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Assessing the promise of biofortification: A case study of high provitamin A maize in Zambia

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ABSTRACT

Introduction: Biofortification is the breeding of new varieties of staple foods for increased micronutrient content. It is seen primarily as a complementary, rural-targeted strategy for better reaching remote populations. This paper presents an *ex ante* analysis of HarvestPlus' provitamin A maize (PVAM) in Zambia and highlights an empirical approach based on the Zambian 2005/06 Living Conditions Monitoring Survey (LCMS). Because more than 115 countries regularly conduct a Household Consumption and Expenditure Survey (HCES), the approach developed in this LCMS-based study can be applied in many other countries to analyze varietal adoption and conduct *ex ante* studies.

Methods: Data from the LCMS and health statistics were used to characterize baseline indicators of vitamin A intake and Disability Adjusted Life Years (DALYs) lost. The introduction and scaling up of PVAM was modeled based on program plans, expert opinion and data on key adoption parameters. An adoption function was specified and expressed in terms of the percent of farmers expected to adopt PVAM over the next 30 years. A logistic regression adoption function was estimated and used to identify the specific LCMS households adopting, producing and consuming PVAM each year. Information from the IFPRI International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) of yearly maize production and demand were used to produce annual estimates of PVAM planted, harvested and consumed. Taking into account an LCMS-empirically-informed, specified market structure, individuals' additional vitamin A intake was calculated. The number of DALYs saved were estimated using the change in vitamin A intake. Combining these estimates with cost data, the cost-effectiveness of PVAM was calculated.

Results: Assuming an adoption ceiling of 20% over 30 years, implementation of PVAM will result in average additional intake of 12% of the Estimated Average Requirement (EAR), a 3 percentage point reduction in the prevalence of inadequate intake, and savings of 23% of total DALYs. Impacts are concentrated among farming households that have adopted PVAM and consume it from their own production. Their consumption will result in an average additional vitamin A intake of 172 μg/day, more than 3 times the additional 54 μg/day among the entire population. Among this group, the reduction in the prevalence of inadequate intake will be more than 5 times the national average (17.5 percentage points). Valuing a DALY at $1000, PVAM's cumulative value of DALYs saved comes to exceed its cumulative total costs starting in 2019. Over 30 years the cost-effectiveness of PVAM in Zambia was estimated to be $24 per DALY saved, making it very cost-effective.

Conclusion: The methodologies employed in this study provide insights and inputs that can be used to target farmers who are most likely to adopt, to measure their vitamin A intake and to craft messages to promote adoption. PVAM is a long term investment that shows great promise in becoming a highly cost-effective addition to the public health arsenal for combatting micronutrient deficiencies if the 20% adoption rate can be achieved and maintained. Doing so will require effective marketing strategies, including efforts to couple this nutrition-sensitive intervention with nutrition-specific activities, such as targeted nutrition messaging and education, in order to increase the likelihood that adopting farmers will prioritize production for home consumption.

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Introduction

Between 1990 and 2010, the global burden of micronutrient deficiencies fell by more than half (Wang et al., 2012). Among vitamin A, iron and zinc deficiencies, the largest disease burden reductions were in the burden of vitamin A, yet it still accounts for the greatest disease burden among these three deficiencies. Despite these positive trends, micronutrient deficiencies remain major public health problems and still rank among the top causes of death and disability, particularly in Sub-Saharan Africa (Lim et al., 2012). Globally, the micronutrient disease burden is shouldered disproportionately by a highly vulnerable group in the most vulnerable countries—children under 5 years of age in sub-Saharan Africa.

Data on Zambian nutrition status, and particularly on vitamin A, is dated. That which is available shows the prevalence of vitamin A deficiency (VAD) has remained persistently and unacceptably high. According to the most recent nationally representative survey, 53% of children 6–59 months old are VAD (MOST, 2003)—a level well above the 20% threshold WHO uses to define when deficiencies constitute a public health problem—and among non-pregnant women of childbearing age (15–49 years) VAD was found to be 13.4%. These most recent available data are 12 years old, suggesting that there is considerable uncertainty about the current situation.

Over the past 15 years, Zambia has made and maintained major commitments to a number of nutrition programs. It has been a pioneer in what have come to be the key programmatic foundations of nutrition policy in the developing world. In 1998, it became the first country in Africa to fortify sugar with vitamin A (Fiedler et al., 2013a), and in 1999 it became the first country in Africa to implement what has come to be known as Child Health Week/Child Health Days (UNICEF, 2011). Child Health Weeks (CHW) are large-scale, mass mobilization-based events undertaken semi-annually to provide an integrated package of high impact child health and nutrition interventions, including vitamin A supplementation, de-worming and vaccinations, growth monitoring and promotion and, intermittently, the distribution of or re-impregnation of insecticide-treated mosquito nets (Fiedler et al., 2012b). From its inception, CHW has been a priority program of the MOH and has achieved high rates of coverage. Still, Zambia's pace of progress in improving nutrition status has been slow, particularly among young children among whom the prevalence rates of VAD is thought to remain high (NFNC, 2010).[1] We estimate that VAD is annually responsible for roughly 3700 lost lives and nearly 110,000 disability adjusted life-years (DALYs) in Zambia.

In addition to Zambia's established portfolio of VAD control programs—which, since 1998, has consisted of CHW and sugar fortification—the country has other options for combating VAD. While not mandated, wheat flour and maize meal fortification programs are under active consideration by the Zambian government which has drafted regulations for their fortification levels (Fiedler et al., 2013a). Vitamin A-fortification of vegetable oil is another possibility, but one that the country has yet to consider. The most recent addition to Zambia's VAD control portfolio is biofortification – the production and consumption of varieties of maize that contain increased levels of provitamin A.

Biofortification is the breeding of new varieties of staple foods for increased macro- and micronutrient content (Bouis et al., 2011). It is seen primarily as a complementary, rural-targeted micronutrient program strategy for better reaching remote populations, which often comprise the majority of the malnourished. Biofortification is the latest micronutrient intervention strategy, with the first releases of biofortified varieties having begun in just the last five years (Gilligan, 2012).

HarvestPlus – a global consortium co-led by the International Food Policy Research Institute and the International Center for Tropical Agriculture – has promoted and released seven, conventionally bred, biofortified crops in 13 countries, and has established an accelerating rate of progress in both the number of countries and the varieties with which it is working (Saltzman et al., 2012). Until 2012, HarvestPlus worked in only Sub-Saharan Africa and South Asia. Starting that year, it teamed with AGROSALUD, a program working to improve the nutrition content of food staples in Latin American and the Caribbean (AgroSalud, 2011). While there are a number of other organizations working on the development of biofortified staples, to date only HarvestPlus has begun actually distributing new varieties. Other efforts include four projects that use genetic engineering and have targeted bananas, cassava, rice and sorghum: Golden Rice Project (2011), Bio-cassava Plus (Sayre et al., 2011), African Biofortified Sorghum (ABS, 2010) and Better Bananas for Africa (QUT, 2011). In addition, there are three smaller, more specialized projects (INSTAPA, 2011; BAGELS, 2008; HarvestZinc, 2011).[2]

This paper presents an *ex ante* analysis of one of the HarvestPlus projects, Zambia's provitamin A maize (PVAM). Since the 1960s, over 60% of the total agricultural area planted in major crops (i.e., sugarcane, rice, wheat, cassava, maize, potatoes, sorghum, and soybeans) in Zambia has been planted in maize (JAICAF, 2008). Maize dominates the Zambian diet, accounting for more than half of available dietary energy (FAO, 2012). The biofortification of maize in Zambia provides an ideal case study for better understanding the potential of biofortification and the key factors that condition its impact. The objectives of this *ex ante* impact study are to analyze the costs and health benefits of PVAM in order to assess its promise as an investment and to estimate its cost-effectiveness to enable readily comparing it to alternative health investments.

This study highlights a data-driven, highly contextualized approach based on the Zambian 2005/06 Living Conditions Monitoring Survey (LCMS) (CSO, 2011). The LCMS is a large scale, recurrent, multi-purpose, nationally representative household survey, very similar to a number of other such surveys that are commonly conducted throughout the world (e.g., household budget surveys, integrated household surveys, household income and expenditure surveys and living conditions monitoring surveys), which together have been referred to as "household consumption and expenditure surveys" or HCES (Fiedler et al., 2012a). More than 115 countries regularly conduct an HCES (Dupreiz et al., 2014). The approach developed in this LCMS-based study, therefore—which features empirically developing many of the program and market parameters—can be applied in many other countries to analyze varietal adoption and conduct *ex ante* studies. To facilitate others replicating the approach, we provide considerable detail about several of the empirical-methodological innovations. It is noteworthy that PVAM is now being introduced in four other countries (Saltzman et al., 2012), each of which has a recent HCES-type of survey available that could be used to conduct a similar study.

