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# Projecting the Contribution of Provitamin A Maize Biofortification and Other Nutrition Interventions to the Nutritional Adequacy and Cost of Diets in Rural Zimbabwe

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A B S T R A C T

**Background:** Evidence of the effectiveness of biofortified maize with higher provitamin A (PVA) to address vitamin A deficiency in rural Africa remains scant.

**Objectives:** This study projects the impact of adopting PVA maize for a diversity of households in an area typical of rural Zimbabwe and models the cost and composition of diets adequate in vitamin A.

**Methods:** Household-level weighed food records were generated from 30 rural households during a week in April and November 2021. Weekly household intakes were calculated, as well as indicative costs of diets using data from market surveys. The impact of PVA maize adoption was modeled assuming all maize products contained observed vitamin A concentrations. The composition and cost of the least expensive indicative diets adequate in vitamin A were calculated using linear programming.

**Results:** Very few households would reach adequate intake of vitamin A with the consumption of PVA maize. However, from a current situation of 33%, 50%–70% of households were projected to reach ≤50% of their requirements (the target of PVA), even with the modest vitamin A concentrations achieved on-farm (mean of 28.3 μg RAE per 100 g). This proportion would increase if higher concentrations recorded on-station were achieved. The estimated daily costs of current diets (mean ± standard deviation) were USD 1.43 ± 0.59 in the wet season and USD 0.96 ± 0.40 in the dry season. By comparison, optimization models suggest that diets adequate in vitamin A could be achieved at daily costs of USD 0.97 and USD 0.79 in the wet and dry seasons, respectively.

**Conclusions:** The adoption of PVA maize would bring a substantial improvement in vitamin A intake in rural Zimbabwe but should be combined with other interventions (e.g., diet diversification) to fully address vitamin A deficiency.

*Keywords*: vitamin A, hidden hunger, malnutrition, fortification, diet diversification

## Introduction

The prevalence of vitamin A deficiency is high in low- and low to middle-income countries [1,2], including (rural) Zimbabwe and neighboring countries [3–5]. It can be addressed through dietary diversification, fortification of industrially processed food (such as cooking oil or sugar), biofortification, and/or supplementation (high dose provided in e.g., oral liquid form) [6–9]. The coverage of vitamin A supplementation programs for children aged 6–59 mo in Zimbabwe was ~40% in recent years but varies widely across years, including a decline during 2020 and 2021, most likely due to COVID-19 [10]. Vitamin A supplementation programs are generally costly and difficult to maintain, and supplementation access varies by sub-population, typically compounding other health and food system inequities (such as vaccination access), including in Zimbabwe [11]. In this context and recognizing that low-income households may not be in a capacity to afford a diverse diet [12], conventional breeding of maize for higher provitamin A concentration—referred to as PVA maize in the rest of the paper—has been presented as having

*Abbreviations:* ANOVA, Analysis of Variance; IREC, Internal Research Ethics Committee; PVA, Provitamin A; RAE, Retinol Activity Equivalent; SAMRC, South African Medical Research Council; SD, Standard Deviation; USD, United States Dollars.

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good potential to address low vitamin A intake in rural Africa [13].

A breeding target of 15 ppm was set to provide 50% of the estimated average requirement for vitamin A [14]. To date, a total of 76 PVA enhanced varieties have been commercialized in Africa [15]. Under on-station conditions, the PVA concentration achieved through breeding has varied from 7.5 to 15 ppm [16] (against a concentration of non-PVA elite maize ≤2 ppm [17]). For illustration, consumption of 250 g/d of maize flour with PVA concentration of 10 ppm would deliver 2.5 mg PVA, equivalent to 208 μg Retinol Activity Equivalent (RAE). This compares with an average adult female requirement of 490 μg RAE [18].

Although the ability to increase PVA content of maize through genetic improvement has been demonstrated, evidence of the effectiveness of maize biofortification programs on vitamin A status remains scant. Consumption of PVA maize improved children's vitamin A status, serum retinol concentrations among children who were vitamin A deficient at baseline [19], and visual ability to see in low-light conditions [19]. Breastfeeding mothers who consumed PVA maize for 3 mo had an improvement in the vitamin A concentration of their breast milk, and the prevalence of low-vitamin A concentration in breast milk was reduced by >50% [20]. In addition, there have been recent criticisms as to the cost effectiveness and impact of biofortification, and even suggestions that it may have diverted resources and efforts away from more promising strategies such as dietary diversification [21,22].

Against this background, the objectives of the study were as follows: *1*) to assess the adequacy of vitamin A in the diets of a diversity of households in a site typical of rural Zimbabwe, *2*) to project the impact of large-scale adoption of PVA maize and other nutrition interventions under farm conditions, and *3*) to model the cost and composition of diets adequate in vitamin A. We hypothesized the following: *1*) that dietary intake of vitamin A would differ across farm types, *2*) that PVA maize could be a viable option to address inadequate vitamin A intake for some farms but not all, and *3*) that the cost of diets adequate in vitamin A would be above the current cost of diets for the majority households.

## Methods

### Study area and selection of representative households

The District of Murehwa (-17.6432, 31.7840, 1400 m.a.s.l.), located within Mashonaland East Province, Zimbabwe, was selected for the study. This district is predominantly rural, with 80% of the population engaged in small-scale agriculture as their primary livelihood strategy. The prevalence of stunting is greater in Murehwa (36%) than the national average and increased by 6% between 2010 and 2018 [23], indicating persistent nutritional challenges. This is despite agricultural productivity being relatively higher than in most other districts. The area receives a mean annual rainfall of 750–1000 mm [24], mostly falling between October and April. The main soil types include relatively infertile Lixisols and comparatively more fertile Luvisols [25]. Cattle and goats are the main livestock species, and maize is the staple crop [26].

The current study was conducted as part of a larger survey, with recruitment methods described previously [27]. Briefly, 2 wards from Murehwa District with contrasting agricultural soil types and elevation were purposively selected: Ward 4 and Ward 27. In September 2020, a total of 306 farms representing around 7.5% of the population were selected at random within these 2 wards, using an adaptation of the Y sampling [28], and the household head was recruited and interviewed following informed consent. From the dataset, 4 farm types were identified using multidimensional scaling and hierarchical clustering [29].

Type 1 can be described as larger farms with larger livestock herds, high-food security, high-dietary diversity, and crop sales as the main source of income. Type 2 are characterized by intermediate farm and herd sizes, high-food security, and low-dietary diversity. Type 3 are predominantly female-headed households, with intermediate farm and herd sizes, lower food security, and intermediate dietary diversity. Finally, Type 4 farms tend to be households with younger heads, smaller farms and herds, lower food security and dietary diversity, and off-farm activities as main source of income. Based on this typology, a representative sample of 30 rural households was selected through stratified sampling (using ward and farm type as strata). The sample was limited to 30 households due to resource constraints.

