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Direct and spillover effects of biofortified sweetpotato interventions on sustained adoption in Malawi

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ABSTRACT

Agriculture-nutrition interventions (ANI) have recently received attention as a promising delivery mechanism for achieving desirable nutritional outcomes. However, more evidence is needed on the effectiveness of such interventions. In this study, we analyze direct and spillover effects of ANIs for biofortified orange-fleshed sweetpotato (OFSP) in Malawi on sustained household outcomes: OFSP adoption, area planted, harvest, and sales. In Malawi, we selected three large-scale OFSP interventions and use a rich dataset of 2,492 smallholder farmers selected from every district of Malawi. Methodologically, we employ bivariate probit, instrumental variables, and propensity score matching techniques. We find positive and sustained participation effects for all outcomes. Second, we find that OFSP interventions spilled over and benefited non-participants who lived in treatment villages. Vine multipliers and vine conservation techniques were key diffusion mechanisms for initial and sustained adoption of OFSP varieties. Interventions promoted higher OFSP root sales which suggests that generating income is an important motivator of adoption, in addition to own-consumption. Also, root sales is an often overlooked diffusion mechanism to reach additional farmers beyond the direct participants. Relevant for policymakers is that OFSP interventions have sustained positive adoption and diffusion effects, and thus feature well as a relatively cost-effective food-based approach among other strategies to eradicate hidden hunger. Designing ANIs with strong supply-push (e.g., (de)centralized vine multipliers, vine conservation techniques) and demand-pull components (e.g., participatory varietal selection and agronomic training) are key and will need to be accompanied by strategies that create a stronger economic case for OFSP, for instance, by investments to strengthen a processing industry for OFSP roots.

1. Introduction

In the stride against hidden hunger, agriculture-nutrition interventions (ANI) have undoubtedly received increasing attention, especially regarding the beneficial nutrition and health effects for smallholder farmers (Kerr et al., 2011; Jenkins et al., 2015; Kumar et al., 2018; Marquis et al., 2018; Ruel et al., 2018; Sharma et al., 2021; Dizon et al., 2021). ANIs have become important vehicles to deliver biofortified crops, such as vitamin A rich orange-fleshed sweetpotato (OFSP), and have risen to become a leading food-based approach in many developing countries (Low et al., 2007; Low and Thiele, 2020). For OFSP, nutrition outcomes are promising: the consumption of OFSP combined with community-based nutrition education has been found to contribute to a reduced prevalence of diarrhea in children under the age of five years (Jones and de Brauw, 2015) and improved nutrition status (Low et al., 2007; Hotz et al., 2012; de Brauw et al., 2015).

Maintaining these desirable outcomes can only be achieved if biofortified crops are available and adopted beyond the initial years of often short-lived ANI operations. ANIs' design and components considerably determine adoption (and thus nutrition and health) outcomes and how sustainable these are. Evidence of intervention-related drivers of sustained technology diffusion and other outcomes are beginning to

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emerge, such as (intensity of) nutrition training (De Brauw et al., 2018), nutrition-health messaging (Okello et al., 2019), or refresher trainings for non-participating households (Nielsen et al., 2018). As this strand of literature is growing, more evidence is needed of what factors worked and why (Di Prima et al., 2022).

Add to this that evidence of sustained adoption – after ANIs ended – is scant. In fact, adoption as well as nutrition and other livelihood outcomes are often measured too close to the intervention/treatment (e.g., de Brauw et al., 2018; Shikuku et al., 2019; Ogutu et al., 2020). Despite important insights regarding initial adoption decisions and short-term impacts, these studies provide little understanding of sustained adoption and medium- to longer-term outcomes. More recently, a growing body of literature has started to analyze and define sustained adoption and other outcomes at least 2 years post intervention/treatment (Wade and Claassen, 2017; de Brauw et al., 2019; Vaiknoras et al., 2019; Amadu et al., 2020a, Amadu et al., 2020b; Dillon et al., 2020).

In addition, ANI spillover effects are important for achieving desirable nutritional outcomes beyond the targeted direct project beneficiaries. All too often, however, spillover effects represent a to-be-controlled-for contamination rather than subject of investigation (Benjamin-Chung et al., 2017; Vaiknoras et al., 2020). The literature on spillover effects in the context of ANIs is thin, but evidence points to positive spillover effects of ANIs on adoption of improved varieties and other (nutrition) outcomes (Bocher et al., 2017; Dillon et al., 2020; Vaiknoras et al., 2020). The total ANI effects on any outcome, may it be adoption or nutrition, need to be inclusive of spillover effects.

The main objective of this study is to analyze direct and spillover effects of agriculture-nutrition interventions on sustained adoption. In more detail, we examine the effects of OFSP interventions on participants and non-participants at least two years after programs ended. The second objective is to assess the same direct and spillover effects on other outcomes, such as area planted to OFSP, harvest/production, and sales. While this study does not provide evidence on specific nutrition outcomes of biofortified crops (e.g., consumption, diet diversity, etc.), the focus is on examining adoption – a precondition of second-order outcomes, including nutrition. This study provides evidence on what (ANI and components) works for adoption and other outcomes, for whom (participants and spillover), and for how long (beyond ANI end).

As case study, we use three large-scale OFSP interventions in Malawi which were implemented between 2014 and 2021. These interventions are similar to other aid-funded ANIs that introduce and promote biofortified crops in Sub-Saharan Africa (de Brauw et al., 2018; Mwiti et al., 2015). OFSP interventions, like others, frequently work in collaboration with international research for development organizations, governments, non-governmental organizations, in-country government extension services, and lead farmers to disseminate and promote agricultural technologies and are often funded by multilateral organizations (Low et al., 2017).

Given the simultaneous implementation of several OFSP interventions in Malawi, experimental designs built into projects (e.g., de Brauw et al., 2018), were not feasible. Instead, we conducted an ex-post cross-sectional analysis using a sample of 2,492 rural households from all districts of Malawi representative of beneficiaries who received OFSP through ANIs. Participants were selected relying on monitoring and evaluation (M&E) data available for the study years and areas. The study design also involves a control group consisting of villages that were not targeted by any OFSP intervention prior to data collection. M&E data comprising of some 70,000 observations were used to create an instrumental variable to control for endogeneity and selection bias in project participation.

For policy-makers, donors, and international organizations our study holds importance. This study provides first-time rigorous evidence of success of OFSP ANIs – in terms of (sustained) adoption and other diffusion mechanisms – in Malawi. This is striking given Malawi ranks first among 119 countries where OFSP cultivation is an important food-based approach to combat vitamin A deficiencies (Harvest Plus, 2021). Our evidence is also relevant for policy-makers in other countries and under-evaluated biofortified crops, particularly for those with distinct morphological characteristics (e.g., flesh color), like biofortified cassava and maize. Against the background that great progress has been achieved in reducing prevalence of vitamin A deficiencies in many low- and middle-income countries, such as Malawi (NSO, 2017), debates have sparked about when and how to scale back costly Vitamin A supplementation programs while shifting responsibility of sustained vitamin A delivery mechanism to food-based approaches, such as biofortified crops and industrial food fortification (GAVA, 2019). To support this discussion, more evidence on what diffusion mechanisms work, for whom, and for how long, is urgently needed.

This paper is organized as follows. In the background section, we present information on agriculture- nutrition OFSP interventions in Malawi. We then embed our study in a theoretical framework and present our analytical strategy before we present and discuss our results. The last section concludes and ends with policy implications.

2. Background

2.1. Agriculture-nutrition interventions in Malawi

Since 2009, a total of six OFSP ANIs were implemented in Malawi by the government and in collaboration with NGOs and the International Potato Center (Gatto et al., 2021a). OFSP interventions differed considerably from one another in terms of starting year, implementation period, beneficiary targets, regional focus, and distributed varieties (see Table 1). For instance, the intervention – *Rooting Out Hunger* – focused on a single local OFSP landrace, Zondeni, which was officially recommended for release in 2008 and disseminated through this delivery project in 2009–2016. The remaining interventions promoted five new orange-fleshed varieties (i.e., Anaakwanire, Mathuthu, Kaphulira, Kadyaubwerere and Chipika) which were bred in Malawi, released in 2011, and disseminated as of 2014/2015.

Implementation and scaling of OFSP ANIs were led by over 40 different national and NGO partners. Project participation followed two criteria which were applied across all projects: households had at least one child under five years of age or at least one household member was pregnant or breastfeeding. Based on these eligibility criteria, implementing partners worked together with village leaders to select participants.