[1] The only additional data on vitamin A since the 2003 national survey is from a 24 HR survey conducted in two districts in 2009. That survey estimated the prevalence of VAD (based on serum retinol concentration levels) at 57% among 24–59 month olds, roughly the same percentages as the 2003 national survey level estimates reported in Table 2 and 3. After adjusting serum retinol levels for infection, the 24HR survey found the VAD level was 48%, and using another methodology (MRDR) to adjust for infection, it found the prevalence rate was markedly less, 22%, but still above the 20% threshold above which WHO defines VAD as constituting a public health problem (NFNC, 2010).

[2] For a discussion of the political controversies involved in the conventionally bred versus genetically engineered approaches see Pray et al. (2007) and Stein (2014).

Methods

The key database in this study is the Zambian 2005/06 Living Conditions Monitoring Survey (LCMS) data. The LCMS was conducted by the Zambian Central Statistical Office. The survey employed a two-stage, stratified cluster sample designed to provide reliable estimates at the provincial and national levels. The sample includes 18,662 households with 97,750 persons. We used weighted interview data from the 9287 farming households that were surveyed in the 2005/06 LCMS to develop estimates for the universe of Zambian maize farmers (CSO, 2011).

Overview

Fig. 1 shows the key methodological components of the study and its data sources for measuring the project's enhanced vitamin A-derived health impact. Health statistics together with a proxy for food consumption data developed from the LCMS were used to characterize the "current situation" (or baseline) by estimating the usual intake of vitamin A, the prevalence of inadequate vitamin A intake and the burden of vitamin A deficiency (VAD) measured using Disability Adjusted Life Years (DALYs).

Next, implementation of the biofortification program was modeled using a combination of program plans, expert opinion and generated data on key adoption parameters. Usual intake of vitamin A at endline was estimated as baseline vitamin A intake plus the estimated quantity of PVAM consumed multiplied by the additional vitamin A from biofortification. Using intake estimates at endline and baseline, new incidence rates of VAD-related health outcomes were calculated, as were the number of DALYs lost after the introduction of PVAM, and the total number of DALYs saved annually. Total health benefits of PVAM were calculated over the lifespan of PVAM as the sum of the annual DALYs saved over the lifespan of PVAM.

Estimates of Vitamin A Intake and DALYs saved

As already noted, the food consumption module from the LCMS was used to estimate the prevalence of inadequate vitamin A intake at baseline as described elsewhere (Fiedler et al., 2013b). The specific way in which DALYs are defined and operationalized in this study follows directly from earlier HarvestPlus work (Stein et al., 2005b). Drawing on the work of Hallberg et al. (2000) and Zimmerman and Qaim (2004), this methodology captures dose–response effects of the improved functional health status of the portion of the population whose vitamin A intake inadequacy gap has been reduced by consuming PVAM, and does so even if that additional intake does not result in a change in the prevalence of inadequate intake.[3]

Vitamin A intake data (baseline and endline) are used in conjunction with age and sex-specific requirements to develop estimates of the effectiveness of the intervention. The effectiveness is then averaged over target groups for which clinically-related health outcomes associated with vitamin A deficiency have been identified and quantified, and the averages are used to calculate new incidence rates for those health outcomes. The new incidence rates are then used to estimate the number of DALYs lost after the introduction of biofortified PVAM.

[3] It is important to point out that in this study, while the analysis of intake levels is in terms of the entire population, the discussion of the adequacy of intake does not include children less than 1 year old. They are excluded from the adequacy analysis because there are no established vitamin A EARs for this target group.

Supply side estimates

Adoption

PVAM has only been available in Zambia in a limited quantity since November 2012: there are no data regarding PVAM adoption. PVAM is a hybrid variety of maize. We used LCMS data identifying hybrid maize growing farmers as a proxy to identify those farmers who would plant PVAM, and using logistic regression estimated the likelihood of farmers planting PVAM. Informed by recent Zambian work of Smale and Mason (2012) on the demand for maize seed and a maize seed varietal study (De Groote et al., 2011), the specification of the model included an index of agricultural inputs, household labor supply, education, an assets index, identified seed sources and the district of residence.[4] The LCMS file of farmers was then rank-ordered by the farmers' predicted probabilities of adoption, providing a tool for identifying the ordered likelihood in which specific Zambian maize farmers could be expected to adopt PVAM.

In order to map out the expansion path of adoption of PVAM, an adoption function was specified. The adoption function was also informed by the De Groote et al. (2011) and Smale and Mason (2012) studies, as well as the three most recent Zambian Living Conditions Monitoring Surveys (2003/04, 2005/06 and 2010), the views and experiences of Zambian public and private sector seed experts, and Zambian maize value chain experts. The function was expressed in terms of the percent of farmers (nationwide) expected to adopt PVAM over the next 30 years and was used with additional parameters (discussed below) to identify spatial and temporal dimensions, and to translate the percentage of farmers into annual estimates of the number of farmers likely to adopt PVAM.

PAN 53 was found to be the most popular variety, grown by 10.7% of the sampled farmers. The historical adoption experience of PAN 53 was used as the basic model for the PVAM adoption function, with some modifications stemming from several additional considerations: (1) the long term trend in the adoption rate of hybrids; (2) a bounce in adoption rates that PVAM's adoption by the Zambia Farmer Input Support Program is expected to provide starting in 2015/16 (Smale and Birol, 2013), and (3) the assumption that PVAM will be able to achieve an adoption rate higher than PAN 53's peak rate to date. This assumption was made because (a) PAN 53 does not appear to have yet reached its zenith, and (b) while PAN53 consists of a single variety, PVAM refers to a collection of varieties. The estimated function (Fig. 2), posits that the adoption rate will reach 16% in the 8th year of implementation, and thereafter, its annual rate of increase will slow considerably, reaching its maximum of 20% of all farmers in year 30 (i.e., 2042).

Implementation

The decision of where to first begin the roll-out of PVAM was based on national and provincial analysis of the production, disposition and consumption patterns of maize, and of hybrid maize. Eastern, Central and Southern provinces were selected as the sites in which PVAM would first be introduced because they exhibited the most favorable conditions for the introduction of PVAM (i.e., high percentages of maize farmers and hybrid maize use; larger maize farms; and lowest average vitamin A intake). Based on program implementation plans, it was assumed that the seed would

[4] The model correctly classified 85% of Zambia's hybrid maize farmers from among all maize farmers, with a sensitivity of 64.4 and a specificity of 88.2. Sensitivity is a measure of how well a logistic regression model predicts true positives; i.e., in this instance, it correctly identifies as hybrid adopters those who in fact did adopt. Specificity is a measure of how well the model correctly categorizes false negatives; i.e., it correctly identifies as non-adopters of hybrid maize, those who, in fact, do not adopt it.

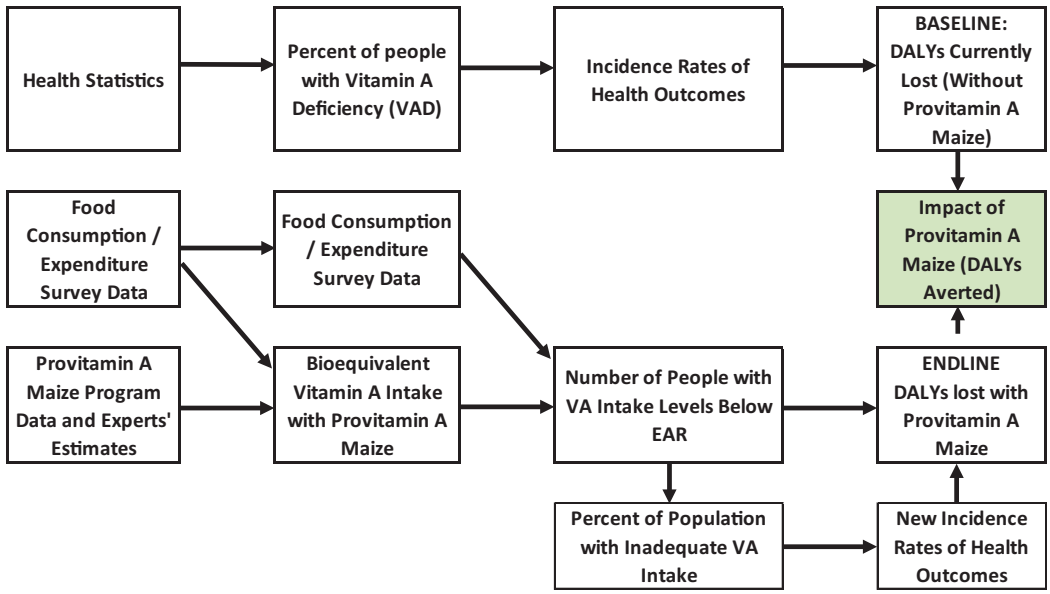

Fig. 1. A framework to estimate health benefits of provitamin A maize in Zambia using multiple data sources. *Source:* Adapted from Stein et al. (2008).