### Meal monitoring and market survey

Ethical approval was obtained from the institutional review board at the International Maize and Wheat Improvement Center (IREC 2020.016). All participants provided written informed consent for their participation in the study. Food consumption data were generated at household level using weighed food records. For a week (7 d) between the period 7 and 16 April 2021 (end of wet season) and for a second week between the period 24 October and 1 November 2021 (end of dry season), all food and drink items consumed as a meal or snack by the 30 selected households and its weight were recorded. Only items consumed at home were recorded. For recipes, every raw ingredient was identified and weighed before cooking. The source of each food item—food production, purchase, gift, hunting/gathering, or other—was also recorded. Records were made at the time of food preparation and consumption by a trained member of the household, typically an adult female, receiving regular visits from a research assistant during some of the meals to ensure data was captured accurately. Research assistants were advised not to accept food from households, even when offered. During these visits, records made in the absence of research assistants were also checked. The weight of each food item consumed was estimated using containers of various sizes (jug, bowl, cup, cooking spoon, table spoon, and tea spoon). The quantity of some food items was also estimated by counting units (e.g., for eggs, small tomatoes, medium-sized sweet potatoes, etc.). For each food item and in each household, the unit of measure was then calibrated by a research assistant using portable scales with a 0.1 g resolution. Inedible portions and food waste from these food items were not estimated (food waste tends to be negligible in the community studied). For every meal (or snack), household members taking part were also recorded, including their sex and age. A total of 4543 individual food items consumed at household level were recorded, and their weight was estimated—2294 during the wet season and 2249 during the dry season.

Market surveys also took place during both monitoring periods to collect the local price of all food items recorded. Prices were collected from more than one source (with a target of 3–5 different sources) for each food item whenever possible, and the median was taken. For some uncommon items (16 items in the wet season and 35 in the dry season), it was only possible to collect market price data from one source. Across both seasons, 564 market prices were recorded (289 during the wet season and 275 during the dry season) for 176 food items (82 during the wet season and 94 during the dry season).

## Calculations, linear programing, and statistical tests

Food consumption data sets were first matched to food composition datasets on a like-for-like basis, considering food description and moisture content. Each food item in the consumption data set was matched to a single representative item from composition tables published by the South African Medical Research Council (SAMRC) [30]. We chose this source because the food tables available for Zimbabwe were published >2 decades ago and were relatively limited in terms of the food items they included [31]. For items that could not be found in SAMRC (2017), we used composition data compiled for Malawi [32]. Finally, for wild fruits and vegetables, we used the database published by Stadlmayr et al. [33]. A few items could not be found in any of these sources, and we therefore used the US Department of Agriculture FoodData Central [34]. Cooking oil and margarine were considered industrially fortified with vitamin A, as this is prevalent in Zimbabwe. The full set of consumption-composition item matches is provided in Supplementary materials – Appendix 1. Weekly household intake of energy, protein, vitamin A, and selected other vitamins and minerals were then calculated by summing the products of quantities and concentrations for each food item consumed.

For each household and each week of observation, requirements for vitamin A were calculated based on the characteristics of household members present each day and using the mean harmonized average requirement values published by Allen et al. [18]. Based on these values, weekly household intakes were then expressed on a per adult male (25–50 y old) equivalent and per day basis, using the requirement value for vitamin A of 570 μg RAE [18]. This assumed food was distributed among household members according to their vitamin A requirements. Using the median of local prices for each food item and assuming all food was sourced from local market purchases, indicative cost of diets was calculated. These costs are indicative as they are estimates of the cost a household would incur if they were to purchase diets from the local market, whereas households in the study area source a significant share of their diets from their own production (and gifts).

To project the impact of large-scale adoption of PVA maize, we modeled the intake of vitamin A assuming all maize products to have a vitamin A concentration equal to one of the following values: the mean concentration recorded on farm (28.3 μg RAE per 100 g of dry matter; [35]), the maximum concentration recorded on-farm (40.4 μg RAE per 100 g of dry matter; [35]), the maximum concentration recorded on-station of a released variety (95.0 μg RAE per 100 g of dry matter; Ndhlela, pers. com.), and to the target concentration according to Bouis et al. [14] (125 μg RAE per 100 g of dry matter).

Finally, the composition and cost of the least expensive indicative diets adequate in vitamin A were calculated using linear programming with the Rstats package *lpSolve* [36]. Models were analyzed for an adult male—25–50 y old—on a per day basis and set to minimize the cost of diets while achieving a daily intake of vitamin A >570 μg RAE (the mean harmonized average requirement value published by Allen et al. [18]). To obtain realistic diets and minimize deviation from current ones, intakes of energy, protein, and selected micronutrients (those displayed Supplementary materials—Appendix 2) were constrained to fall between 100%–200% of baseline values (mean values recorded for the total sample of 30 households). The same rule was applied to intake (in g of dry matter) in food belonging to the food groups ‘cereals,’ ‘dark green leafy vegetables,’ and ‘legumes, nuts, and seeds’ (groups according to Kennedy et al. [37]), as these food groups dominated observed diets. A constraint of intake lower than twice the mean values recorded for the total sample of households was set for the other food groups.

Differences between types were tested through ANOVA, followed by a Tukey post hoc test when differences between types were revealed, using the Rstats package *stats* [38].

# Results

## Description of participants and current diets

The size of households included in the study was larger during the wet season than during the dry season: 8.1 ± 5.0 compared with 5.8 ± 2.8, respectively (Table 1). During both seasons, children (aged 1–17 y) represented the dominant group (3.0 ± 2.1 and 2.5 ± 1.9 during the wet season and the dry season, respectively), followed by young female adults (aged 18–50 y; 1.8 ± 1.7 and 2.5 ± 1.9 during the wet season and the dry season, respectively). No statistically significant differences in household size and household composition were found between the 4 farm types, except Type 2 farms having significantly more children than Type 1 farms during the dry season (Table 1).

During both seasons, diets were dominated by cereals, with mean daily quantities consumed estimated at 396.0 and 509.1 g/d per adult male equivalent during the wet and the dry season, respectively (Table 2). Other important food groups were ‘legumes, nuts, and seeds,’ ‘white roots and tubers,’ and ‘sweets.’ Consumptions of eggs, organ meat, and vitamin A-rich fruits were very low (<5 g/d per adult male equivalent) in both seasons. The mean (±SD) energy intake was 14,662 ± 4549 kJ per day per adult male equivalent during the wet season and 13,370 ± 3455 kJ per day per adult male equivalent during the dry season (Table 3). These values are plausible given the minimum recommended dietary allowances published by Otten et al. [39] (2006).