Participants received different forms of training and were exposed to different nutrition messaging formats, depending on the project. The differences and similarities of selected projects are listed in Table 2. Reception of 1–2 bundles of OFSP vines,[1] agronomic training, and participation in mother-baby-trials[2] were integral parts of every intervention. As initial vine amounts were limited, the mother-baby trials served the multiplication of the initial bundles of distributed vines to also reach non-participating farmers.

Other supply and demand creating mechanisms are noteworthy. For instance, large-scale and centralized vine multipliers were used in the project "Scaling Up Sweetpotato for Agriculture and Nutrition"

[1] 1 bundle of vines consists of 100 cuttings which can cover about 12.5% of an acre if standard recommended farming practices are followed (Stathers et al., 2018) and yield >300kg of roots, assuming average yields of 7t/ha (Van Vugt and Franke, 2018).

[2] A mother-baby trial is an on-farm participatory approach to demonstrate varietal performance and training on recommended agronomic practices. Typically, there are two types of trials. In the *mother* trial, OFSP varieties are planted under recommended agronomic best practices on-farm for demonstration purposes. In the *baby* trial, OFSP varieties are planted by farmers under farmer management and farmer resources (Witcombe et al., 2005).

Table 1
OFSP interventions - key descriptors.

No.	Project name	Start	End	Direct Beneficiaries (HH)	Region	Number of Disseminated Varieties
1	Rooting out Hunger	2009	2016	106,000	Central, South	1
2	SUSTAIN I	2014	2017	75,000	North, Central, South	2–6
3	MISST	2015	2019	55,000	Central, South	2–6
4	RTC-Action	2016	2021	44,000	South	2–6
5	DIVERSIFY	2017	2020	3,000	South	2–6
6	SUSTAIN II	2018	2019	30,000	North, Central	2–6

Source: Gatto et al., (2021a); 1 = Zondeni, 2 = Anaakwanire, 3 = Mathuthu, 4 = Kaphulira, 5 = Kadyaubwerere 6 = Chipika; SUSTAIN= "Scaling Up Sweetpotato for Agriculture and Nutrition"; MISST= "Malawi Improved Seed Systems and Technologies"; RTC-Action= "Root and Tuber Crops for Agricultural Transformation"; DIVERSIFY= "Developing Integrated Value Chains to Enhance Rural Smallholders' Incomes and Food".

Table 2
Project activities for selected OFSP projects.

Project activity	SUSTAIN I	MISST	RTC-Action
Vine dissemination	X	X	X
Mother-baby trials	X	X	X
Agronomic training	X	X	X
Nutrition counselling	X		X
Nutritional sensitization: radio	X	X	X
Nutritional sensitization: flyer	X	X	X
Demand creation: drama, theater, songs		X	
Demand creation: cooking & recipes	X		X
Demand creation: media		X	X
Post-harvest training: grading/sorting	X	X	X
Post-harvest training: packaging			X
Post-harvest training: transportation capacity			X
Post-harvest training: triple S			X
Market linkages: fresh roots	X	X	X
Market linkages: processing			X

Source: Gatto et al., (2021a). SUSTAIN= "Scaling Up Sweetpotato for Agriculture and Nutrition"; MISST= "Malawi Improved Seed Systems and Technologies"; RTC-Action= "Root and Tuber Crops for Agricultural Transformation".

(*SUSTAIN 1*)[3] while other projects relied on many (de)centralized vine multipliers. (De)centralized vine multipliers received financial support which covered production costs, training, and high-quality planting material of OFSP varieties the projects aimed to disseminate. In addition, training sessions on market linkages for fresh root and vines were provided to participants with the aim to increase economic value of OFSP varieties and stimulate market exchanges. On the demand side, projects implemented, for example, extensive nutritional training sessions, such as cooking demonstrations, theaters, flyers or OFSP songs to sensitize many farmers – participating and non-participating. The intervention "Root and Tuber Crops for Agricultural Transformation" (*RTC-Action)* used intensive nutrition counselling sessions for sensitization and demand creating purposes. By 2021, a total of over 300,000 direct beneficiaries[4] (the total figure including indirect beneficiaries is higher) have been reached with biofortified OFSP varieties and intervention-related activities (Gatto et al., 2021a).

3. Materials and methods

3.1. Theoretical framework

In this section, we draw out the impact pathways that show the effects of OFSP ANIs on the relevant household outcomes. We embed this impact pathway in a framework of project cost-effectiveness and post-project continuity. This allows us to better understand how project intervention components, non-participants first- and second-order outcomes – e.g., OFSP adoption, harvest, sales, or consumption[5] – contribute to the cost-effectiveness of projects and "lasting" behavioral changes of smallholder farmers. This theoretical framework is illustrated in Fig. 1.

The impact pathway starts with a project or intervention, its objectives, and components (e.g., vine dissemination, agronomic training, nutrition training and counselling, marketing training) selected participants receive and are exposed to at project start in time 0. Adoption[6] of OFSP vines is required to participate in the agronomic training, particularly mother-baby trials. During the harvest of mother-baby trials, some of the vines are shared with/given to other community members while the remaining vines are kept for the next season. The roots that are harvested are either consumed, shared, or sold at local (spot) markets. In subsequent years, planting material are either accessible through preserving own vines, from others, or through (de)centralized vine multipliers, which are established by projects. In contrast to initial adoption of OFSP, now decisions are made on the extent of adoption – i.e., continue or discontinue the adoption of OFSP, area planted to OFSP and consequently harvested. Again, decisions are made on whether to consume, sell/share, or preserve vines and roots, and household-level outcomes can be observed for vitamin A deficiency levels, diet diversity, income, etc. (Ruel et al., 2018; Sharma et al., 2021; Dizon et al., 2021).

The 'participants space' (quadrants A & B in Fig. 1) is traditionally the focus of scientific investigation. The 'non-participants space' (quadrants C & D in Fig. 1) is where project spillover – often referred to as diffusion – occurs. Such spillovers mostly happen if non-participating households live in geographical or social proximity to participating households (Aramburu et al., 2019). Rather than directly receiving vines from the project in the year of implementation (t0), these indirect beneficiaries receive vines and roots through farmer-to-farmer diffusion. Diffusion usually takes one or more seasons (Okello et al., 2019). However, in t0, non-participants can be exposed to project activities that are non-exclusive, such as agronomic practices, through radio-broad casts, songs, flyers, theaters which may sensitize them and result in increased root consumption in t0 and higher probability of adoption/planting in sub-sequent years. Here, the amounts of OFSP roots sold (and thus consumed by others) will be an important outcome variable that allows for the exploration of whether ANIs can benefit non-participating populations through participants who received planting material. At the same time, root sales are indicative of the economic value of OFSP and of generating additional incomes which, in turn, presents an additional driver of OFSP adoption, next to own consumption. While people can be excluded from receiving training, the acquired agricultural knowledge is non-exclusive and can be shared in social networks. Vines produced

[3] SUSTAIN projects were implemented in two phases. SUSTAIN 1 project was implemented during 2014–2017 while SUSTAIN 2 was implemented during 2018–2019. For more details, refer to Gatto et al., (2021a).

[4] In this paper, being a beneficiary of an OFSP intervention is a synonym for being a participant in an OFSP intervention.

[5] Despite consumption is not the study focus, it is important to mention in the theoretical framework.

[6] Despite participants decide to "adopt" OFSP vines, they did so by receiving vines at no costs through the project in t0.

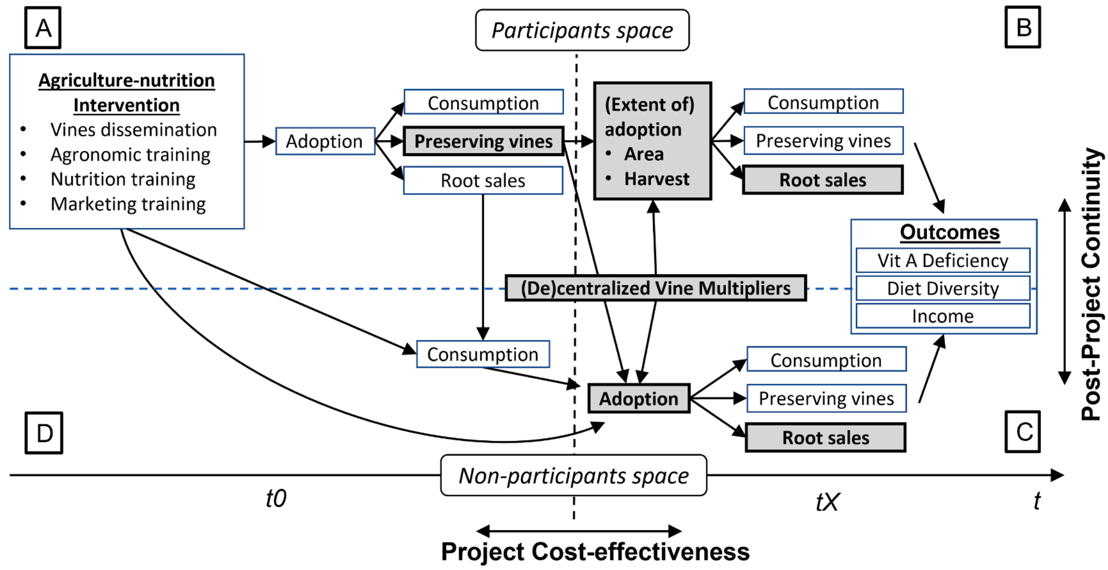

Fig. 1. Theoretical Framework. Notes: Project cost-effectiveness can be defined as the degree to which a project is effective in meeting its objectives in relation to project costs. It is mostly calculated by comparing actual implementation costs between different interventions (e.g., De Brauw et al., 2018). Illustrated, effects that occur in (1) 'non-participants space' and (2) all effects that occur after projects end in time X (quadrants B, C, D Fig. 1) all contribute to increased cost-effectiveness of ANIs. Post-project continuity is defined as those project effects that occur after projects end in time X (quadrants B & C in Fig. 1).

