38	1.02
S-western vs. central	0.01	−0.01	1.01	0.99	0.01	0.04	1.01	1.05	−0.01	0.05	0.99	1.04
Mid-west vs. central	−0.03	−0.04	0.98	0.97	−0.03	0.05	0.98	1.04	−0.04	−0.01	0.96	0.98
Eastern vs. central	−0.39	−0.02	0.63	0.98	−0.39	−0.06	0.63	0.94	−0.36	0.02	0.63	1.03
BXW trainee (woman = 1)	0.00	0.00	0.99	1.00	0.00	0.04	0.99	1.08	−0.01	0.06	0.97	1.09
Farmer-to-farmer (Yes = 1)	0.63	0.21	0.94	0.98	0.63	0.03	0.94	1.00	0.67	−0.05	0.90	1.03
Radio source (Yes = 1)	0.53	0.18	1.14	1.03	0.53	−0.08	1.14	0.99	0.55	−0.02	1.13	1.00
Exchange visits (Yes = 1)	0.23	0.06	1.13	1.04	0.23	0.08	1.13	1.06	0.24	0.11	1.13	1.02
Off-farm income (Yes = 1)	−0.21	−0.16	0.91	0.93	−0.21	0.03	0.91	1.01	−0.22	−0.01	0.91	0.99
Use any two* vs. *no adoption												
Male-headed HH (Yes = 1)	0.17	0.04	0.80	0.94	0.17	0.03	0.80	0.96	0.18	0.00	0.79	1.00
Age of HH head	−0.17	−0.06	0.99	1.03	−0.17	0.13	0.99	1.05	−0.21	−0.01	1.02	1.05
Age squared	−0.17	−0.06	0.90	0.99	−0.17	0.13	0.90	1.08	−0.20	0.00	0.91	1.01
Subsistence (Yes = 1)	0.39	0.26	1.40	1.27	0.39	0.01	1.40	1.01	0.42	0.04	1.45	1.03
S-western vs. central	0.12	−0.01	1.12	0.99	0.12	0.00	1.12	1.00	0.10	0.10	1.09	1.07
Mid-west vs. central	−0.32	−0.07	0.67	0.92	−0.32	0.03	0.67	1.04	−0.34	−0.03	0.65	0.95
Eastern vs. central	−0.34	−0.04	0.68	0.96	−0.34	−0.04	0.68	0.97	−0.32	0.00	0.67	1.00
BXW trainee (woman = 1)	0.17	0.05	1.31	1.08	0.17	−0.06	1.31	0.91	0.15	0.05	1.26	1.07
Farmer-to-farmer (Yes = 1)	0.63	0.23	0.94	0.96	0.63	0.08	0.94	0.99	0.66	0.03	0.90	0.98
Radio source (Yes = 1)	0.69	0.26	1.07	1.00	0.69	0.05	1.07	1.00	0.71	0.02	1.06	0.99
Exchange visits (Yes = 1)	0.45	0.16	1.16	1.05	0.45	0.15	1.16	1.05	0.46	0.15	1.14	1.02
Off-farm income (Yes = 1)	−0.25	−0.15	0.89	0.93	−0.25	0.12	0.89	1.05	−0.25	0.02	0.89	1.01

Table A1. *Cont.*

	NN5				Kernel				AIPW			
	Std. Differences		**Variance Ratio**		**Std. Differences**		**Variance Ratio**		**Std. Differences**		**Variance Ratio**	
	Raw	**Matched**	**Raw**	**Matched**	**Raw**	**Matched**	**Raw**	**Matched**	**Raw**	**Weighted**	**Raw**	**Weighted**
Use all three* vs. *no adoption												
Male-headed HH (Yes = 1)	0.32	0.09	0.61	0.87	0.32	−0.05	0.61	1.08	0.34	−0.02	0.58	1.03
Age of HH head	−0.10	−0.12	1.22	1.09	−0.10	−0.08	1.22	1.01	−0.12	−0.11	1.25	1.01
Age squared	−0.07	−0.10	1.21	1.10	−0.07	−0.08	1.21	1.01	−0.08	−0.10	1.22	1.00
Subsistence (Yes = 1)	0.43	0.37	1.42	1.41	0.43	−0.04	1.42	0.97	0.42	−0.03	1.46	0.97
S-western vs. central	0.66	0.13	1.28	1.04	0.66	0.02	1.28	1.01	0.65	0.04	1.23	1.03
Mid-west vs. central	−0.43	−0.12	0.54	0.84	−0.43	−0.04	0.54	0.95	−0.47	0.01	0.50	1.01
Eastern vs. central	−0.57	−0.06	0.42	0.92	−0.57	0.05	0.42	1.07	−0.53	0.00	0.43	1.00
BXW trainee (woman = 1)	0.46	0.12	1.72	1.17	0.46	0.07	1.72	1.10	0.44	0.01	1.64	1.02
Farmer-to-farmer (Yes = 1)	0.67	0.12	0.91	0.98	0.67	0.08	0.91	1.00	0.70	−0.08	0.88	1.04
Radio source (Yes = 1)	0.75	0.20	1.04	1.02	0.75	0.06	1.04	1.01	0.76	−0.04	1.03	1.01
Exchange visits (Yes = 1)	0.62	0.15	1.11	1.02	0.62	0.05	1.11	1.00	0.62	0.11	1.08	1.02
Off-farm income (Yes = 1)	−0.23	−0.23	0.90	0.91	−0.23	0.08	0.90	1.04	−0.24	0.05	0.90	1.03

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