Out of the 30 households under observation, only 3 had a diet adequate in vitamin A during the wet season and only 1 during the dry season (Figure 1). During both seasons, 10 households reached at least half of the daily requirement in vitamin A. Inadequacies were also commonly observed for several other nutrients, including protein, riboflavin, vitamin B12, choline, and calcium during both seasons, and vitamin C during the dry season (see values in Table 3 compared with Supplementary materials – Appendix 2). Vitamin A was predominantly supplied by meals, with a small contribution from snacks during the wet season (Figure 1 A and B). The main sources of vitamin A were foods produced on the farm and purchased food, during both seasons (Figure 1 C and D). The food groups contributing to most of the vitamin A were ‘dark green leafy vegetables’ (55.6% and 55.3% of the average diet in the wet season and the dry season, respectively) and ‘vitamin A-

**TABLE 1**
Mean household size and household composition for the 30 households included in the study. Standard deviations are given in parentheses. *F*-values and *P*-values are given for ANOVA tests comparing means between the 4 farm types.

| Household members (by season) | Overall | By farm type | | | | | |
|---|---|---|---|---|---|---|---|
| | | Type 1 | Type 2 | Type 3 | Type 4 | *F* value | *P value* |
| Wet season | | | | | | | |
| Total | 8.1 (5.0) | 7.9 (5.7) | 9.6 (4.0) | 7.9 (5.4) | 7.0 (5.5) | 0.268 | 0.848 |
| Infants | 0.5 (0.8) | 0.4 (1.0) | 0.4 (0.8) | 0.6 (0.7) | 0.4 (0.5) | 0.054 | 0.983 |
| Children | 3.0 (2.1) | 1.9 (1.8) | 4.6 (2.7) | 3.0 (1.3) | 3.0 (2.2) | 2.396 | 0.091 |
| Young male adults | 1.3 (1.9) | 1.8 (2.6) | 1.4 (1.3) | 1.1 (2.0) | 0.6 (0.9) | 0.431 | 0.733 |
| Young female adults | 1.8 (1.7) | 1.6 (1.7) | 2.0 (1.2) | 2.0 (2.0) | 1.8 (2.4) | 0.114 | 0.951 |
| Older male adults | 0.5 (0.6) | 0.8 (0.7) | 0.4 (0.8) | 0.3 (0.5) | 0.4 (0.5) | 0.853 | 0.478 |
| Older female adults | 1.0 (1.0) | 1.4 (1.4) | 0.7 (0.8) | 0.9 (0.8) | 0.8 (0.8) | 0.843 | 0.483 |
| Dry season | | | | | | | |
| Total | 5.8 (2.8) | 5.0 (2.8) | 7.1 (3.4) | 6.0 (2.4) | 5.0 (2.1) | 0.956 | 0.428 |
| Infants | 0.1 (0.3) | 0.0 (0.0) | 0.3 (0.5) | 0.1 (0.3) | 0.0 (0.0) | 1.431 | 0.256 |
| Children | 2.5 (1.9) | 1.1 (1.6)[1] | 3.7 (1.9)[1] | 2.6 (1.2) | 3.4 (2.4) | 3.537 | 0.028 |
| Young male adults | 1.0 (1.3) | 1.2 (1.5) | 1.1 (1.8) | 0.9 (1.1) | 0.4 (0.5) | 0.459 | 0.713 |
| Young female adults | 1.1 (1.3) | 1.0 (1.6) | 1.4 (1.0) | 1.3 (1.7) | 0.4 (0.5) | 0.671 | 0.578 |
| Older male adults | 0.4 (0.6) | 0.8 (0.7) | 0.3 (0.5) | 0.3 (0.5) | 0.2 (0.4) | 1.762 | 0.179 |
| Older female adults | 0.7 (0.5) | 0.9 (0.6) | 0.3 (0.5) | 0.8 (0.4) | 0.6 (0.5) | 1.953 | 0.146 |

[1] Significant difference between means (from Tukey post hoc test)

**TABLE 2**
Mean quantities of food groups consumed in current diets and in diets adequate in vitamin A at minimum cost (expressed in grams per adult male—25–50 y old—equivalent and per day) and percentage change from the former to the latter.

| Food group (by season) | Current | Optimized | % Change |
|---|---|---|---|
| Wet season | | | |
| Cereals | 396.0 | 462.8 | 16.9 |
| Dark green leafy vegetables | 8.3 | 16.6 | 99.8 |
| Eggs | 2.6 | 2.7 | 0.8 |
| Fish and seafood | 6.8 | 6.8 | 0.2 |
| Flesh meat | 7.7 | 9.9 | 28.0 |
| Legumes nuts and seeds | 164.7 | 160.4 | -2.6 |
| Milk and milk products | 5.8 | 5.8 | -0.4 |
| Oils and fats | 12.0 | 12.0 | 0.1 |
| Organ meat | 0.0 | 0.0 | - |
| Other fruits | 8.9 | 8.9 | 0.0 |
| Other vegetables | 15.8 | 15.8 | 0.0 |
| Sweets | 60.9 | 0.0 | -100.0 |
| Vitamin A-rich fruits | 0.0 | 0.0 | - |
| Vitamin A-rich vegetables and tubers | 9.3 | 1.8 | -80.9 |
| White roots and tubers | 62.3 | 62.3 | 0.0 |
| Wet season | | | |
| Cereals | 509.1 | 509.1 | 0.0 |
| Dark green leafy vegetables | 8.6 | 17.1 | 99.8 |
| Eggs | 5.0 | 5.0 | -0.3 |
| Fish and seafood | 7.4 | 7.4 | -0.2 |
| Flesh meat | 9.4 | 11.6 | 23.9 |
| Legumes nuts and seeds | 71.9 | 73.6 | 2.4 |
| Milk and milk products | 6.6 | 6.6 | 0.2 |
| Oils and fats | 6.6 | 12.2 | 85.8 |
| Organ meat | 3.8 | 0.0 | -100.0 |
| Other fruits | 12.4 | 12.4 | 0.1 |
| Other vegetables | 11.2 | 11.2 | -0.2 |
| Sweets | 59.8 | 0.0 | -100.0 |
| Vitamin A-rich fruits | 3.9 | 0.0 | -100.0 |
| Vitamin A-rich vegetables and tubers | 19.7 | 0.0 | -100.0 |
| White roots and tubers | 36.4 | 36.4 | 0.0 |

rich vegetables and tubers' (25.4% and 23.2% of the average diet in the wet season and the dry season, respectively) (Figure 1 E and F). Although Type 4 farms in the wet season and Type 2 and Type 4 farms in the dry season tended to have lower average intake of vitamin A compared with the other farm types, vitamin A intake did not statistically differ between farm types during the wet or dry season (Figure 1 G and H, Table 3).