from vine multipliers are also non-exclusive as all interested farmers can access those vines. Among these mechanisms, radio programs can seamlessly transfer knowledge beyond village boundaries, potentially sensitizing any household on nutritional benefits of OFSP. Spillover effects may follow various pathways. In our case, social network theory is most suitable according to which farmers adopt new technologies if they observe the benefits and constraints of adoption in their social family and friends' networks (e.g., Bandiera and Rasul, 2006; Ward and Pede, 2015; Vaiknoras et al., 2019).

3.2. Data

We purposively selected three of the six OFSP interventions (i.e., SUSTAIN 1, RTC-Action, MISST) for this study (see Table 1). The reasons are twofold: first, in following our objective to examine sustained adoption, that is, at least 2 years post intervention, implementation was required to take place at least 2 years earlier than the year of data collection (2019). This corresponds to the year 2017. Second, to rule out any outcome differences stemming from heterogeneity in varietal genetic gains, selected interventions all disseminated the same set of OFSP varieties (i.e., Anaakwanire, Mathuthu, Kaphulira, Kadyaubwerere and Chipika). The selected OFSP interventions jointly covered every district of Malawi which were all included in our study. The multi-stage sampling procedure relied on established M&E records through which OFSP intervention areas could be clearly identified.[7] Based on this knowledge, in every district we randomly selected first Extension Planning Areas – the next lower administrative border below a district – and then treatment villages which were included in OFSP intervention. The identification of control villages (i.e., villages without any OFSP intervention in the past) also relied on M&E records. In every district, we created lists of Extension Planning Areas where OFSP interventions had not been implemented. Once these non-OFSP intervention Extension Planning Areas were identified and randomly selected, villages were also randomly selected from established village lists. Village leaders were contacted prior to data collection to verify if OFSP intervention had occurred in intervention villages and, in turn, had not occurred in control villages. Infrequently, we had to replace a village. Noteworthy, despite that villages were selected based on non-OFSP intervention, farmers in control villages may have adopted OFSP, as a spillover from OFSP interventions.

Probability proportionate to size sampling method was used to account for differences in OFSP interventions with higher intervention intensities observed in the southern and central parts of the country compared to the North.

We collected a rich dataset of 2,492 randomly selected households sampled from 166 villages across all districts of Malawi. The sample is representative of beneficiaries who received OFSP through ANIs in Malawi. In this study, *participation* is defined as a household that directly received 1–2 bundles of OFSP vines in addition to agronomic training, and attended mother-baby trials all through the same OFSP intervention. To address our study objective – to analyze direct and spillover effects of agriculture-nutrition interventions - we randomly selected 1,439 participating and 666 non-participating households from treated villages that received an OFSP intervention. An additional 387 households were selected from control villages that did not receive an OFSP intervention in the past. This sampling strategy was based on a power calculation performed prior to data collection (for more details, see Gatto et al., 2021a).

For participants, M&E data were used to establish household lists prior to data collection. At the time of interviews, participants were clearly identified by cross-checking recipients' names with respondents' names. For non-participants, complete household lists were established with the help of village leaders prior to data collection. Non-participants were eligible to be interviewed if they cultivated sweetpotato in the past. Infrequently, we initially sampled farmers who turned out to be a participant but were not recorded in M&E lists. If this was the case, the farmer was replaced by another non-participating farmer at the time of the interview.

Data collection took place between May and August 2019. The household survey consisted of a questionnaire which was enumerated using tablets. In addition, a short village-level questionnaire was enumerated with village leaders also using tablets. Both household- and village-level questionnaires were refined using enumerator local knowledge and inputs. During the two-week training we ensured that

[7] While MISST and SUSTAIN I projects started in the years 2015 and 2016, respectively, unfortunately, M&E data is unavailable for these 2 years. This is unfortunate because its inclusion would have allowed for an analysis going back 4 years instead of 2 years.

every question was adequately addressed and translated into local languages. The questionnaires were piloted extensively prior to data collection. Ethical clearance for the study was obtained from the National Committee on Research Ethics in the Social Sciences and Humanities in Malawi (Reference number: NCST/RFF/2/6).

3.3. Modelling direct effects of OFSP interventions

The study objective is to analyze direct and indirect effects of OFSP agriculture-nutrition interventions. To achieve this, participation effects of ANIs are examined at least two years after project ended. Households are assumed to participate in OFSP interventions if the utility of participation (U^p) is larger than the utility of non-participation (U^{np}). Whereas the utility of participation cannot be observed, we do observe the decision to participate (P). Formally, we can write:

$$P = 1 \text{ if } U^p > U^{np} > 0; \tag{1}$$

$$P = 0 \text{ if } U^{np} > U^p > 0$$

Based on Eq. (1), the participation decision can be formulated as a latent variable, expressed as:

$$P_h^* = \beta Z_h + \zeta_h, \text{ for } P = 1, P_h^* > 0 \tag{2}$$

Where P_h^* is a latent variable that indexes household participation (P) equal to 1 if the household was a participant in 2016/2017 and 0 if the household was living in a control village; Z_h is a vector of household- and village-level determinants of OFSP project participation; β is a vector of coefficients to be estimated; and ζ is a normally distributed error term with zero mean and constant variance.

Based on Eq. (2), we further express the outcome equation as a binary probit model in which participation in intervention villages is included as dummy variable alongside other covariates:

$$Y_h = \theta P_h + \eta X_h + \xi_h, \tag{3}$$

where Y_h is 1 if a household adopted OFSP in 2019 and zero otherwise; P_h is the OFSP project participation dummy with participation occurrence in 2016/2017; X_h is a vector of determinants affecting OFSP adoption, such as household characteristics, project-related factors, and climatic shocks; θ and η are coefficients to be estimated; and ξ is the error term which is robust to heteroscedasticity.

3.4. Modeling indirect effects of OFSP interventions

Using a probit model, indirect or spillover effects can be expressed as follows:

$$Y1_h = \alpha_1 + \alpha_2 NonP_h + \alpha_2 X1_h + \varepsilon_h \tag{4}$$

Where $Y1_h$ is 1 if the household adopted an OFSP variety in 2019 and zero otherwise; $NonP_h$ is 1 if the household is a non-participant living in an intervention village and 0 if the household was living in a control village without intervention; $X1_h$ is a vector of household- and village-level determinants of adoption; ε_h is the error term which is robust to heteroscedasticity and assumed to be normally distributed.

3.5. Alternative outcome variables

An important outcome variable to assess in the context of our study is market sales of OFSP roots because through market exchanges diffusion is promoted, and likely demand created. In addition, in the base model we modeled adoption as a binary variable. As a robustness check, we introduce alternative measures of adoption, such as area planted to OFSP in 2019 and quantities of OFSP roots produced in 2019. As these are continuous outcome variables, we employ instrumental variables models.

3.6. Endogeneity and self-selection

Participation in OFSP interventions occurred in a non-random fashion. Firstly, lead farmers were often selected to support the multiplication and dissemination of initial limited vine bundles, in addition to the mentioned eligibility criteria. Hence, farmers self-selected into project participation. While there are many observable factors we can control for, we are more concerned about factors we did not measure, many of which are unobservable, such as relationship with village elite who decided on the final selection of participating farmers, personal motivation and entrepreneurial ability. If endogeneity was left unaddressed, these unobservable covariates could lead to biased estimates.