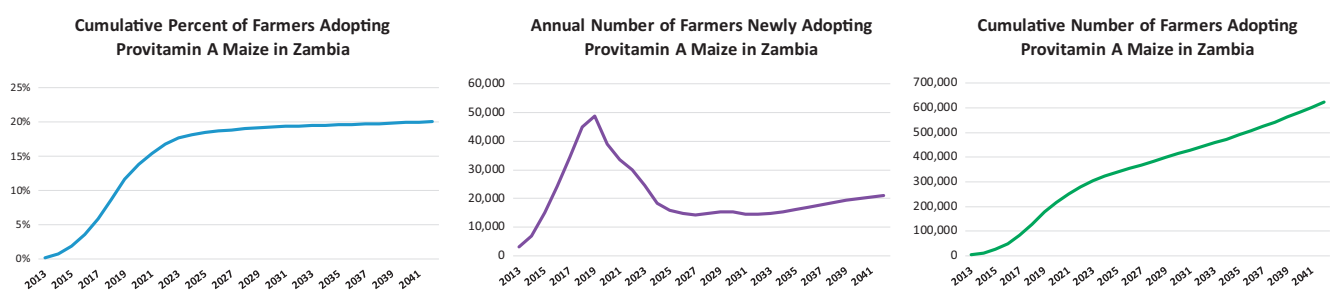

Fig. 2. Provitamin A maize adoption parameters, Zambia 2013–2042. *Source:* Authors' calculations.

be disseminated to farmers in 3 specific districts in each of the 3 provinces initially. To develop the district-specific level estimates, the farmers in the LCMS were rank-ordered within each district by their predicted probability of adopting PVAM. The farmers' rank-ordered predicted probabilities of PVAM adoption were used to identify the specific farmers who would be the first adopters in 2013. The specific farmers selected were those whose rank-ordered cumulative number was equal number to the adoption function-estimated number of adopting farmers. The annual number of PVAM adopters in each district in a province were aggregated to develop the provincial-level estimated number of PVAM adopters. Similarly, the annual aggregations of the provincial estimates provided the total national number of farmers adopting PVAM. After the initial implementation of PVAM in the first 3 districts of Central, Eastern and Southern provinces, it was assumed that implementation would begin in all other districts and provinces in year 2.

Production

Drawing on recent past experiences and the views of public extension and private seed company specialists, it was assumed that each household would receive one 5 kg pack of PVAM seed (this is the standard seed package in Zambia), enough seed to plant 0.25 hectares (or what Zambians refer to as 1 lima). Once specific adopters were identified from the rank-ordered LCMS file, the area planted in PVAM by each farmer was estimated based on an initial assumption of 0.5 limas (half of the seed pack) and increased by 0.5 limas per year up to a farm-specific maximum set equal to each farm's maximum amount of area planted in maize as identified in the LCMS. The total area planted in PVAM was the sum of the land planted in PVAM by all of the identified, individual PVAM farmers.

The estimation of annual changes in PVAM production was also in part a function of annual changes in total maize production, cultivated area and yield. The source of the 2013–2042 annual data was the IFPRI International Model for Policy Analysis of Agricultural Commodities and Trade (IMPAACT).[5] IMPACT's estimates of the changing total maize area were used in combination with the LCMS-provided baseline area to calculate the rate of change of total maize area planted, allowing each individual farm's yield and area to change annually.

In the first year of the analysis it was assumed that PVAM yield was equal to that attained in HarvestPlus field trials, 375 kg/lima (1500 tons/Ha). In each subsequent year, PVAM yield was calculated by multiplying this initial yield by the annual rate of change of (all) maize yields as estimated by IMPACT. For each PVAM producer, multiplying the area planted in PVAM by the IMPACT-estimated yield provided an estimate of each producer's PVAM production,

[5] IMPACT is a multi-commodity, multi-country, partial equilibrium model that generates projections of global food supply, demand, trade and prices. IMPACT develops estimates of 46 crop and livestock commodities and includes 115 countries/regions which are each inter-linked through international trade and 281 food producing units (grouped according to political boundaries and major river basins). Demand is a function of prices, income and population growth. Crop production is determined by crop and input prices, the rate of productivity growth and water availability (Rosegrant et al., 2012).

and total PVAM production was calculated as the sum of all individual PVAM producers' output. Based on information from the African Postharvest Losses Information System (APHLIS, 2012), it was assumed that all PVAM farmers experience post-harvest losses of 15%.

Demand side estimates

Empirical analysis of the production, disposition, marketing and consumption of maize guided our approach to modeling PVAM. Analysis of the LCMS revealed that 68% of all maize consumed in Zambia is maize that the household consuming it has itself produced. With respect to the residual, the Food Security Research Project's 2008 Supplemental Survey of 7825 smallholders revealed that maize markets in Zambia are very local phenomena (Mason and Jayne, 2009). Only 20–25% of the maize produced in Zambia enters the market, and a substantial share of that which does is sold at local or district markets. Comparing the agriculture/production and consumption modules from the LCMS revealed that each province has relatively equal quantities of maize production and maize consumption; each province is, or could be, a largely independently functioning market.[6] Eastern and Central are the only exceptions.

These empirical findings about the adoption, production, consumption and marketing of maize shaped our approach to modeling PVAM. It was assumed that all PVAM produced is retained by the PVAM-producing household to meet its maize consumption needs, and is not sold until that need is surfeited. Those PVAM farmers who produce more PVAM than the maximum quantity of maize they annually consume from their own production, sell the "excess". The PVAM which is sold was assumed to be sold into a provincial-level market where it is available for purchase by all other households—including farming households that have not adopted PVAM and non-farming households.

In provinces in which the provincial demand for PVAM market is surfeited, it was assumed that the excess PVAM spills over into other provinces. In light of the fact that 85% of the maize purchased in Zambia is purchased either in Lusaka or Copperbelt, the inter-provincial market was defined as consisting of just these two provinces. The proportion of households' maize consumption that was assumed to be purchased in the market was equal to the ratio of PVAM in the market (i.e., the residual after PVAM farmers have met their household's maize consumption needs) to the amount of maize that is consumed from purchases in the market (including all maize forms, grain and meals).

The average concentration of provitamin A among the three initial varieties released in 2012 was 7.5 μg/g (HarvestPlus, 2013). By 2018, it is expected that varieties with 15 μg/g of provitamin A will be released. Thus in this study, we assumed that the concentration of provitamin A in PVAM was 7.5 μg/g until 2018, thereafter increasing to 15 μg/g. In addition, based on studies conducted on the bioconversion rates of provitamin A to vitamin A when PVAM is eaten, it was assumed that 6.5 μg of provitamin A would yield 1 μg of vitamin A (as retinol activity equivalents or RAE) (HarvestPlus, 2013).

Costs

The value of the resources that will be required to promote, release, monitor and maintain PVAM in Zambia were estimated using a combination of HarvestPlus expenditures and budgets, together with information provided by key Zambian partners and stakeholders. It was assumed that costs started being incurred in 2010 and that there will be an active "project-like" phase from 2010 through 2019, with release occurring in 2013 and promotion and dissemination efforts continuing through 2019. Thereafter, the significant costs are those related to monitoring the quality of the PVAM and maintaining the integrity of its seed bank. It was assumed that this Maintenance & Monitoring (M&M) would continue throughout the remainder of the accounting period after the initial release of PVAM. Thus the cost analysis covers a period of 33 years.

Benefit-cost and cost-effectiveness analysis

The cost-effectiveness of biofortification was estimated using the PVAM cost analysis and the PVAM DALYs saved analysis. Three measures commonly used in financial investment decision-making were calculated: the cost per DALY saved, the benefit-cost ratio and the internal rate of return. A value of 3 percent (which is generally used for health projects) was used for the discount rate. The benefit-cost ratio was calculated by assigning a fixed value of $1000 per DALY (Meenakshi et al., 2007; Nestel et al., 2006; Stein et al., 2005a). Finally, a breakeven analysis was performed in order to examine how long it will take for benefits generated by PVAM to outweigh costs.