## Cost of current diets

The mean (± SD) indicative cost of current diets was USD 1.43 ± 0.59 day$^{-1}$ during the wet season and USD 0.96 ± 0.40 day$^{-1}$ during the dry season (Figure 2). The food groups that accounted for the largest proportion of this cost were 'legumes, nuts and seeds,' 'cereals,' 'other vegetables,' and 'other fruits' during the wet season (20.5%, 20.3%, 12.9%, and 12.6% of the mean cost, respectively), and 'cereals,' 'legumes, nuts and seeds,' 'vitamin A-rich vegetables and tubers,' and 'white roots and tubers' during the dry season (24.3%, 13.7%, 9.4%, and 8.0% of the mean cost, respectively). Kale and covo (2 different cultivars of *Brassica oleracea* var. acephala) and rape (*Brassica napus*) were among the least expensive sources of vitamin A during both the wet and the dry season (Figure 3). Kale was the least expensive source during the wet season, and carrot was the least expensive during the dry season.

## Projected impact of the adoption of large-scale PVA maize adoption

If all maize products consumed were PVA maize with a vitamin A concentration of 28.3 µg RAE per 100 g of dry matter (the mean concentration recorded on farm), diets would only be adequate in vitamin A for 4 households (out of 30) during the wet season, and 2 during the dry season (Figure 4). This means that only 2 additional households during the wet season and one additional household during the dry season would reach vitamin A adequacy compared with the current situation. However, 50% of the households would reach at least half of their daily

**TABLE 3**

Mean intake (expressed as adult male—25–50 y old—equivalent per day) for energy, protein and selected vitamins and minerals. Standard deviations are given in parentheses. *F*-values and *P*-values are given for ANOVA tests comparing means between the 4 farm types.

| Energy, protein, vitamins and minerals (by season) | Overall | By farm type | | | | | |
|---|---|---|---|---|---|---|---|
| | | Type 1 | Type 2 | Type 3 | Type 4 | *F*-value | *P-value* |
| Wet season | | | | | | | |
| Energy (kJ) | 14,662.0 (4,549.0) | 12,743.7 (3,772.3) | 16,923.9 (4,028.4) | 16,045.0 (5,431.3) | 12,458.8 (3,259.4) | 1.954 | 0.146 |
| Protein (g) | 19.3 (12.5) | 28.0 (18.6)[1] | 17.7 (6.0) | 14.6 (7.4)[1] | 14.5 (5.1) | 2.493 | 0.082 |
| Vitamin A (μg RAE) | 272.0 (181.3) | 295.3 (196.8) | 274.0 (223.2) | 302.7 (165.6) | 172.1 (124.7) | 0.617 | 0.610 |
| Vitamin C (mg) | 178.4 (156.6) | 219.9 (251.0) | 181.3 (126.3) | 152.2 (86.6) | 146.7 (78.0) | 0.339 | 0.797 |
| Vitamin D (μg) | 0.6 (0.7) | 1.1 (0.6)[1] | 0.6 (0.5) | 0.2 (0.5)[1] | 0.4 (0.8) | 3.596 | 0.027 |
| Vitamin E (mg) | 22.8 (10.6) | 18.8 (9.5) | 23.6 (7.7) | 27.8 (13.5) | 19.8 (8.4) | 1.296 | 0.297 |
| Riboflavin (mg) | 1.0 (0.3) | 0.9 (0.3) | 1.1 (0.2) | 1.0 (0.3) | 0.8 (0.3) | 0.968 | 0.423 |
| Vitamin B12 (μg) | 1.0 (1.7) | 2.2 (2.7) | 0.8 (0.9) | 0.2 (0.3) | 0.5 (0.8) | 2.742 | 0.064 |
| Cholin (mg) | 25.6 (32.8) | 45.6 (37.8) | 34.2 (31.8) | 11.3 (25.5) | 3.3 (4.6) | 3.213 | 0.039 |
| Calcium (mg) | 453.1 (171.3) | 484.6 (217.6) | 456.4 (160.8) | 480.2 (159.0) | 343.2 (97.5) | 0.851 | 0.479 |
| Iron (mg) | 28.5 (8.4) | 26.5 (7.6) | 30.8 (6.0) | 31.4 (11.0) | 24.0 (5.6) | 1.217 | 0.323 |
| Zinc (mg) | 16.9 (4.8) | 15.3 (3.7) | 18.3 (3.4) | 18.6 (6.5) | 14.6 (4.2) | 1.315 | 0.291 |
| Dry season | | | | | | | |
| Energy (kJ) | 13,369.7 (3,455.1) | 13,729.9 (1,319.4) | 13,196.1 (4,210.8) | 14,500.3 (4,489.0) | 10,929.1 (2,345.4) | 1.218 | 0.323 |
| Protein (g) | 19.6 (9.9) | 27.2 (12.2) [1] | 17.3 (4.1) | 17.9 (8.8) | 12.1 (3.7)[1] | 3.841 | 0.021 |
| Vitamin A (μg RAE) | 250.3 (125.6) | 239.4 (101.9) | 204.5 (85.9) | 326.9 (166.9) | 196.0 (77.3) | 1.931 | 0.149 |
| Vitamin C (mg) | 79.1 (56.8) | 111.4 (66.5) | 58.1 (31.8) | 85.7 (59.8) | 38.7 (25.2) | 2.509 | 0.081 |
| Vitamin D (μg) | 1.0 (1.2) | 1.6 (1.6) | 0.9 (1.2) | 0.8 (0.9) | 0.2 (0.4) | 1.765 | 0.178 |
| Vitamin E (mg) | 12.8 (4.1) | 14.4 (3.8) | 12.6 (3.4) | 13.5 (4.9) | 9.0 (1.8) | 2.243 | 0.107 |
| Riboflavin (mg) | 0.9 (0.2) | 0.9 (0.1) | 0.9 (0.3) | 1.0 (0.3) | 0.8 (0.1) | 1.502 | 0.237 |
| Vitamin B12 (μg) | 0.6 (0.8) | 0.7 (0.7) | 0.6 (0.7) | 0.6 (1.2) | 0.5 (0.7) | 0.030 | 0.993 |
| Cholin (mg) | 47.7 (60.5) | 75.8 (75.9) | 49.1 (62.0) | 37.7 (51.0) | 13.0 (22.7) | 1.319 | 0.290 |
| Calcium (mg) | 340.7 (139.7) | 365.6 (89.4) | 268.7 (75.3) | 386.6 (153.2) | 313.8 (232.4) | 1.114 | 0.361 |
| Iron (mg) | 25.8 (6.7) | 25.7 (1.8) | 24.2 (6.6) | 29.1 (9.8) | 22.0 (3.6) | 1.494 | 0.240 |
| Zinc (mg) | 15.4 (3.9) | 15.0 (2.3) | 15.5 (4.5) | 16.8 (5.3) | 13.8 (2.3) | 0.711 | 0.554 |

[1] Significant difference between means (from Tukey post hoc test)

requirements during the wet season and 70% during the dry season (from the current situation of 33% during both seasons).