We employ recursive bivariate probit (RBP) models to account for endogeneity while simultaneously controlling for selection bias in the assignment of treatment (Li et al., 2019). The RBP was selected because there were two interrelated decisions that the farming household had to make: (1) to participate in the ANI and (2) to adopt OFSP. The RBP model is a higher-level extension of the normal probit regression model estimated in a similar context as a seemingly unrelated regression model due to the correlation in the disturbance terms of participation in the ANI equation and adoption of the OFSP equation (Heckman, 1978). RBP models are being increasingly applied in impact assessment studies with binary outcome variables (Abdulai, 2016; Ma et al., 2018; Amadu et al., 2020a). Unlike popular matching techniques used in non-experimental impact evaluation techniques, the use of the RBP model ensures that unobserved confounding factors that can negate the estimated impact are statistically controlled for (see Marra et al., 2013). Rather than following a stepwise estimation, RBP jointly estimates the selection and outcome equations specified in Eqs. (2) & (3). The corresponding variance covariance matrix of the bivariate probit distribution can be expressed as:

$$\varphi = \begin{pmatrix} 1 & \rho \\ \rho & 1 \end{pmatrix} \begin{pmatrix} 1 & \rho \\ \rho & 1 \end{pmatrix} \tag{5}$$

Where φ represents the standard bivariate normal distribution and ρ represents the correlation coefficient of the unobserved explanatory variables in the systems of equations (Amadu et al., 2020a). A significant ρ means that the error terms are correlated and unobserved heterogeneity is an issue in our model specification and that the use of RBP was the right choice (Abdulai, 2016). According to Heckman (1978), ρ provides the extent of correlation between the unobserved confounders in the two related equations of selection and adoption of OFSP. When $\rho = 0$, the error terms (i.e., unobserved confounders) in the two equations are hence uncorrelated implying that there is no problem of endogeneity. In such a case, the estimation of the second equation of adoption of OFSP yields consistent parameters.

3.7. Instrument based on M&E data

Endogeneity and self-selection biases need to be accounted for to arrive at unbiased estimates. For proper identification, the RBP requires at least one variable in the selection equation which is not included in the outcome equation. Such a variable is frequently called an instrumental variable (IV).

We identified participation intensity as an instrument. Participation intensity is the variation in OFSP-project beneficiaries found across villages. Accounting for regional differences in abundance of villages (and thus population), participation intensity was established controlling for total number of villages. The rationale is that a higher overall participation intensity increases the probability of individual project participation. In contrast, lower overall participation intensity naturally reduces the probability of individual project participation. Participation intensity is a function of variables related to the management and strategies applied by ANI implementing partners. For instance, these were able to decide on the number of vines and vine bundle size, and thus were able to influence the total number of beneficiaries. These processes were unlikely being influenced by individual farmers. However, we cannot completely rule out that implementers chose high potential areas (i.e., areas in which adoption is more likely) to influence the success rate of the project. We argue that possibly a few implementers followed such a rationale, but that the combined rationale of all 20 + implementing partners was free of such bias. We further argue that project intensity had an indirect effect, mediated by participation, on adoption in the implementation year and beyond. As Kubitza and Krishna (2020) point out, higher-level events (such as project participation), may affect several variables in addition to the outcome variable of interest. For instance, participation intensity may influence the availability of vines in a village as projects likely established decentralized vine multipliers in areas of high project intensity. Likewise, higher participation intensity may result in higher adoption by participants, in turn, leads to an increased availability of vines in social networks. Analyzing (and controlling for) intervention spillovers is part of the objective of this paper.

For the purpose of this study, we established the instrument – participation intensity (M&E) – based on M&E data. As a robustness check, we also established an alternative participation intensity instrument based on Principal Component Analysis (PCA). More details on how the instruments were calculated can be found in Supplementary Materials 1.

The theoretical soundness of our IV is supported by building statistical confidence in the validity of our IV. We do this by using the zero-first-stage test, as applied in increasing numbers of studies (Altonji et al., 2005; Angrist et al., 2010; Amadu et al., 2020a). The zero-first stage refers to the effect of the IV on the treatment variable being zero for a subsample. In this case, intuitively, the reduced form–the effect of the IV on the outcome variable–should also be zero to satisfy the exclusion restriction (van Kippersluis and Rietveld, 2018). In our study, the control group (i.e., households that live in a control non-intervention village) constitutes a valid sub-sample for which the effect of participation intensity on participation (treatment) and on the outcome (i.e., adoption) of participation is zero because they never participated. Both instruments perform well, which means that we find overall insignificant effects on the outcome variables (i.e., OFSP adoption 2019, OFSP area, OFSP harvest, OFSP sales) for the identified sub-sample (see Table S1 in Appendix). Only participation intensity (M&E) enters significantly in one of the probit models explaining OFSP area. This suggests dismissing participation intensity (M&E) as valid instrument in explaining OFSP area and we advise caution when interpreting the results.

3.8. Two-stage least squares

As the RBP only allows to include binary dependent variables – adoption in our case – two-stage least square (2SLS) estimation techniques are employed for analyzing all continuous variables used as additional and alternative measures to/of adoption. Recall that the continuous variables are area planted to OFSP, OFSP harvest, and OFSP sales.

The same instrument – participation intensity (M&E) – is used jointly with 2SLS to control for endogeneity. Instrument weakness and endogeneity tests were conducted to assess IV strength and if 2SLS is preferred over regular ordinary least squares (OLS) estimation techniques.

3.9. Indirect effects – Orange-fleshed sweetpotato adoption

The selection of non-participants or spillover households was conditional on sweetpotato adoption in the past. Crop choice (i.e., sweetpotato) likely occurred in a non-random manner. This means that various confounding factors might have influenced the adoption of those crops. These same factors might have, likewise, influenced the household's decision to adopt OFSP, which could result in biased estimates. Various econometric estimation techniques (e.g., Heckman selection model, recursive bivariate probit, propensity score matching (PSM), etc.) can be used to control for the endogeneity caused by self-selection. Usually, a valid instrument is identified and included in the model (Wooldridge, 2015). However, we were unable to identify an instrument. We therefore dealt with endogeneity by using PSM techniques (Rosenbaum and Rubin, 1983; Heckman et al., 1997). PSM is frequently used in impact assessment studies, including in relation to technology adoption (e.g., Abebaw and Haile, 2013; Wossen et al., 2017; Okello et al., 2020). Note that PSM cannot control for unobserved heterogeneity (e.g., risk aversion, motivation, etc.) which will remain a limitation.

The idea is to estimate OFSP adoption amongst non-participants by comparing OFSP adopters with a matched control group while accounting for the potential effects of confounding factors. Technically, the PSM results are expressed as Average Treatment Effects on the Treated (ATT) which computes the average differences in outcomes of adopters (within the non-participants group) with and without a technology (i.e., sweetpotato). As we do not observe outcomes of adopters without a technology, a matched sub-sample of 'non-adopters' is created using a set of observable characteristics which serves as the control group. We used the 'nearest neighbor' as the primary PSM algorithm. Two other matching estimators (i.e., radius, kernel) were used as robustness checks for our results.

Note that matching is done on observable factors, commonly referred to as conditional independence assumption. However, a bias might still arise from unobservables that jointly affect sweetpotato and OFSP adoption. The conditional independence assumption, unfortunately, cannot directly be tested. We address this issue, as done in recent literature (e.g., Abebaw and Haile, 2013), by including several covariates in the propensity score estimation to minimize omitted variables bias. See Supplementary Materials 2 for details on covariates used in intermediary calculations for propensity score matching.

3.10. Variables and expected signs

The study considers various factors from literature and theory likely to affect outcomes variables. These include sources of vines and distance to vine source; project intervention factors like radio programs, nutrition training; demographic factors like household size, presence of children in the household, gender of household head, marital status, wealth status, land owned; institutional factors like distance to the market, distance to extension officer, membership to farmer association, access to credit; and shock and response factors like facing a drought or floods. Table S2 in Appendix summarizes the key variables used in this study and provides expectations of the effects.

4. Results

4.1. Descriptive statistics

The descriptive statistics by household category (i.e., participants, non-participants, control) are summarized in Table 3.

In terms of household composition and characteristics, respondents were similar. For instance, participants had 5.68 household members, non-participants 5.61 and control group 5.75. For the same household categories, 29–33 % of households took care of an infant (0–2 years), 39–43 % had a child between 3 and 5 years of age, 12 % had a disabled member, and 26–33 % had a breastfeeding /pregnant woman in the household. In addition, household heads were married in 74–78 % of the cases and a smaller share of households were headed by women (19–23 %). In these cases, the husband was mostly either divorced/separated (42 %) or passed away (36 %) (Gatto et al., 2021a), likely making female-headed households relatively more vulnerable because an important stream of income was missing. Further, for household

Table 3
Descriptive statistics.