Results

Adoption and production

Fig. 2 shows the annual number of new adopters, as well as the cumulative percent and number of adopting farmers over the 30-year period. The peak in the annual number of adopters is assumed to happen relatively early, in 2019, when the adoption curve is the steepest during the growth phase. Figs. 3 and 4 show the production of PVAM and the number of households growing PVAM annually over the 2013–2042 period. Production of VAM is dominated by Eastern, Southern and Central provinces.

Marketing and consumption

The size and evolution of the quantities of PVAM involved in the inter-provincial market are shown in Fig. 5. While both intra- and inter-provincial markets grow throughout the analytic period, without question the most dynamic market over time is the intra-provincial one.

Fig. 6 analyzes households' consumption levels by their status as (1) PVAM adopting farmers (Adopter), (2) Non-PVAM Adopting farmers (Non-Adopters) or (3) non-farming households. Initially, consumption is concentrated among the PVAM adopters but their rate of increase in consumption slows in 2022, while the level of non-farmers continues to increase. By 2027, the non-farmers' consumption level overtakes that of PVAM adopters. While a larger proportion of the total benefits are garnered by purchasers as a group, the average level of benefits accruing to adopting farmers are greater due to the farmers' relatively greater average consumption levels.

Vitamin A intake

Baseline

Baseline estimates of vitamin A intake in 2013 and their evolution over time are shown in Fig. 7. The average intake of Zambians will improve over the next 30 years in the absence of any vitamin A intervention due simply to increasing general food consumption patterns and the changing composition of foods consumed. The

[6] We say "could be" because these are net quantities and do not take into account the timing or cumulative quantities of households' total maize sales and total maize purchases over the course of the year.

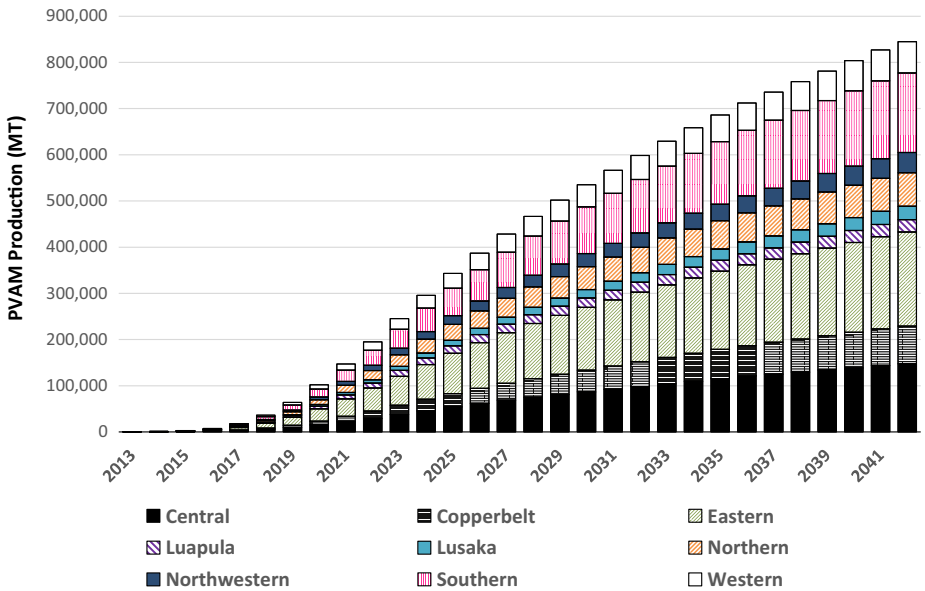

Fig. 3. Annual production of PVAM by province (MT), Zambia 2013–2042. *Source:* Authors' calculations.

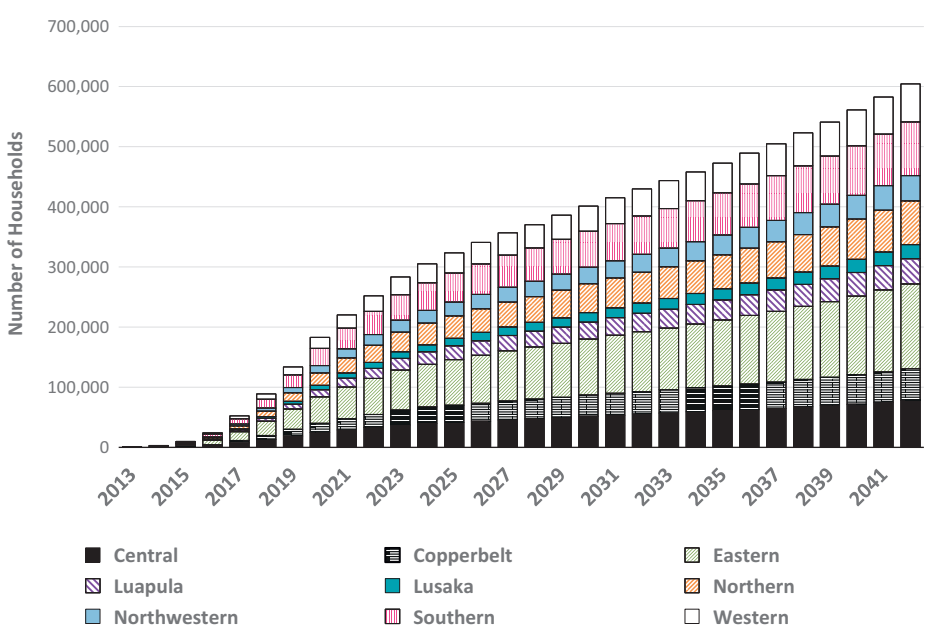

Fig. 4. Number of households growing PVAM by province and year, Zambia 2013–2042. *Source:* Authors' calculations.

improvements, however, will be modest, with average intakes increasing from 229 to 260 μg/day and from 51.1 to 57.9 percent of the Estimated Average Requirement (EAR). Those improvements will result in less than a 2% reduction in the prevalence of inadequate intake. The number of DALYs that will be lost due to inadequate vitamin A intake will increase more than two and a half times, increasing from 108,557 to more than 267,056. Other things being equal, this suggests that Zambia will continue to need vitamin A intervention programs throughout the next 3 decades.

It is important to note that while the baseline number of DALYs that Zambia will incur over this period increases each year, this increase is due to population growth. Controlling for population growth (by calculating the number of DALYs per 1000 population), the number of vitamin A-attributable DALYs the average Zambian child under five or pregnant-lactating woman will incur over the next 30 years, will decrease slightly over time, even without any vitamin A interventions.

Endline

The endline vitamin A intake with biofortification is shown in Fig. 7. In addition, Table 1 presents five endline indicators for three populations- the entire population; children under 5 years of age; and women ages 15–49 years. The major impact of PVAM is concentrated in the 8-year period between 2018 and 2025. During those 8 years, half of the change in the endline indicators made over the entire 30 period is realized, including: 50% of the increase in the endline vitamin A intake; 62% of the additional vitamin A intake; 50% of the increase in the percent of the vitamin A EAR;

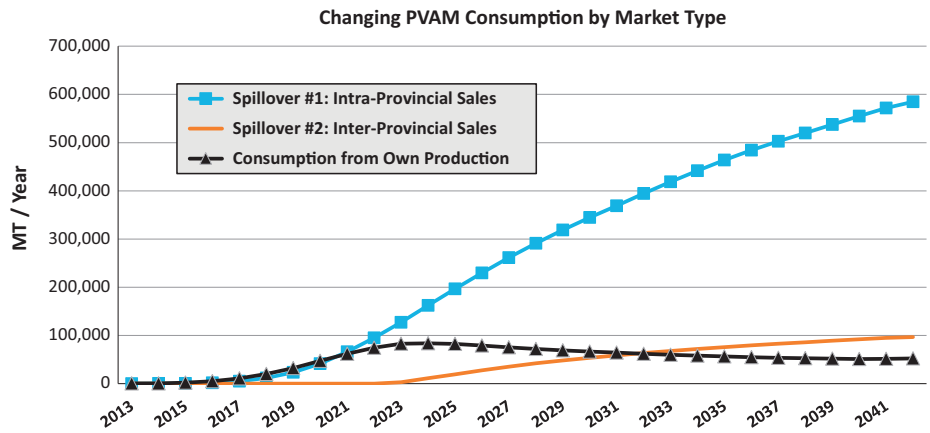

Fig. 5. Annual provitamin A maize consumption by market type, Zambia 2013–2042. *Source:* Authors' calculations.