With a vitamin A concentration of 40.4 μg RAE per 100 g of dry matter for all maize products (the maximum concentration recorded on farm), the number of households reaching adequacy in vitamin A intake would become 6 during the wet season and 2 during the dry season. The percentage of households reaching at least half of their daily requirements would become 63% during the wet season and 90% during the dry season. With a vitamin A concentration of 95 μg RAE per 100 g of dry matter for all maize products (the maximum concentration recorded on station), the number of households reaching adequacy in vitamin A intake would become 12 during the wet season and 19 during the dry season. The percentage of households reaching at least half of their vitamin A daily requirement would become 90% during the wet season and 97% during the dry season. Finally, with a vitamin A concentration of 125 μg RAE per 100 g of dry matter for all maize products (the target concentration), the number of households reaching adequacy in vitamin A intake would become 18 during the wet season and 25 during the dry season. The percentage of households reaching at least half of their daily requirements would become 97% during both the wet and the dry seasons.

## Minimum cost of diets adequate in vitamin A

The estimated minimum cost (per adult male equivalent per day) of a diet adequate in vitamin A was USD 0.975 day$^{-1}$ during the wet season and USD 0.793 day$^{-1}$ during the dry season (Figure 5), i.e., above the current cost of diets for only 6 households during the wet season and 12 households during the dry season (Figure 2). Compared with the average current diet, the diet adequate in vitamin A at minimum cost would imply a doubling in the consumption of 'dark green leafy vegetables' (Table 2). It would also require a substantial increase in the consumption of 'flesh meat' during both seasons and 'oils and fats' during the dry season.

If all maize products consumed were PVA maize, with a vitamin A concentration of 28.3 μg RAE per 100 g (the mean concentration recorded on farm) and assuming no difference in cost with current maize products, the cost of a diet adequate in vitamin A is expected to be reduced to USD 0.923 day$^{-1}$ during the wet season and to USD 0.766 day$^{-1}$ during the dry season (Figure 5). With a vitamin A concentration of 40.4 μg RAE per 100 g (the maximum concentration recorded on farm) and 95 μg RAE per 100 g (the maximum concentration recorded on station) for all maize products, this cost during the wet season would become USD 0.919 day$^{-1}$ and USD 0.914 day$^{-1}$, respectively, and during the dry season USD 0.759 day$^{-1}$ and USD 0.750 day$^{-1}$, respectively. No difference in the cost of a diet adequate in vitamin A would be expected between a vitamin A concentration of all maize products of 95 μg RAE per 100 g or 125 μg RAE per 100 g (the target concentration).

# Discussion

To date, all studies (to the best of our knowledge) focusing on the potential health impact of biofortified crops, including

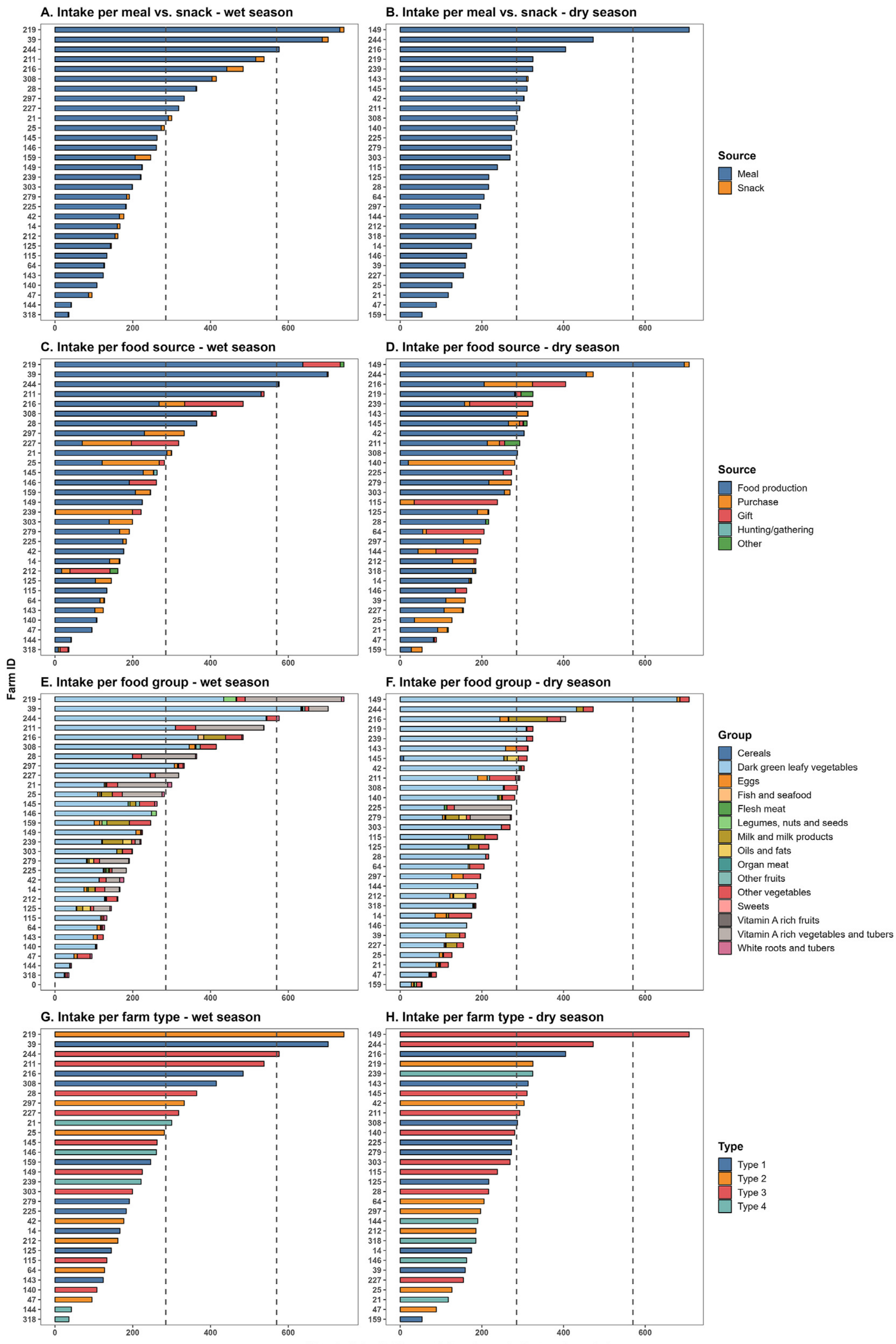


**FIGURE 1.** Vitamin A intake for the 30 households assessed during the wet season (A, C, E, G) and the dry season (B, D, F, H), for meal vs. snacks (A, B), per food source (C, D), per food group (E, F) and per farm type (G, H), and expressed in μg RAE per adult male (25–50 y old) equivalent per day. Dashed vertical lines represent the harmonized average requirement for an adult male – 25–50 y old – according to Allen et al. [18] (2020) – 570 μg RAE per day – and 50% of this value.