	Participants (n = 1,439) (1)		Non-participants (n = 666) (2)		Control (n = 387) (3)		Difference		
Variable	Mean	S.D.	Mean	S.D.	Mean	S.D.	(1)-(2)	(1)-(3)	(2)-(3)
Adoption (in 2019)	0.65	0.48	0.46	0.49	0.27	0.45	0.19***	0.38***	0.19***
OFSP area (acres)	0.06	0.16	0.03	0.11	0.001	0.06	0.03***	0.05***	0.02*
OFSP harvested (kg)	135	278	116	380	78.1	255	19.1	56.8***	37.7
OFSP sales (kg)	94.8	239	84.9	343	52.4	206	9.83	42.4**	32.6
Vine sources									
DVM in village	0.21	0.41	0.23	0.42	0.04	0.19	−0.02	0.17***	0.18***
Distance to DVM (min)	55.8	39.7	62.6	57.4	73.2	57.4	−6.78***	−17.4***	−10.6***
Vine conservation	0.79	0.41	0.75	0.44	0.72	0.45	0.04*	0.07**	0.02
Project/intervention characteristics									
Listened to OFSP radio program	0.45	0.49	0.39	0.49	0.39	0.49	0.05***	0.05	−0.002
Demographic variables									
Number of household members	5.68	2.22	5.61	2.21	5.75	2.28	0.07	−0.07	−0.15
Infants in household (0-2y)	0.29	0.45	0.33	0.47	0.31	0.46	−0.04	−0.02	0.02
Children in household (3-5y)	0.39	0.49	0.43	0.49	0.41	0.49	−0.04	−0.01	0.03
Breastfeeding household member	0.26	0.44	0.33	0.47	0.32	0.47	−0.07***	−0.06*	0.01
Disabled household member	0.12	0.33	0.12	0.33	0.12	0.33	0.00	0.00	0.00
Household characteristics									
Household head is female	0.23	0.42	0.23	0.42	0.19	0.39	0.01	0.05	0.04
Household head is literate	0.78	0.42	0.74	0.44	0.75	0.44	0.04	0.03	0.00
Age of household head	45.8	14.4	45.1	15.1	44.8	14.5	0.76	1.03	0.27
Education of household head (years)	6.02	3.62	5.68	3.66	6.14	5.03	0.34	−0.12	−0.45
Household head is married	0.74	0.44	0.77	0.42	0.79	0.41	−0.03	−0.05	−0.02
Land ownership (acre)	2.51	2.34	2.39	2.08	3.22	2.76	0.12	−0.71***	−0.83***
Wealth index 1 (1–5)	0.19	0.39	0.24	0.43	0.18	0.02	−0.05**	0.00	0.05*
Women decision sweetpotato cultivation	0.32	0.47	0.31	0.46	0.26	0.44	0.02	0.07**	0.05
Institutional and access variables									
Distance to market (min)	80.1	58.5	81.8	61.2	96.3	75.6	−1.73	−16.2***	−14.5***
Distance to extension officer (min)	87.1	62.8	86.5	61.5	108.4	76.2	0.58	−21.4***	−21.9***
Distance to all-weather road (min)	38.2	49.9	47.5	62.5	50.5	62.7	−9.29***	−12.3***	−3.03
Farmer association membership	0.15	0.34	0.09	0.27	0.09	0.29	0.06***	0.05**	−0.01
Saving/credit group membership	0.19	0.38	0.14	0.34	0.17	0.37	0.05***	0.02	−0.03
Shocks and response									
Drought in 2018	0.36	0.48	0.34	0.48	0.53	0.49	0.02	−0.17***	−0.19***
Flood in 2018	0.10	0.30	0.07	0.26	0.12	0.32	0.03	−0.02	−0.04**
OFSP distribution in 2018 or 2019	0.48	0.49	0.44	0.49			0.02		
Project and regional dummies									
SUSTAIN	0.35	0.48	0.29	0.45			0.06***		
RTC-Action	0.24	0.43	0.21	0.41			0.03**		
MISST	0.39	0.49	0.31	0.46			0.09***		
North	0.10	0.30	0.08	0.27	0.23	0.42	0.09	−0.13***	−0.15***
Central	0.39	0.49	0.37	0.48	0.39	0.49	0.02	−0.00	−0.02
South	0.51	0.50	0.56	0.50	0.38	0.49	−0.04	0.14***	0.18***
Instrument									
Participation intensity (M&E)	7.47	8.93	7.43	8.94	3.81	5.91	0.03	3.65***	3.62***

Notes: S.D.: standard deviation. ***significance at the 1%-level; **significance at the 5%-level; *significance at the 1%-level; Differences tests are Sidak pairwise comparisons. DVM= decentralized vine multiplier. The Sidak pairwise comparison uses t-tests to compare group means between (1) participants and non-participants; (2) participants and control; and (3) non-participants and control. We present this in columns (1)-(2); (1)-(3) and (2)-(3) respectively. Sidak adjusts the significance level for multiple comparisons and provides tighter bounds thus providing a robust test of significant differences between means.

categories, the average household head ranged between 5.7 and 6.1 years of education and was literate in 74–78 % of the cases. In terms of wealth, the share of households that were classified as "resource-poorest" were equally distributed across the sample. But significant differences exist regarding land ownership. The control group had, on average, some 22 % more land than participants and non-participants, which may be explained by the fact that control villages were located in remoter areas where land may be more readily available than in treated villages. This greater remoteness is reflected in the distance to market, distance to extension officer, and distance to all-weather road which were significantly longer for control villages by an average of 16 min, 21 min, and 12 min, respectively, compared with treatment villages. Strikingly, control villages also experienced more often a drought in 2018 (53 %) compared with participant villages (36 %); but exposure to floods in 2018 was similar. In the regression analysis that follows, all these variables are included.

OFSP adoption rates in 2019 were the highest for participants (65 %), followed by non-participants (46 %), and control group (27 %). This is in line with adoption rates found for other OFSP interventions in Mozambique and Uganda (de Brauw et al., 2018) and Tanzania (Shikuku et al., 2019). While control villages were selected for this study because these were not included in any OFSP intervention in the past, the adoption rates observed in the control group suggests that OFSP spilled over from any of the OFSP interventions implemented in the past (Table 3). Area cultivated to OFSP was generally small (participants: 0.06 acres; non-participants: 0.03 acres; control: 0.001 acres) which is indicative of OFSP being mainly planted in home gardens. However, participants and non-participants both planted significantly larger areas to OFSP compared to the control group. Consequently, participants' OFSP production was also significantly higher (135 kg) compared to the control group (78 kg), suggesting that participants benefited from training on farming practices and input recommendations. The same training effect is not observed for non-participants who produced similar quantities (117 kg) than the control group. Jointly, for the entire sample average OFSP area and harvest was 0.044 acres and 121 kg, respectively, resulting in an average yield of 6.8 t/ha. These results are corroborated by findings for OFSP yields in Malawi under farmer field conditions which were between 5 and 9 t/ha (van Vugt and Franke, 2018). OFSP sales were highest for participants (95 kg), followed by non-participants (84.9 kg) and lowest for control group (52 kg). In relation to total production, participants kept 40.2 kg (for consumption or later sales, etc.) while control group only kept 25.7 kg. These figures, noteworthy, only represent the main harvest during the season. Not included are figures for minor harvests which include piece-meal harvesting of OFSP done throughout the entire season and mainly for consumption purposes.

Finally, we selected half of the sample from the south region (some 50 %) as intervention implementation was the most intense there in contrast to the central and northern regions. Participation intensity (M&E), our instrument, is highest for treatment areas: per village, on average, some 7.5 households participated. In contrast, project intensity was much lower in control villages (3.8 households per village) if these had been treated.[8]

4.2. Determinants of project participation in OFSP interventions

Table 4 presents results of the selection equation showing factors that determine participation in OFSP interventions. Recall that to identify the RBP model, both selection and outcome equations use the same set of regressors, except for one variable – the instrument – which is included in the selection but not outcome equation. This is important because not all regressors in the selection equation can be interpreted as a cause of participation. These are, nonetheless, included to control for observable differences between participants, non-participants, and control group.

First of all, the hypothesis of zero error term correlation (rho = 0) can be rejected at the 1 %-significance level (Wald test of rho = 0: 11.90; p-value: 0.00), which suggests that unobservable factors co-determine participation and sustained adoption. It further suggests that the RBP model with IV is the right model choice to control for endogeneity.