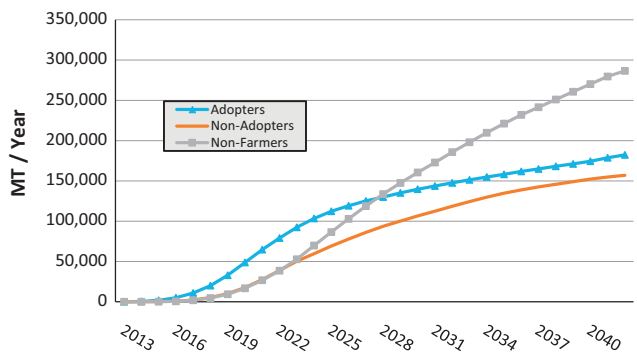

Fig. 6. Provitamin A maize consumption by household category, Zambia 2013–2042. *Source:* Authors' calculations.

and half of the small reduction in prevalence. PVAM is able to interrupt what is otherwise a steady March upward of the total number of vitamin A-attributable DALYs in Zambia over the next 30 years. The contribution of PVAM to vitamin A nutriture in Zambia is the provision of a widely experienced surge in vitamin A intake that takes the national average intake level to a higher plane.

Table 2 presents impact measures of PVAM. The first three rows present indicators reporting changes between baseline and endline values of vitamin A intake (μg/day), changes in prevalence (the reduction in the percent of inadequate vitamin A intake prevalence) and the change in the vitamin A intake as a percent of the EAR between baseline and endline. With an assumed maximum

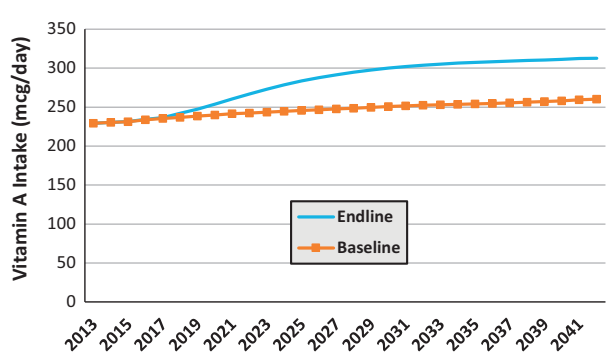

Fig. 7. Vitamin A intake at baseline and with biofortified provitamin A maize. *Source:* Authors' calculations.

adoption ceiling of 20% over the 30 years, the average impacts nationwide will be barely visible in the first five years, while adoption is still taking root. Over the 30-year period, however, provitamin A biofortification of maize will result in an average additional vitamin A intake of 54 μg/day; an additional 12% of the vitamin A EAR; a reduction in the prevalence of inadequate vitamin A intake of three percentage points; and a savings of 53,133 DALYs (23% of the total).

The impact measures just discussed are national average impacts. How do PVAM's impacts affect different sub-populations? Fig. 8 juxtaposes the average additional vitamin A intake of the entire population, unconditioned on consumption of PVAM, and farming households that have adopted PVAM and consume it from their own production. Every year, the average impact of PVAM on this population is far greater than the nationwide average impact. In 2042, the average additional vitamin A intake will be 172 μg/day, more than 3 times the additional 54 μg/day among the entire population. Whereas the reduction in the prevalence of inadequate vitamin A intake is roughly three percentage points among the entire population in 2042, among adopters consuming from home production, the reduction will be more than 5 times greater, 17.5 percentage points due to their much greater average consumption levels (Fig. 9).

Costs

The cost results are shown in Table 3 by activity and year. The greatest percentage of costs is accounted for by the administrative functioning of HarvestPlus' headquarters and its country office. This is followed by the costs of production and then by identification & release and promotion activities.

Fig. 10 shows the evolution of annual costs over the entire analytic period. The bulk of costs are incurred early-on in the project, reflecting both the "active project" phase and, more specifically, the ramping up of activities in preparation for the "big push" for early, large scale adoption. PVAM annual costs peak just prior to release in 2012. Thereafter, they slowly decrease until the closing of the country office in 2019, marking the end of the "active project" phase. In 2020, they fall precipitously to $200,000 per year, a level at which they persist, as they come to consist of just M&M costs.

Benefit-cost and cost-effectiveness analysis

Based on this analysis, PVAM will generate a total savings of 1,192,384 DALYs, which have a present value of 649,062 and a cost

Table 1
Endline indicators of biofortified provitamin A maize by 3-year averages. *Source:* Authors' calculations.

Indicator	Target pop.	2013–15	2016–18	2019–21	2022–24	2025–27	2028–30	2031–33	2034–36	2037–39	2040–42
Endline vitamin A Intake (μg/day)	Everyone	230	238	254	273	288	297	304	307	310	312
	Children 1–4	129	133	141	151	159	164	167	169	170	171
	Children <5	121	125	133	142	149	154	157	158	159	160
	Women 15–49	237	244	261	280	296	306	313	317	320	323
Additional vitamin A intake (μg/day)	Everyone	0	2	14	29	41	48	51	53	53	53
	Children 1–4	0	1	7	15	21	25	27	27	27	27
	Children <5	0	1	6	14	19	22	24	25	25	24
	Women 15–49	0	2	14	30	42	49	53	56	56	55
Percent of vitamin A EAR	Everyone	51%	53%	56%	61%	64%	66%	68%	68%	69%	69%
	Children 1–4	58%	60%	64%	69%	72%	74%	76%	76%	77%	77%
	Children <5	58%	60%	64%	69%	72%	74%	76%	76%	77%	77%
	Women 15–49	48%	49%	52%	56%	59%	62%	63%	64%	64%	65%
Prevalence of vitamin A intake inadequacy	Everyone	87%	87%	86%	85%	85%	84%	84%	83%	83%	83%
	Children 1–4	85%	85%	84%	83%	82%	81%	81%	81%	80%	80%
	Children <5	85%	85%	84%	83%	82%	81%	81%	81%	80%	80%
	Women 15–49	83%	83%	82%	81%	80%	80%	79%	79%	79%	79%
Change in prevalence	Everyone	0.0%	0.0%	0.4%	1.2%	1.8%	2.3%	2.6%	2.8%	2.8%	2.9%
	Children 1–4	0.0%	0.0%	0.4%	1.4%	2.2%	2.8%	2.9%	3.2%	3.4%	3.3%
	Children <5	0.0%	0.0%	0.4%	1.4%	2.2%	2.8%	2.9%	3.2%	3.4%	3.3%
	Women 15–49	0.0%	0.0%	0.4%	1.1%	1.6%	2.0%	2.4%	2.7%	2.8%	2.8%
Endline DALYs	Total DALYs	1,12,086	1,21,756	1,25,262	1,27,485	1,32,157	1,40,704	1,52,244	1,65,718	1,81,436	1,99,292
	Children U5	1,09,199	1,18,639	1,22,090	1,24,299	1,28,914	1,37,291	1,48,580	1,61,745	1,77,095	1,94,526
	P/L Women	2887	3116	3172	3186	3243	3413	3664	3972	4341	4766

Table 2
Impact measures of biofortified provitamin A maize by 3-year averages with no other interventions. *Source:* Authors' calculations.