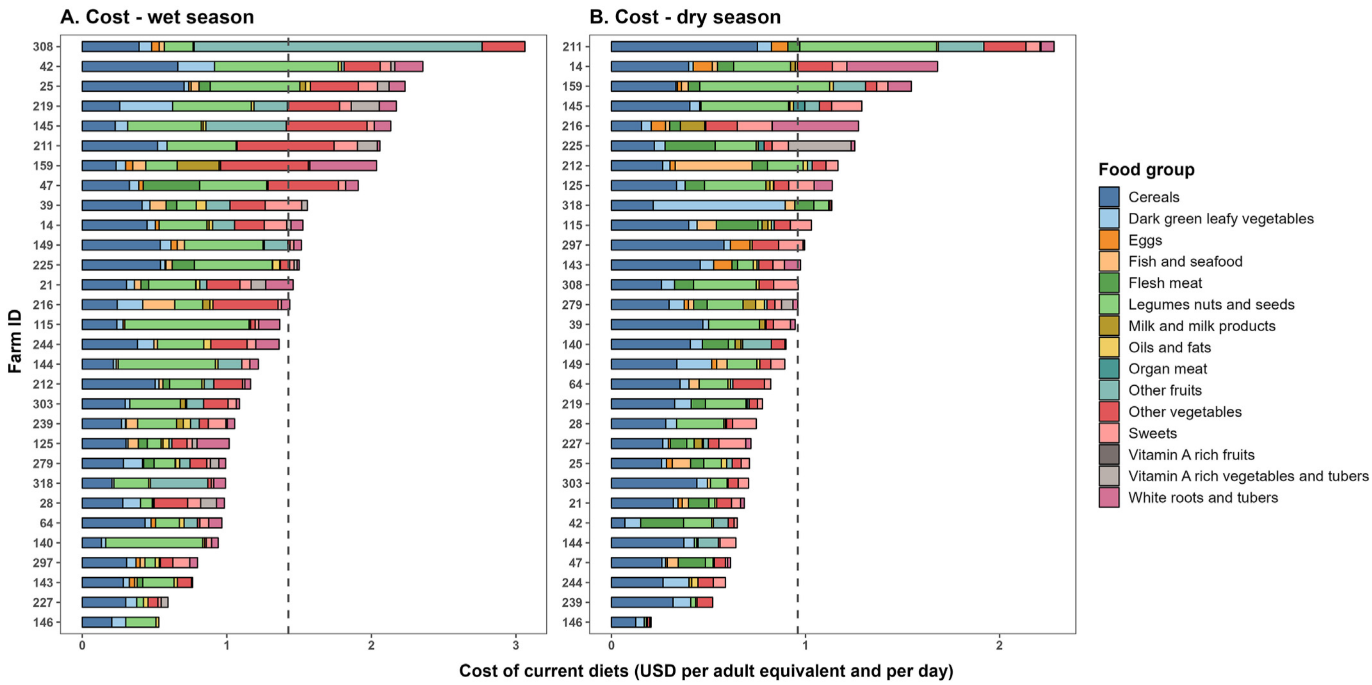


**FIGURE 2.** Cost of current diets (expressed in USD per adult male – 25–50 y old – equivalent per day) during the wet season (A) and during the dry season (B) by food groups. Dashed vertical lines represent mean cost for the sample of farms considered (1.426 USD/d during the wet season and 0.960 USD/d during the dry season).

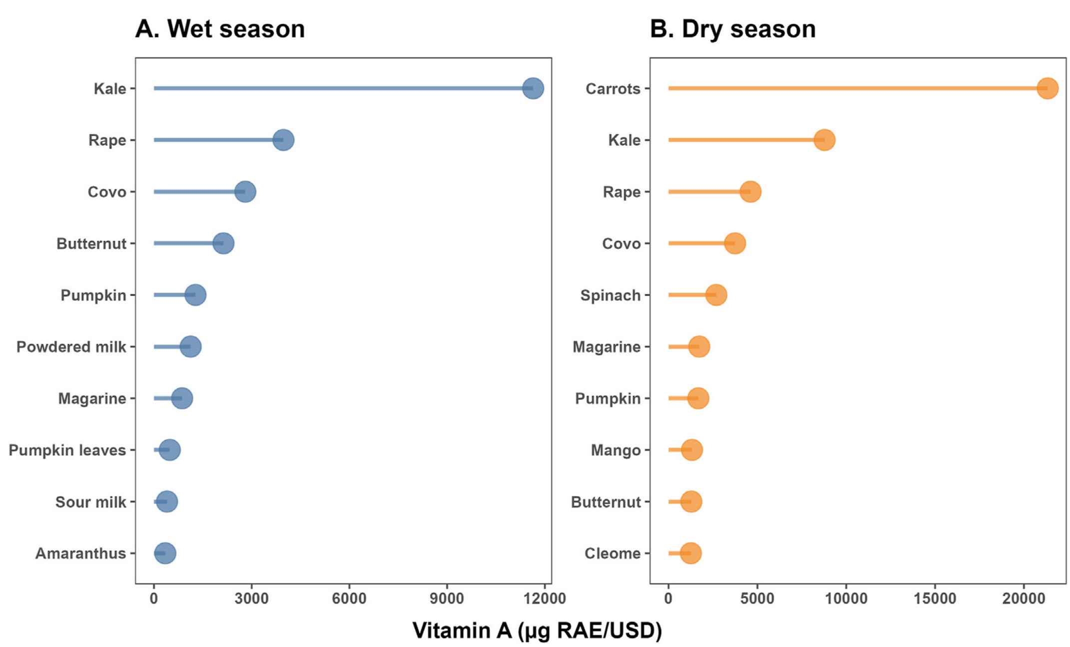


**FIGURE 3.** Cost of the 10 least expensive vitamin A-rich food items during the wet season (A) and the dry season (B) expressed in µg RAE per USD.

maize, have used crops produced under optimal conditions on-station or on commercial farms [19,20,40,41]. However, the nutritional concentration of biofortified crops decreases under suboptimal conditions and thus when produced by resource constrained smallholder farmers [42]. In the secondary data used in this research, the mean vitamin A concentration of maize grown in smallholder farmers' fields was ~ 1/3 of that of PVA maize grown under optimal conditions (irrigated, well-fertilized, and nondegraded soils [35]). To our knowledge, this is the first study to account for a range of micronutrient concentrations (in this case, vitamin A) of biofortified crops in the projection of their likely impact.