Various household characteristics, such as household size and other demographics, household head sex, years of education, literacy, age, and household wealth, all enter insignificantly into the model explaining participation. This suggests that participation in OFSP interventions was not explained by these factors. In contrast, distance to decentralized vine multiplier, conserving vines from previous season, conservation, marital status, land ownership, farmer membership, and 'drought 2018' significantly explained participation. These are important observable differences determining participation and to control for before analyzing sustained adoption.

4.3. Direct OFSP intervention participation effects

Table 4 further presents the estimation results for sustained adoption. For interpretation reasons, we only discuss the marginal effects.

We find a strong and large participation effect on sustained OFSP adoption - that is, planting OFSP vines at least two years post intervention. Project participants were 46.1 % more likely to sustainably adopt OFSP than non-participants and households living in control villages combined. The conservation of vines from previous season was a key practice increasing the probability of sustained adoption by 18.4 %. In addition, (de)centralized vine multipliers were also important: the existence of a (de)centralized vine multipliers in a village increased the probability of sustained adoption by 7.1 percentage points, while households that were farther away from (de)centralized vine multipliers have a reduced likelihood of sustained adoption (3.0 % for every additional hour). Next, perceived exposure to OFSP radio program in the past also increased probability of sustained adoption by 6.6 percentage points. The results further show a positive institutional membership effect. Household membership in farmer associations and saving groups increased probability of sustained adoption by 8.0 % and 2.9 %, respectively. Exposure to climatic shocks, such as a drought in the previous season, reduced the likelihood of sustained adoption by 6.3 %. In contrast, reception of OFSP vines as aid had a strong expected positive effect (11.9 %) on sustained adoption.

Almost all household demographic and characteristics enter the model insignificantly, except for the wealth index. A household classified as "resource-poorest" had a 3.8 % reduced probability to sustainably adopt OFSP.

Membership in farmer associations made sustained adoption 8.6 % more likely. Rather than as a source for vines, farmer association membership was likely important for exchange of agronomic and nutritional knowledge regarding OFSP cultivation. This is supported by other studies investigating the importance of farmer association for technology adoption and outcomes (e.g., Okello et al., 2017).

2SLS regression results for additional outcomes variables – OFSP area, harvest, and sales – are presented in Table 5. The test of endogeneity suggests that participation variables in 'OFSP area regression' are indeed endogenous. In turn, the null hypothesis for existence of endogeneity can be rejected in OFSP harvest and sales regressions. We thus also present simple OLS regressions results which are presented in Table 6.

Results from both estimation techniques show that area planted to OFSP varieties is significantly larger for participants compared to households living in control villages (2SLS: 0.213; OLS: 0.047). While coefficients for participation enter insignificantly in 2SLS model explaining OFSP harvest (180.9) and OFSP sales (77.4), in the OLS model both coefficients are significant (OFSP harvest: 46.76; OFSP sales: 38.44). This suggests that participation resulted in higher harvests and sales two years post intervention compared to harvests and sales for households living in control villages.

Several control variables enter significantly into the regression which are worth mentioning. First, households with a disabled household member harvested (2SLS: 36.11 kg; OLS: 35.61 kg) and sold (2SLS: 37.65 kg; OLS: 37.15 kg) more than households without a disabled member. Second, households with larger land area also had larger OFSP area (2SLS: 0.007; OLS: 0.005), harvested more (2SLS: 16.79 kg; OLS: 15.05 kg) and sold more (2SLS: 13.46; OLS: 12.95 kg). Third, households with the lowest wealth score (i.e., "resource-poorest") had lower OFSP area (2SLS: −0.015; OLS: −0.015), harvested less (2SLS: −26.98 kg; OLS: −27.29 kg) and sold less (2SLS: −22.32 kg; OLS: −12.41 kg). Fourth, households in which women make sweetpotato planting decisions harvested less (2SLS: −50.79 kg; OLS: −48.68) and sold less (2SLS: −31.49; OLS: −30.88).

As a robustness check, all regressions using the instrument project intensity (M&E) were re-estimated using the alternative instrument – project intensity (PCA). The results are overall robust to the alternative instrument (see Supplementary Materials 3).

4.4. Indirect OFSP intervention participation effects

The results for indirect ANI effects, such as OFSP interventions, which are effects on households that live in intervention villages but did not participate in the project, are presented in Table 7. Using propensity score matching techniques, we find that indirect participation resulted in higher OFSP adoption (0.201–0.219), larger area planted to OFSP (0.016–0.019 acres), higher OFSP harvests (50.77–60.54 kg), and larger OFSP sales (41.33–48.78 kg). Findings of propensity score matching techniques "nearest neighbor", "Radius", and "Kernel" are similar (see Table 7).

[8] Note that we report here the findings for project intensity (M&E) and control villages results are proxied by average project intensity found in the respective district the control village is located in (see Supplementary Materials 1).

Table 4
Recursive Bivariate Probit estimation results for participation on sustained adoption.

	Selection/participation		Sustained Adoption		Marginal effects	
Variable	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.
Constant	0.197	0.192	−1.767***	0.202		
Participation			1.726***	0.132	0.461***	0.061
Vine Sources						
DVM in village	0.101	0.071	0.168**	0.070	0.071***	0.018
Distance to DVM (hour)	−0.260***	0.043	0.138***	0.036	−0.030***	0.011
Vine conservation	0.150**	0.064	0.544***	0.085	0.184***	0.017
Project/intervention characteristics						
Listened to OFSP radio program	0.086	0.054	0.163***	0.056	0.066***	0.015
Demographic variables						
Household (HH) size	0.021	0.013	−0.018	0.012	0.001	0.003
Infants in HH (0-2y)	0.031	0.078	−0.024	0.074	0.002	0.021
Children in HH (3-5y)	−0.082	0.057	0.115**	0.054	0.009	0.015
Breastfeeding HH member	−0.250***	0.079	0.225***	0.074	−0.004	0.021
Disabled HH member	−0.037	0.080	0.118	0.077	0.022	0.021
Household characteristics						
Female HH head	−0.092	0.123	0.074	0.118	−0.004	0.032
Literate HH head	0.083	0.081	−0.004	0.076	0.020	0.021
Age of HH head	−0.000	0.002	−0.001	0.002	−0.000	0.001
Education of HH head (years)	0.007	0.009	−0.011	0.008	−0.001	0.002
Married HH head	−0.262**	0.117	0.251**	0.109	−0.000	0.029
Land ownership (acre)	−0.023**	0.012	0.021**	0.011	−0.000	0.003
Wealth index 1 (1–5)	−0.086	0.071	−0.055	0.069	−0.038**	0.018
Women decision sweetpotato cultivation	0.019	0.088	0.064	0.082	0.022	0.023
Institutional and access variables						
Distance to market (hour)	−0.019	0.027	0.023	0.026	0.001	0.007
Distance to extension officer (hour)	−0.001	0.026	0.007	0.026	0.001	0.007
Farmer association membership	0.376***	0.084	−0.064	0.083	0.080***	0.023
Saving/credit group membership	0.214***	0.072	−0.096	0.069	0.029*	0.019
Shocks and response						
Drought in 2018	−0.159***	0.054	−0.082	0.057	−0.063***	0.015
Flood in 2018	0.051	0.086	0.044	0.084	0.025	0.023
OFSP distribution in 2018 or 2019	0.494***	0.056	−0.032	0.071	0.119***	0.017
Instrumental Variable						
Participation intensity (M&E data)	0.012***	0.003				
Diagnostics						
Number of observations	2492					
Log pseudolikelihood	−3079.82					
Wald chi2 test	1342.20***					
Rho	−0.781***	0.118				
Wald test of rho = 0 chi2 (1)	11.90					
P-value	0.000					

Notes: S.E.: standard error. ***significance at the 1%-level; **significance at the 5%-level; *significance at the 1%-level; DVM = (De)centralized vine multiplier.

5. Discussion

The results show a large direct participation effect of OFSP interventions on sustained adoption in Malawi. As such, the findings are in line with recent studies conducted on OFSP in other countries, such as Mozambique and Uganda (de Brauw et al., 2018) or Tanzania (Shikuku et al., 2019). Strikingly, while OFSP adoption rates have dropped significantly 3 years post intervention in Mozambique and Uganda (de Brauw et al., 2019), adoption rates for participants in Malawi remain high in the medium-term. The reason could partly be that OFSP varieties were locally adapted and bred in Malawi making these more suitable for local conditions, whereas in Mozambique, the varieties were not bred in country (de Brauw et al., 2018). More research is warranted to analyze how post-project adoption rates become after longer periods (e.g., 5–7 years) post intervention.