Indicator	Target pop.	2013–15	2016–18	2019–21	2022–24	2025–27	2028–30	2031–33	2034–36	2037–39	2040–42
Additional vitamin A intake (μg/day)	Everyone	0	2	14	29	41	48	51	53	53	53
	Children 1–4	0	1	7	15	21	25	27	27	27	27
	Children <5	0	1	6	14	19	22	24	25	25	24
	Women 15–49	0	2	14	30	42	49	53	56	56	55
Change in prevalence (reduction in %)	Everyone	0.0%	0.0%	0.4%	1.2%	1.8%	2.3%	2.6%	2.8%	2.8%	2.9%
	Children 1–4	0.0%	0.0%	0.4%	1.4%	2.2%	2.8%	2.9%	3.2%	3.4%	3.3%
	Children <5	0.0%	0.0%	0.4%	1.4%	2.2%	2.8%	2.9%	3.2%	3.4%	3.3%
	Women 15–49	0.0%	0.0%	0.4%	1.1%	1.6%	2.0%	2.4%	2.7%	2.8%	2.8%
Change in average EAR (reduction in %)	Everyone	0.0%	0.5%	3.1%	6.5%	9.1%	10.6%	11.4%	11.8%	11.8%	11.7%
	Children 1–4	0.0%	0.5%	3.1%	6.9%	9.6%	11.2%	12.0%	12.4%	12.4%	12.1%
	Children U5	0.0%	0.5%	3.1%	6.9%	9.6%	11.2%	12.0%	12.4%	12.4%	12.1%
	Women 15–49	0.0%	0.5%	2.8%	6.0%	8.5%	9.9%	10.7%	11.2%	11.2%	11.1%
Number of DALYs saved-efficiency measure	Total DALYs	63	1944	10,898	21,936	31,559	38,649	44,304	49,715	54,862	59,807
	Children U5	60	1880	10,564	21,268	30,570	37,419	42,873	48,099	53,070	57,843
	P/L Women	3	65	333	668	989	1231	1430	1617	1793	1964
% DALYs saved-efficiency measure	Total DALYs	0.1%	1.5%	8.0%	14.6%	19.3%	21.5%	22.5%	23.1%	23.2%	23.1%
	Children U5	0.1%	1.5%	7.9%	14.6%	19.1%	21.4%	22.4%	22.9%	23.1%	22.9%
	P/L Women	0.1%	2.0%	9.4%	17.3%	23.3%	26.5%	28.1%	28.9%	29.2%	29.2%

of $24 per DALY saved. It has a benefit-cost ratio of 42 and a rate of return of 40%.

The World Bank and WHO have suggested benchmarks for interpreting costs per DALY. Based on the World Bank approach, a public health intervention with a cost per DALY of less than US$260 is "very cost-effective" (World Bank, 1993).[7] Using a different comparator, WHO's CHOICE (***Cho***osing ***I***nterventions that are ***C***ost ***E***ffective) Working Group has suggested that a health intervention should be considered "cost-effective" if its cost per DALY saved is less than 3 times per capita income and it should be regarded as "very cost-effective" if its costs per DALY saved is less than per capita income (WHO, 2003). Given the 2010 Zambia per capita gross domestic income of US$1,533 current US$ (World Bank, 2015), and using the WHO criterion, if the cost per DALY saved is less than US$4,599 PVAM can be considered a cost-effective intervention, and if it is less than $1,533 it can be considered "very cost-effective". By the WHO criterion, PVAM qualifies as a "very cost-effective" intervention.

In Fig. 11 the breakeven point occurs where the cumulative costs and cumulative benefits (valuing a DALY saved at $1000) intersect. PVAM's cumulative value of DALYs saved comes to exceed its cumulative total cost occurs starting in 2019, and each year thereafter its net savings increases.

With its cost front-loaded and its benefits accruing slowly over time, PVAM is a time sensitive intervention. If the accounting period is cut from 30 to 20 years, it reduces the DALYs that PVAM saves much more than it affects costs, and its cost per DALY saved increases from $24 to $44. If the accounting period is further reduced to 10 years, PVAM's cost-effectiveness is further reduced and its cost per DALY jumps to $235.

[7] This is the authors' adjusted original 1993 World Development Report figure, which was expressed in 1990 dollars. It has been adjusted to the dollar's average value in 2011 through November (USBLS, 2012).

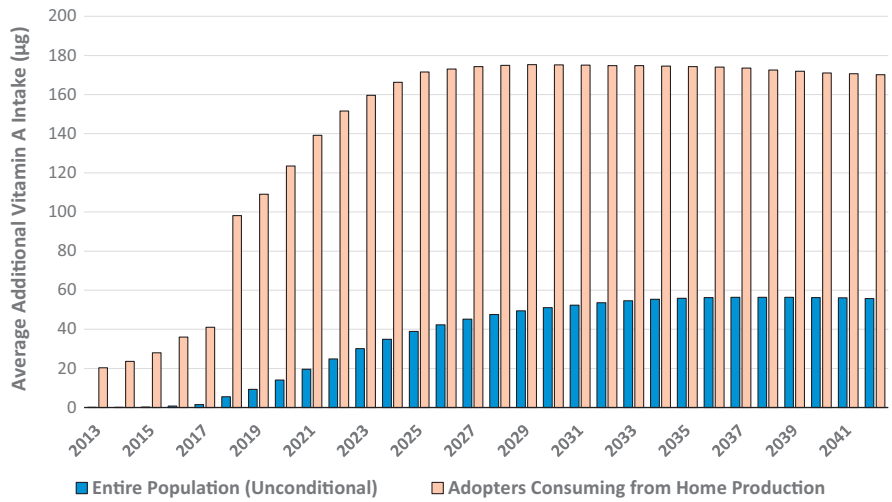

Fig. 8. Average additional vitamin A intake (µg) due to biofortification of maize. *Source:* Authors' calculations.

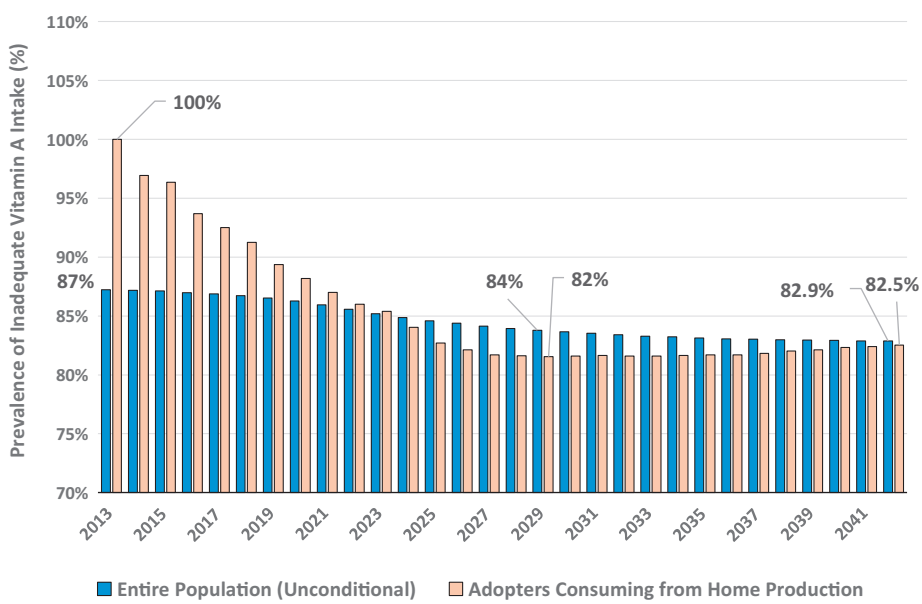

Fig. 9. Prevalence of inadequate vitamin A intake. *Source:* Authors' calculations.

Table 3
Estimated undiscounted costs of the release and scale up of high provitamin A maize in Zambia in thousands of US$. *Source:* Authors' calculations.

Activity/sub-activity	2010	2011	2012	2013	2014	2010–14 total	2015	2016	2017	2018	2019	2015–19 total	Grand total
1. Nutrition target setting	5	72	467	3	0	547							547
2. Identification and release	84	294	200	85	85	748	95	95	95	95	95	475	1223
3. Seed production	1	70	160	260	260	751	150	150	150	150	150	750	1501
4. Seed dissemination		21	80	105	155	363	95	40	40	40	40	287	650
5. Training and extension work		45	120	120	150	435	30	30	30	30	30	150	585
6. Advocacy	15	272	200			487							487
7. Promotion		135	140	230	130	635	130	130	130	130	130	650	1285
8. Impact assessment		100	50	95	105	350	165	15	15	15	265	475	825
9. Administration – country Office	163	584	979	912	870	3509	1000	1000	1000	1000	1000	5000	8509
Total	268	1592	2396	1810	1755	7824	1665	1460	1460	1460	1710	7787	15,611

Discussion

Biofortification is a nascent technology with promise, but about which we still know relatively little. It is commonly described as a new, distinct platform that is food-based; enables targeting a heretofore neglected population—isolated, subsistence farmers; is complementary, beginning in rural areas and reaching to urban areas as markets develop (as opposed to other interventions which begin in urban areas); which, after an initial investment, becomes sustainable, low cost and cost-effective; and will deliver roughly 50% of the EAR in the case of vitamin A[8] (Bouis et al., 2011).

[8] For iron and zinc, initial biofortification targets are estimated to deliver roughly 30% and 40% of the EAR, respectively.