Our results suggest that large-scale adoption of PVA maize in the area (without additional interventions) would not lead to an adequate vitamin A intake for most households unless concentrations currently not achieved on-farm (concentrations of 95.0 µg RAE per 100 g dry matter or more) could be reached (Figure 4). However, the consumption of PVA maize grown under

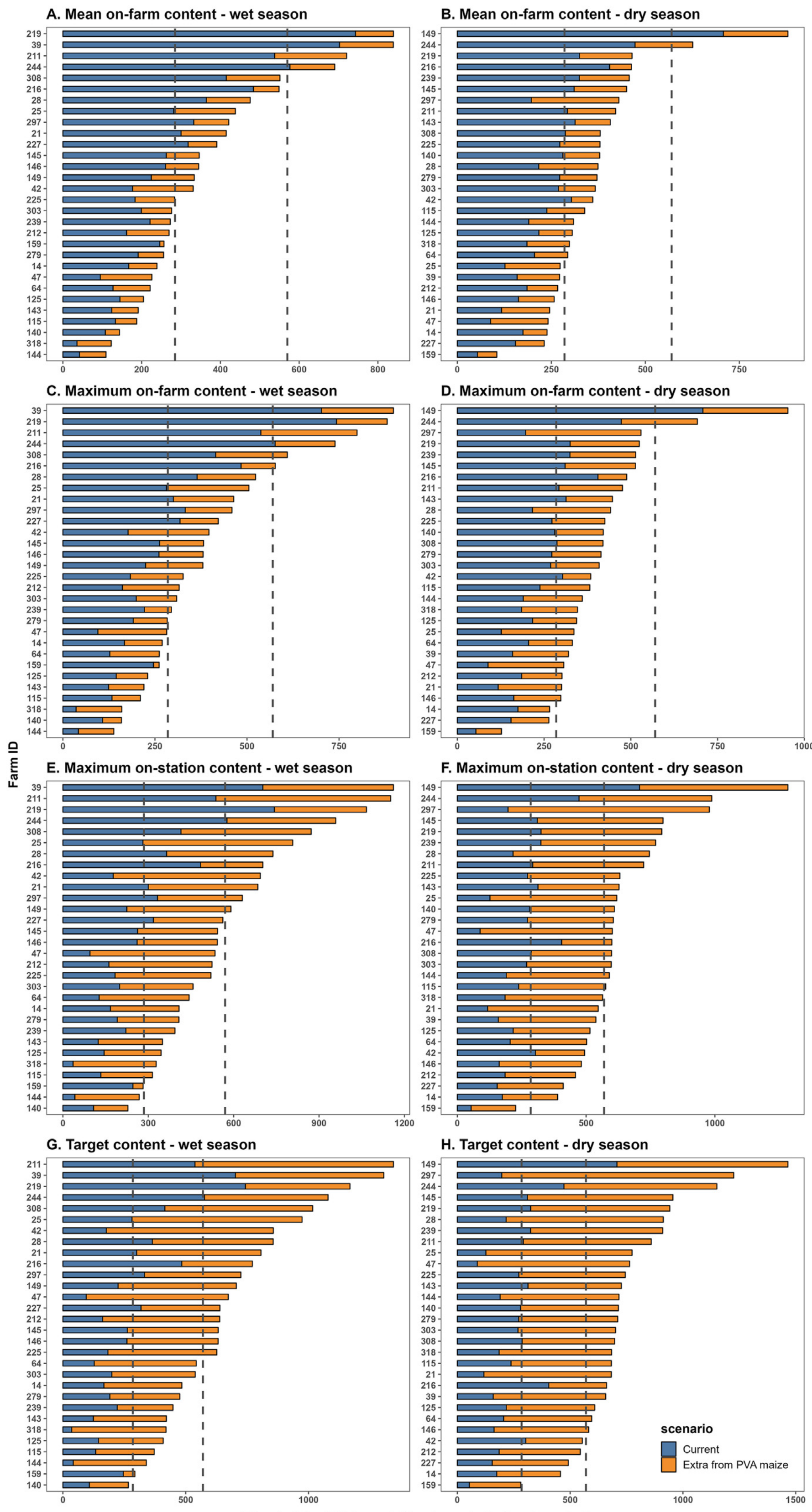


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**FIGURE 4.** Vitamin A intake (expressed in μg RAE per adult male – 25–50 y old – equivalent per day) in current diets and in modeled diets in which all maize products consumed are assumed to have a vitamin A content equal to the mean content recorded on farm (28.3 μg RAE per 100 g of dry matter; A, B), to the maximum content recorded on-farm (40.4 μg RAE per 100 g of dry matter; C, D), to the maximum content recorded on-station (95.0 μg RAE per 100 g of dry matter; E, F), and to the target content according to Bouis et al. [14] (2011) (125.0 μg RAE per 100 g of dry matter; G, H), during the wet season (A, C, E, G) and the dry season (B, D, F, H). Dashed vertical lines represent 50% and 100% the harmonized average requirement for an adult male – 25–50 y – according to Allen et al. [18] (2020): 570 μg RAE per day.

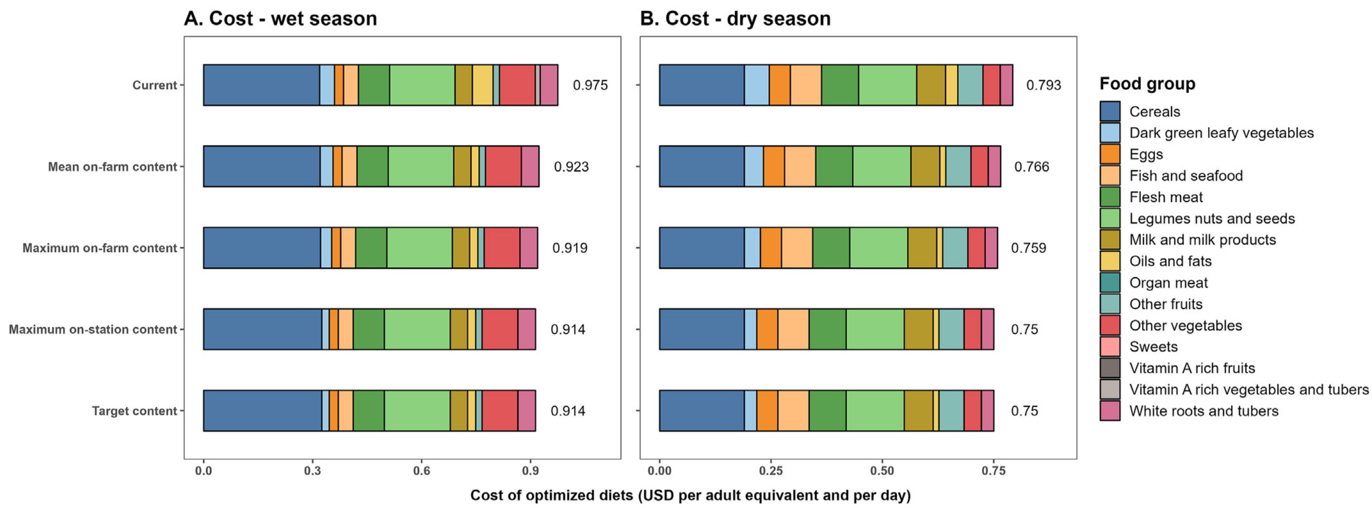


**FIGURE 5.** Cost by food groups of the least expensive indicative diet adequate in vitamin A during the wet season (A) and the dry season (B) with current vitamin A content of all maize products, and assuming all maize products consumed have a vitamin A content equal to the mean content recorded on farm (28.29 μg RAE per 100 g), to the maximum content recorded on-farm (40.40 μg RAE per 100 g), to the maximum content recorded on-station (95 μg RAE per 100 g), and to the target content according to Bouis et al. [14] (2011) (125 μg RAE per 100 g).