We find evidence that OFSP interventions had positive indirect or spillover effects on those households that did not participate but lived in a village that received the intervention. This is also in line with other recent studies (Benjamin-Chung et al., 2017; Vaiknoras et al., 2020; Bocher et al., 2017) and points to the importance of social networks (e.g., Bandiera and Rasul, 2006; Ward and Pede, 2015; Vaiknoras et al., 2019), in which OFSP planting materials are exchanged with non-participants. Interestingly, we find that farmer-to-farmer diffusion likely occurs through informal networks as the coefficients are insignificant for formal institutions, such as farmer association or saving group membership. That the adoption coefficient for participation is larger than for non-participants, however, may partly be explained by the lag time that affected the timing of distribution of OFSP vines. As noted, non-participants generally received/bought OFSP one season after project participants.

The high adoption rates for participants, non-participants and control groups may be explained by various factors. We find that (de) centralized vine multipliers in the village are a crucial source of planting material for both participants and non-participants. The latter suggests that (de)centralized vine multipliers contributed to positive spillover effects of OFSP interventions. However, establishing (de)centralized vine multipliers is not a one-off task, as farmers need to be incentivized to continue to multiply vines after projects end. Otherwise, many farmers who started-off as (de)centralized vine multipliers may discontinue after project end, as found in an OFSP intervention in Tanzania (McEwan et al., 2017). In addition, conserving vines from the previous season was equally important to access planting material for all respondents. Our results underscore recent findings that point to conservation practices and the number of vine conservation strategies as important determinants of adoption (Okello et al., 2015).

The positive significant results for OFSP area and harvest as alternative measures of adoption confirm the positive participation effect in OFSP ANIs in Malawi. Note, however, that the area planted to OFSP was rather small, even for project participants. This is acceptable because participants only received 1–2 bundles of OFSP vines which only served

Table 5
Instrumental variable 2SLS estimation results for OFSP area, harvests, and sales.

	OFSP area (acre)		OFSP harvest (kg)		OFSP sales (kg)	
Variable	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.
Participant	0.213***	0.085	180.9	138.9	77.44	112.9
Non-participant/spillover	0.151**	0.069	144.3	112.7	65.89	90.37
Vine Sources						
DVM in village	0.001	0.009	−3.559	18.68	−5.799	16.07
Distance to DVM (hour)	0.003	0.006	−0.842	15.66	−3.478	12.59
Vine conservation	0.024***	0.006	79.55***	12.29	61.32***	10.43
Project/intervention characteristics						
Listened to OFSP radio program	0.018**	0.006	36.38***	13.11	31.12***	11.51
Demographic variables						
Household (HH) size	0.001	0.001	2.442	3.217	1.574	2.721
Infants in HH (0-2y)	−0.010	0.009	0.887	15.09	3.112	12.53
Children in HH (3-5y)	0.004	0.006	22.55*	12.73	17.41	11.14
Breastfeeding HH member	0.009	0.009	4.751	16.99	3.332	14.02
Disabled HH member	0.014	0.011	36.11*	21.75	37.65**	19.11
Household characteristics						
Female HH head	0.016	0.013	31.46	37.06	32.35	30.92
Literate HH head	0.002	0.008	−17.31	15.71	−9.581	13.79
Age of HH head	−0.001***	0.001	−1.708***	0.353	−1.439***	0.296
Education of HH head (years)	0.001	0.001	1.992	2.057	1.420	1.787
Married HH head	0.016	0.013	13.36	33.11	19.49	26.23
Land ownership (acre)	0.007***	0.013	16.79***	5.036	13.46***	4.307
Wealth index 1 (1–5)	−0.015**	0.002	−26.98**	11.54	−22.32**	9.617
Women decision sweetpotato cultivation	−0.007	0.009	−50.79***	16.53	−31.49**	13.57
Institutional and access variables						
Distance to market (hour)	−0.004	0.003	0.567	5.491	0.394	4.753
Distance to extension officer (hour)	0.003	0.004	−7.109	7.139	−5.380	6.319
Farmer association membership	−0.005	0.011	−21.39	18.68	−19.16	16.14
Saving/credit group membership	−0.026***	0.007	−13.47	14.21	−12.92	12.01
Shocks and response						
Drought in 2018	0.015	0.011	23.33	21.19	13.49	17.93
Flood in 2018	0.021*	0.012	63.38**	32.72	57.29*	30.04
OFSP distribution in 2018 or 2019	−0.034*	0.021	−0.099	37.24	15.44	31.06
Constant	−0.151**	0.069	−86.96	124.3	−37.93	99.34
Diagnostics						
Number of observations	2492	2492		2492		
Wald chi2 test	132.23***	187.62***		153.22***		
R-squared	.		0.051		0.057	
Test of endogeneity chi2(1)	4.008		1.010		0.129	
P-value	0.045		0.315		0.719	

Notes: S.E.: standard error. ***significance at the 1%-level; **significance at the 5%-level; *significance at the 1%-level; DVM = (De)centralized vine multiplier.

to plant small land areas (see footnote 1). To arrive at conclusions about increased demand for OFSP derived from area changes, monitoring households over longer periods of time will be required.

Both outcomes, OFSP harvested and OFSP sales, are also in line with the positive findings for adoption and area. Compared with non-participants and control group, participants harvested and sold more OFSP. Here, however, OLS and 2SLS estimation results differ. Though the null hypothesis for existence of endogeneity can be rejected in OFSP harvest and sales regressions, which means that OLS estimation techniques are preferred, we generally argue to apply caution in interpreting the results for OFSP harvest and sales as being attributed to participation. Irrespective of whether attribution is possible to participation in OFSP interventions, we find that a large share (about 70 %) of OFSP harvest is sold. This suggests that generating an income from OFSP is a key motivation for sustained OFSP adoption, in addition to consumption of OFSP and speaks to its economic value.

The finding that households with a disabled family member harvested and sold significantly more is interesting. Despite area planted to OFSP is insignificant, the results may suggest that OFSP is particularly important for households experiencing physical impairments. Sweetpotato cultivation is a preferred crop for households with access to marginal land and labour constraints (Saranraj et al., 2019; Gatto et al., 2021b). Unsurprisingly, households with larger land ownership are also able to plant more OFSP, harvest more and consequently sell more. In line with our adoption findings is that resource-poorest households plant least area to OFSP varieties, and harvest and sell relatively least amounts. This is striking because OFSP cultivation is relatively less resource-demanding, as discussed, which should especially benefit the resource-poorest households. Yet another interesting finding is that households in which women make decisions to plant sweetpotatoes, harvest and sell less OFSP. While there is no area effect (i.e., area planted to OFSP enters insignificantly), this result suggests that women who are in charge harvest less during the main harvest and more during minor harvests – piece-meal throughout the season. As such, less OFSP is sold and more consumed and shared with others. This underlines the importance of women for household nutritional outcomes (Mudege et al., 2017; Mudege et al., 2020) but, in turn, also reveals that women may be less involved in market exchanges of OFSP. Finally, distance to markets largely enters insignificantly in all regressions which suggests that markets for OFSP (possibly sweetpotato in general) are not well developed to stimulate farmers to increase area under OFSP and increase supply. Most of the OFSP markets remain spot markets in rural areas.

5.1. Limitations

We were unable to investigate which conservation strategies were important and if access to lowlands mattered for vine multiplication and thus adoption (Rakotoarisoa et al., 2017). In addition to those delivery mechanisms, given the cross-sectional nature of our study, we were unable to investigate the specific effects of other project components,

Table 6
OLS Regressions results for participation effects.