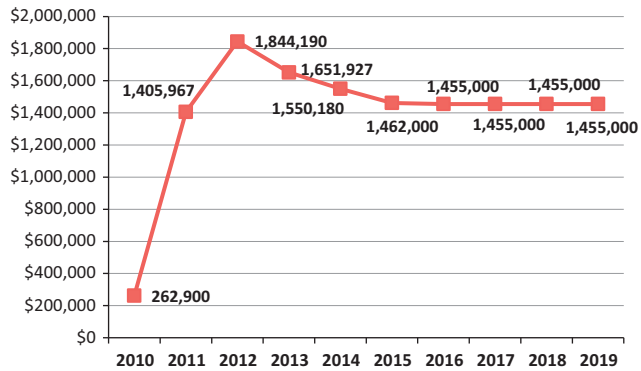

Fig. 10. Vitamin A maize program, release and scale up costs by year, Zambia (US$). *Source:* Authors' calculations.

Acknowledging that quantitative information on food and nutrient intakes for most target populations does not exist, initial targets were set as "minimum" targets based on assumptions about food consumption, bioavailability, and retention after storage and cooking losses, and as new information became available, these parameters and targets would be revised. For maize, the original estimates assumed consumption of roughly 400 g/day among non-pregnant/non-lactating women and about 200 g/day among children 4–6 years old (Bouis et al., 2011). Are the findings of this study consistent with this portrait?

Targeting isolated, hard-to-reach rural populations initially, and extending to urban areas as markets develop

Initially, cultivators of PVAM in rural areas consume more PVAM than either non-adopters or non-farmers and they remain the largest consuming group for the first 15 years. In addition, individually, PVAM cultivators benefit relatively more from PVAM than non-cultivators due to their greater conditional consumption of PVAM. Overall, however, owing to differences in the sizes of the groups, most of the benefits of PVAM go to purchasers of PVAM from both rural and urban areas. Rural areas account for the majority of PVAM consumption initially and cumulatively over the 30 years. Over time, however, urban areas account for an increasing proportion of annual PVAM consumption, and in 2037, the urban areas' annual consumption surpasses that of rural areas. This is consistent with the expectation that biofortification would initially be targeted to rural areas and that its coverage and impact would extend to urban areas as the PVAM market developed.

In light of PVAM's high nationwide coverage and impacts, how does it fit with other possible micronutrient interventions? In a separate analysis of the LCMS 2005 (Fiedler and Lividini, 2014), we found that PVAM is not the only vitamin A intervention that is likely to achieve high coverage in rural areas in Zambia. Despite Zambia's under-developed infrastructure and markets, two common vitamin A fortification vehicles also have high rural penetration rates: 63% of the rural population purchases sugar (which has been fortified in Zambia since 1996) and 63% purchases vegetable oil (which is currently not fortified in Zambia). While the coverage and consumption of these vehicles is greater in urban areas, it is clear that rural markets for these vehicles are already substantially more developed, leaving less space for PVAM's incremental coverage and impact, than had previously been thought existed. Still, the addition of PVAM to the current vitamin A program portfolio of just fortified sugar would increase coverage an additional 25 percentage points above sugar alone and provide 89% of rural Zambian households with the coverage of either PVAM or sugar or both (Fiedler and Lividini, 2014). Given that neither sugar nor PVAM alone will sufficiently alleviate the prevalence of inadequate vitamin A intake in either rural or urban areas; that roughly 37% of the rural population does not consume sugar; and that sugar already exhibits high coverage and consumption rates in urban areas, biofortification provides an important complementary intervention to sugar.

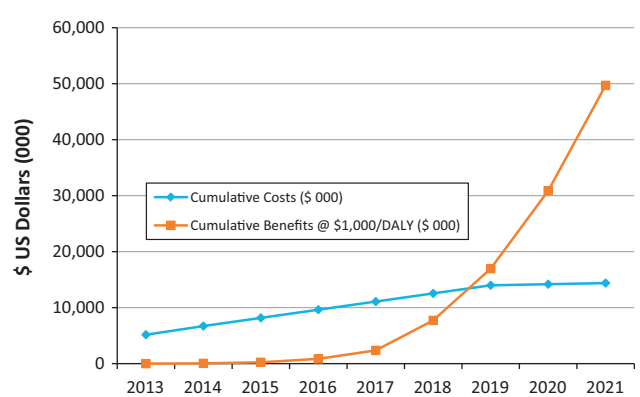

Fig. 11. PVAM cumulative costs and cumulative DALYs saved, Zambia 2013–2021. *Source:* Authors' calculations.

A second implication of the PVAM's transformation over time from having a rural-concentrated impact to having an urban-dominated impact is that it underscores the significance of the post-harvest PVAM market in conditioning PVAM's long term success. A better understanding of the characteristics of the market through which biofortified crops are likely to be traded is essential to crafting efforts to facilitate and accelerate its adoption, production, consumption and impact. The rural-directed, supply-focused, push strategy, must be complemented with an urban-directed, demand-focused, pull strategy which over time is likely to become as important in PVAM's achieving scale and permanence. Cultivating the urban-based PVAM market should not be regarded as a strategy of secondary importance. After all, PVAM farmers' sales of PVAM can also help to improve the nutrition status of their households indirectly, by increasing incomes. PVAM can be and should be promoted, therefore, as both a nutrition-specific, as well as a nutrition-sensitive, intervention, and both push- and pull-approaches should be developed as early-on in the program as possible.

These two findings—the higher than expected rural coverage of fortifiable foods and PVAM's increasingly greater urban impact—both underscore the need to adopt a new approach in analyzing nutrition programs. They demonstrate the importance of supplanting the piecemeal, program-by-program analysis with one that analyzes biofortification and fortification as parts of a portfolio of interventions in which individuals and households may be participating simultaneously in order to understand changing needs, to better economize on programs by adjusting scale and targeting efforts, and to better protect public health from both inadequate intakes as well as the risk of exposure to excess intakes. Adopting such an approach will require the use of HCES or other databases that are capable of examining the participation of individuals or households in multiple programs.

After an initial investment, costs fall dramatically resulting in a low cost and cost-effective intervention

Time preference and risk averseness are important considerations in assessing the costs of biofortification, and in particular its costs relative to other vitamin A interventions. As has been shown, biofortification's costs are front-loaded, while its benefits accrue slowly. In contrast, both the costs and benefits of other vitamin A interventions are much more time invariant. In our comparative analysis of vitamin A interventions in Zambia which uses the same methodology (Fiedler and Lividini, 2014), we show that

biofortification's cost fall dramatically relative to other interventions starting in 2019, making biofortification the cheapest option on an annual basis from that point forward. PVAM's total cumulative costs, however, remain much greater than those of other interventions' for many years (14 for wheat flour, 17 for CHW, and 20 for sugar). Over a 30 year period, biofortification's cumulative costs never become less than those of vegetable oil.

The decision to invest in biofortification therefore is not a simple one from a cost standpoint: it depends on a host of factors including the time horizon for achieving target reductions in micronutrient deficiency (rate of discount) and risk averseness, as its benefits accrue only slowly. In addition, it depends on the long-term commitment to biofortification that will be required in order for it to become sustainable enough to produce greater benefits at lower costs over time. These outcomes are not inevitable, and will require sustained commitment to achieve them.

A cost-effective intervention

As already discussed, based on WHO and World Bank benchmarks, this study has found biofortification is highly cost-effective. Again, drawing on our Zambia portfolio analysis (Fiedler and Lividini, 2014) of the cost-effectiveness of five other vitamin A interventions in Zambia—vitamin A supplementation through Child Health Week, vitamin A fortification of sugar, vegetable oil, wheat flour and maize meal—we found that over a 30 year accounting period PVAM was less cost-effective than either sugar or oil fortification and vitamin A supplementation and more cost-effective than either wheat flour or maize meal fortification. In addition, the combination of biofortified PVAM and fortified oil was found to be the most cost-effective 2-intervention portfolio. This highlights the importance of explicitly identifying the comparator when discussing cost-effectiveness and drawing on a number of indicators. Even though (using WHO and World Bank metrics) we find biofortified PVAM is a cost-effective intervention in Zambia, other criteria are necessary to determine which intervention or portfolio of interventions should be implemented. Which vitamin A intervention is "the best", and whether or not a portfolio of vitamin A interventions should be implemented, are distinct questions that may be addressed using cost-effectiveness analysis, but requires additional criteria, such as the magnitude of the public health impact (i.e., total DALYs saved), affordability (total cost), coverage and effective coverage (see Fiedler and Lividini, 2014 for further analysis and discussion). Moreover, given the very different temporal characteristics of biofortification's cost and benefit streams vis-à-vis those of alternative vitamin A programs, the outcome of a cost-effectiveness analysis will depend in part on the planning horizon: biofortification will be relatively less cost-effective for shorter-term planning periods.