Variable	OFSP area (acre) Coeff.	S.E.	OFSP harvest (kg) Coeff.	S.E.	OFSP sales (kg) Coeff.	S.E.
Participant	0.047***	0.007	46.76***	17.86	38.44**	15.41
Non-participant/spillover	0.016***	0.006	35.58*	19.69	34.41**	17.08
Vine Sources						
DVM in village	0.014*	0.008	7.301	16.09	−2.643	13.97
Distance to DVM (hour)	−0.007*	0.004	−8.916	12.54	−5.824	9.112
Vine conservation	0.032***	0.004	85.81***	9.759	63.14***	8.327
Project/intervention characteristics						
Listened to OFSP radio program	0.021***	0.006	39.14***	12.51	31.92***	11.01
Demographic variables						
Household (HH) size	0.002	0.001	2.681	3.195	1.642	2.715
Infants in HH (0-2y)	−0.007	0.008	2.852	14.72	3.683	12.46
Children in HH (3-5y)	0.003	0.006	22.33*	12.68	17.35	11.22
Breastfeeding HH member	0.001	0.008	−1.499	14.91	1.516	12.66
Disabled HH member	0.013	0.009	35.61*	21.62	37.15**	19.14
Household characteristics						
Female HH head	0.015	0.012	30.78	37.27	32.15	31.09
Literate HH head	0.008	0.007	−12.23	15.37	−8.105	13.32
Age of HH head	−0.001***	0.001	−1.691***	0.351	−1.435***	0.297
Education of HH head (years)	0.001	0.001	1.863	2.167	1.383	1.831
Married HH head	0.011	0.012	9.149	32.84	18.27	25.97
Land ownership (acre)	0.005***	0.001	15.05***	4.694	12.95***	3.945
Wealth index 1 (1–5)	−0.015***	0.006	−27.29**	11.36	−22.41**	9.654
Women decision sweetpotato cultivation	−0.005	0.008	−48.68	16.43	−30.88**	13.72
Institutional and access variables						
Distance to market (hour)	−0.005**	0.002	−0.803	5.208	−0.004	4.578
Distance to extension officer (hour)	0.001	0.003	−9.174	6.573	−5.981	5.966
Farmer association membership	0.001	0.009	−16.51	18.56	−17.73	16.61
Saving/credit group membership	−0.024***	0.006	−12.14	14.14	−12.54	12.16
Shocks and response						
Drought in 2018	−0.004	0.005	7.774	12.35	8.973	10.82
Flood in 2018	0.015	0.011	58.56*	33.68	55.89*	31.22
OFSP distribution in 2018 or 2019	0.003	0.007	30.07**	14.91	24.21*	13.42
Constant	−0.015	0.018	21.89	47.11	−6.289	35.22
Diagnostics						
Number of observations	2492	2492		2492		
F	6.33***	7.89***		6.34***		
R-squared	0.078		0.076		0.059	

Notes: DVM = (De)centralized vine multiplier.

Table 7
Propensity Score Matching Results (ATT) for non-participation on OFSP adoption.

	Nearest Neighbor *Treat: 666* *Control: 252*		**Radius** *Treat: 666* *Control: 385*		**Kernel** *Treat: 666* *Control: 385*	
	ATT	S.E.	ATT	S.E.	ATT	S.E.
OFSP adoption	0.219***	0.039	0.201***	0.031	0.201***	0.033
OFSP area	0.019***	0.007	0.016***	0.006	0.016***	0.006
OFSP harvest	60.07***	23.49	60.54***	19.67	50.77***	17.15
OFSP sales	48.78***	21.21	47.86***	16.34	41.33***	13.56

Notes: ATT: Average treatment effect on the treated; S.E: standard error; S.E. are bootstrapped. ***significance at the 1%-level.

such as training, exposure to skits, dramas, nutrition counselling, etc. and their intensity (de Brauw et al., 2015). Moreover, all farmers, irrespective of intervention category, with access to a radio had the possibility of being exposed to an OFSP radio program, as these were broadcasted nationwide, and thus received information on nutritional and health aspects of OFSP. While these positive effects are in line with other recent findings in the context of willingness-to-pay for biofortified beans (Oparinde et al., 2016; Pérez et al., 2018), the direct impact pathway remains unclear. For instance, radio program content, frequency of exposure, and gender of recipient could all be important in this regard. In addition, radio exposure may be subject to a reverse causality issue: farmers may remember hearing about OFSP radio programs if they adopted.

Furthermore, the use of cross-sectional data only allows for an ex-post assessment of ANIs. Unlike other studies, where a randomized controlled trial was built into the design of the intervention at the very start of the project (e.g., de Brauw et al., 2018), in Malawi, this was not possible. The random assignment of households in project villages to treatments such as various project components (e.g., agriculture training, nutrition training, cooking-demonstration, etc.) and control group was not feasible. However, random sampling of sample households and ex-post identification of control villages was achieved for this study.

Second, our post-project adoption variable is based on interviewees' responses which may not reflect the true identities of the varieties cultivated in farmers' fields and, thus, result in biased adoption rates. DNA fingerprinting results for a sub-sample of our study sample reveal that 20 % of respondents underreported (sustained) adoption of OFSP varieties (Gatto et al., 2021a). This is favorable for our study findings, adding to the success of OFSP interventions. Third, area and harvest data are based on farmer recall which can be subject to considerable measurement error (Kilic et al., 2017). While more precise methods for area measurements (e.g., remote sensing, measuring ropes) are available, timing, distance to plots, and high costs often prevent the use of such methods. For a sub-sample, we find that farmers with small plot sizes (i.e., 50–1,000 m^2) over-estimated the size of their plots by a factor of between 1 and 11, compared with measuring area using ropes. There is a clear negative correlation between plot size and measuring error. Future research is required to link these robustness checks in data quality to our research findings which was beyond the scope of this study. Fourth, our study excludes an investigation of participation in OFSP interventions on nutrition outcomes at household levels, such as consumption and dietary diversity, frequently measured for children, women, and at household level. While this is in part addressed by analyzing sales from roots which, we assume, is consumed by the buying household. Future research is warranted to have an in-depth look at nutritional outcomes, in particular in Malawi.

6. Conclusions

This study evaluates direct and spillover effects of OFSP ANIs on sustained adoption, and other outcomes, such as OFSP area, harvest, and sales in Malawi. We utilize a large dataset of 2,492 households and employ recursive bivariate probit, instrumental variables, and propensity score matching techniques.

This study provides evidence that ANIs for the specific case of OFSP in Malawi had positive effects on sustained adoption, area planted to OFSP, harvest, and sales at least two years after the interventions ended (the "what" works and for "how long"). We find that specific ANI components – (de)centralized vine multipliers and vine conservation techniques, such as Triple S (Namanda et al., 2013) – were instrumental in significantly and positively affecting studied farmer outcomes. We further find significant positive spillover effects, which are smaller than the participation effects but larger than outcomes in control group (the "for whom" it works).

6.1. Policy implications

The provision of robust and largely positive evidence on sustained direct and spillover effects of ANIs in Malawi is encouraging and of relevance for policy-makers and funders alike. Especially, as debates have sparked about when and how to scale back costly vitamin A supplementation programs while shifting responsibility of sustained vitamin A delivery mechanism to food-based approaches, such as biofortified crops and industrial food fortification (GAVA, 2019). The OFSP interventions in Malawi appear to be such effective delivery mechanisms. This, in turn, adds to the evidence base for Africa on the positive effects of supply-side agricultural interventions, such as biofortification (for Asia see Dizon et al., 2021).

Another key takeaway message is that irrespective, despite or because of the nutritional benefits associated with OFSP crops, root sales and the associated income-generating potential appears to be another key motivator for sustained OFSP adoption decisions. Future ANIs are advised to continue or increase emphasizing economic and marketing aspects compared to past interventions which had a strong focus on nutritional aspects. In doing so, increased root sales will likely improve nutritional outcomes of a much broader group of people (i.e., OFSP producing and *non*-producing households). This impact pathway deserves more attention in future evaluations of ANIs in terms of outreach and cost-effectiveness.

A stronger economic case for OFSP would also be instrumental for more and sustained adoption. This could be achieved by positioning OFSP as a premium crop and creating stronger agricultural supply-push and demand-pull factors, ideally built into future ANIs. For instance, participatory processes for varietal selection, varietal performance and agronomic training (e.g., mother-baby trials) are main pillars of success. Access to affordable planting material, created through (de)centralized vine multipliers but also advanced vine conservation techniques are evidently an effective push-factor (this research), viable beyond project end. Developing value chains through promoting a processing industry for OFSP roots may be pull-factors to consider in future ANIs. This approach has already started in Malawi and Kenya where the bakery sector is now utilizing OFSP-puree as a major ingredient for bread production (Moyo et al., 2022).

Finally, in the stride of combatting hidden hunger, there are no silver bullets. All currently available strategies (i.e., supplementation, food fortification and biofortification) are required, despite their extensively varying degrees of cost-effectiveness. Concerted efforts are required to attract *additional* investments into broadening the technology base and making these and their delivery mechanisms more effective. ANIs can be effective delivery mechanisms (e.g., Dizon et al., 2021; Sharma et al., 2021). Future ANIs could become more successful in achieving their nutritional objectives, if more emphasis is placed on the various (indirect) impact pathways, and if combinations of strategies, technologies and mechanisms, such as biofortification, home gardens, post-harvest fortification, or diet diversity, are considered.

CRediT authorship contribution statement

Marcel Gatto: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Wisdom R. Mgomezulu:** Conceptualization, Investigation, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. **Julius J. Okello:** Conceptualization, Methodology, Investigation, Validation, Supervision, Writing – review & editing. **Willy Pradel:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Norman Kwikiriza:** Data curation, Formal analysis, Methodology, Supervision, Validation. **Guy G. Hareau:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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