PVAM is a long term investment: it will take more than a decade for biofortified PVAM to begin "paying off". Once it does, however, in each subsequent year throughout the remainder of the 30-year analytic period and beyond, its net cumulative benefits grow. It is noteworthy, however, that fulfillment of PVAM's promise as a very cost-effective intervention cannot be considered a foregone conclusion. It will require vigilance to ensure that the adoption and consumption rates estimated here are achieved and maintained even after PVAM's active project cycle ends in 2019. It would be prudent, therefore—particularly given the substantial front-loaded investment in PVAM—to consider extending the active project phase beyond 2019 so as to ensure that the adoption and consumption rates of the scenario analyzed here are achieved. While that, of course, will mean some increase in costs with uncertain effects on impacts (and thus might risk some reduction in PVAM's estimated cost-effectiveness), in light of PVAM's high benefit-cost ratio, however, there is room to be more cautious. It would seem prudent, therefore, to extend the active project phase, thereby reducing the risks of its adoption and consumption rates not growing as quickly, or not reaching the levels, assumed here. Another strategic consideration would be to actively pursue "mainstreaming"; the process of breeding the enhanced nutrient content into an increasing number of all new seed varieties of the crop.

Biofortified maize will provide 50% of the EAR

Results of the modeling exercise suggest that by 2028–2030 PVAM will deliver a 10.6 percentage point increase in the average EAR of the general population (Table 2). That level is expected to edge up to 11.7 percentage points by 2040–2042, less than a quarter of the 50% mark. When the analysis is limited to only PVAM consumers, however, its average is considerably higher; among all PVAM consumers, it will deliver 20–25% of the EAR, 22% among women 15–49 years and 24% among children 4–6 years. Among adopting farmers PVAM will deliver roughly 35% of the EAR, which is 70% of the original target.

A number of factors contribute to PVAM's impact being lower than had initially been anticipated. First, estimated maize consumption levels were found to be lower: women were assumed to consume about 400 g/day and children 4–6 years were assumed to consume 200 g/day. In this study, we found these figures to be 252 and 143 g/day. Moreover, in this study biofortified maize is not expected to account for 100% of maize consumption: among PVAM consumers it was estimated to be 117 g/day among women and 71 g/day among children 4–6 years—29% and 36%, respectively, of their initial estimated levels.

Second, the retention of provitamin A after cooking and storage was assumed to be 50%, but was later found to be 37.5% (Mugode et al., 2014). Third, and working in the opposite direction and contributing to larger PVAM impacts than had originally been estimated, the bioconversion rate of provitamin A to vitamin A which had been assumed to be 12:1, was later found to be 6.5:1 (Li et al., 2010). These changes in the key drivers of PVAM's impact reflect the nascent nature of biofortification, our still-evolving understanding about how biofortification programs will be implemented and evolve, as well as the still evolving elements of nutrition science needed to fully understand biofortification.

These results suggest a number of policy implications. First, in order to achieve the initial targets of delivering 50% of the EAR to beneficiaries of PVAM, continuing to breed for higher levels of provitamin A (above 15 ppm) and/or more stability of provitamin A in the biofortified maize is essential. Second, engaging in effective behavioral change communication (BCC) campaigns to ensure that those who adopt and grow PVAM primarily use it for their own consumption will be important in order to maximize the benefits of PVAM. Prioritizing PVAM production for consumption will help to achieve delivery of up to 50% of the EAR among growers but may also reduce the added degradation of provitamin A that is likely to occur as marketed PVAM moves through the value chain. Finally, as noted above, sustained commitment to the active project phase will be critical to achieving high rates of adoption of PVAM, both for reaching a high proportion of rural farmers and also for achieving considerable displacement of white maize by PVAM in the market. Reaching such levels will be important to ensuring that biofortification's impact extends beyond rural farmers to those accessing PVAM through markets.

In sum, while the initial estimates were based on assumption and simplified analyses, there continue to be many areas of uncertainty underscoring the need for continued monitoring and updating of the analysis of biofortification programs to provide feedback into the management and design of biofortification programs as implementation progresses, in Zambia and elsewhere. In Zambia, it looks as though biofortified PVAM will be a cost-effective,

long-term, complementary vitamin A intervention, that will initially be focused in rural areas, but that over time and with sustained commitment will have a spreading affect that will come to make an important contribution to the vitamin A status of Zambians in rural and urban areas.

Contextualization: The power of HCES in ex ante modeling of biofortification

The specific characteristics of biofortification and other micronutrient interventions, and the specific ways in which they might be combined with the tradeoffs between potential intervention portfolios in terms of coverage, cost and impact, is a function of a host of country-specific considerations and underscores the importance of using the highly contextualized approach of this study. That approach consists of empirically developing many of the parameters used in this analysis and using these parameters to model biofortification.

The central distinguishing feature of this approach is its modeling the likelihood of PVAM planting (as proxied by cultivating hybrid maize) and the use of the fitted equation to identify in the LCMS the specific households that are likely to adopt. In most *ex ante* adoption studies, these parameters are not empirically-derived. More typically, national-level parameters are assumed (Demont and Stein, 2013). By identifying the specific farming households that adopt biofortified PVAM, this method provides a better understanding of the likely characteristics of PVAM producers and consumers, and roots the study within the household level with the constellation of characteristics of actual Zambian households. As such, it provides insights into how to identify those households and how to promote their adoption, both of which can be important tools for designing, planning and monitoring biofortification interventions and better ensuring its success.

The important contextual considerations we derive from the LCMS agriculture module data include: individual farmer proclivity to adopt modern varieties, individual farm-size, individual farm yield, how much of the biofortified crop is consumed by each household producing it and how much of it is sold. It also incorporates important contextual considerations drawing on aspects of households' consumption module data, including: whether or not the household purchases the biofortified food, in what quantities and what individuals' apparent vitamin A intake status is before and after consuming it. The particular strength of this highly contextualized approach is that it empirically derives all four of the most important measures in an *ex ante* analysis of the nutrition impact of a biofortified crop within the same household—viz., the production and the consumption of the biofortified crop, and the baseline and endline nutrient intakes—rather than assuming their levels or having to rely on distribution-free averages which mask important effects and relationships.

One part of the contextualization of the study is our empirically-informed approach to how we defined the market structure of PVAM. The comparison of the agriculture/production and consumption modules revealed that each province is, or could be, a largely independently functioning market, with Eastern and Central Provinces as the only exceptions. We chose to be guided by these empirical findings about the maize market to determine the disposition of PVAM once it is produced, rather than adopting the more conventional approach of *ex ante* analyses, which is to assess impact using a single, nation-wide approach. Instead, it was assumed that maize markets more closely approximate provincial markets. Adopting this approach we found significant provincial variations in the quantity of PVAM consumed by households, how PVAM consumers acquired it and how the impact of biofortification varies by subpopulation. Given the widespread availability of multi-purpose household consumption and expenditure surveys similar to the LCMS used here (Fiedler et al., 2012a), there is great opportunity for conducting similar studies in many other countries, and similar types of assessment of biofortified crops are underway or have been completed in Bangladesh, India and elsewhere.

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Appendix A. Key assumptions of PVAM production and consumption

The Key PVAM Production and Consumption Assumptions
1. Each adopting farming household plants 0.5 lima (1/4 ha) in its first year
2. Average yield for PVAM is 1.5 tons/ha or 375 kg/lima
3. Cumulative post-harvest losses of PVAM are estimated to be 17.9%
4. In year 2 and each subsequent year, the farming household continues planting PVAM. An additional 0.5 lima is planted in PVAM; the maximum area that a farm may plant in PVAM is the amount of land the farm currently plants in maize
5. The concentration of provitamin A in PVAM is 7.5 ppm or 7.5 μg/g in 2013 and increases to 15 μg/g beginning in 2018
6. Retention of provitamin A in PVAM is 37.5%
7. The bioconversion rate of provitamin A carotenoids in PVAM to vitamin A is assumed to be 6.5
8. Maize is primarily consumed in the form of nshima, a thick porridge that is made by first grinding or milling the maize
9. Different maize forms have different extraction rates: breakfast meal = 70%, roller meal = 90%, hammer meal = 90%
10. Initially, all PVAM produced is used for home consumption and not sold. PVAM producers who produce more PVAM than the amount of maize they consume from home production, sell the excess PVAM. All PVAM that is sold is assumed to be sold, purchased and consumed within the same provincial market. Once the provincial market demand is surfeited, PVAM is sold to consumers in other provinces

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