smallholder farmers management (mean vitamin A concentration recorded on-farm of 28.3 μg RAE per 100 g of dry matter) would ensure that most households reach at least half of their daily requirements, which was the original target for PVA maize breeding [14], with a stronger effect during the dry season (Figure 4).

Better understanding the links between soil fertility, fertilizer use, and vitamin A concentration remains an interesting avenue not yet fully explored, to potentially increase the benefit of PVA maize produced under typical smallholder conditions. Earlier studies have shown a significant positive contribution of soil fertility management to grain micronutrient concentration in cereals [43–46]. Pathways between soil fertility and grain concentration would probably be different for vitamin A and for micronutrients that can be supplied through fertilizers and/or organic soil amendments. Recent results in the study area indicate that lower PVA concentrations in the grain on-farm might be related to a generally lower energy status of the plant under limiting conditions [35].

In addition to highlighting the likely impact of PVA maize consumption on vitamin A intake, our study points to the importance of complementary nutrition interventions, including diet diversification, industrial fortification, and supplementation. Contrary to our original hypothesis, we found that most households could obtain a diet adequate in vitamin A from food produced on their farms or available in local markets at a cost that does not exceed the current cost of their diets (Figures 2 and 5). However, the large-scale adoption of PVA maize – assuming no price difference between biofortified and nonbiofortified maize products—would only lead to a modest reduction in the cost of diets adequate in vitamin A, even at higher concentrations of vitamin A in maize (Figure 5). Adopting a diet adequate in vitamin A at minimum cost would imply a substantial increase in the consumption of 'dark green leafy vegetables' and 'flesh meat' (Table 2), which could be supported by targeted interventions. The promotion of home gardens in South Africa has been demonstrated to significantly improve the consumption of dark green leafy vegetables and reduce vitamin A deficiencies [47]. Similarly, the promotion of small livestock rearing in Ethiopia has been found to significantly increase the consumption of micronutrient-rich meat and milk [48].

In addition to 'dark green leafy vegetables,' 'oils and fats' are a food group that makes a significant contribution to diets adequate in vitamin A during the dry season (Table 2). These food items are industrially fortified with vitamin A in Zimbabwe and represent a cheap source of vitamin A, although mainly for adults rather than infants and children whose food habits tend to differ [9]. The latter group, however, may benefit from high-dose vitamin A supplementation programs that run every 6 mo, targeting children from birth until the age of 5 y [10]. Industrial fortification could also be expanded to include sugar and cereal products, in addition to cooking oil [49]: the universal fortification of these staples would increase dietary vitamin A supplies, including potentially for vulnerable communities, although very low-income households may still have dietary vitamin A shortfalls as seen in Malawi [3]. In addition, local small-scale food fortification of flour is currently being piloted in parts of sub-Saharan Africa, targeting that milled maize flour is fortified with essential micronutrients before consumption and could be expanded to the study area [50].

The lack of association between vitamin A intake and farm type (Figures 1 G and H) demonstrates that vitamin A adequacy is independent of wealth and suggests that complementary interventions, including the promotion of dietary diversification, focusing on vitamin A-rich sources, may be important in the context of rural Zimbabwe, as previously demonstrated in other contexts [51]. Some of the households studied used sun-drying of vegetables, which ensured a consistent supply of vitamin A, including during the drier months, a practice that could be promoted to other households (although vitamin A concentration may be affected by the practice [52]). Although the contribution of wild foods to vitamin A intake was found to be insignificant in this study (Figures 1 C and D), they have been found to be important in other communities of Zimbabwe [53] and could play a role in promoting year-round consumption of vitamin A-rich food in Murehwa.

There were several limitations of this study, which are highlighted to guide future studies. First, this research was conducted at household level and assumed foods were distributed among household members according to their vitamin A requirements. Although studies have found reasonably equitable distribution of food within the household context [54] it is not always the case, with household members—mainly children and females—who may be undernourished in households that are nutritionally adequate [55]. Intrahousehold food distribution may be particularly unequal for nutrient-dense food such as animal-sourced food [56]. Therefore, future research should assess vitamin A intake at individual level, with a focus on children aged $\geq$5 y, girls, and women of reproductive age as they have the highest requirements for most nutrients [57]. Second, vitamin A intake may have been overestimated. Both storage and processing/cooking (i.e., drying of vegetables) have been shown to reduce vitamin A content [52,58] and were not monitored in this study. Food waste within the household was also not considered, although this tends to be low in low-income countries [59]. Third, food composition data used in this study originated from neighboring countries, which may differ from actual compositions. Finally, this study could be improved by assessing serum retinol concentration as a biomarker of vitamin A status, which may be poorly correlated with vitamin A intake [60].

## Conclusions

In conclusion, this study confirms that diets in rural Zimbabwe tend to be inadequate in vitamin A (as well as proteins and several other micronutrients, including riboflavin, vitamin B12, choline, calcium, and vitamin C), often only reaching less than half the dietary requirements. Our results demonstrate that the adoption of PVA maize would ensure that most households reach at least half of their daily vitamin A requirement, which was the original target for PVA maize breeding, even when accounting for the lower vitamin A concentration achieved on-farm. However, our study also shows that the adoption of PVA maize alone will not lead to adequate vitamin A intake (i.e., meeting 100% of daily requirements) for most households unless nutrient concentrations achieved under typical on-farm management increased. In addition to PVA maize, this study found evidence that other nutrition interventions could have a positive effect on vitamin A intake, including dietary diversification, industrial fortification (as already practiced for cooking oil and margarine), and supplementation.

Although PVA maize can help alleviate the problem of low intake of vitamin A, the current adoption of PVA maize in Zimbabwe remains very low. In a nationally representative survey conducted in 2018, only 6% and 2% of rural households were found to consume and grow biofortified crops, respectively [61]. In a survey of 295 farms in Ward 4 and Ward 27 of Murehwa District conducted in February 2023, 35% of the farms were found to grow PVA maize, but seed was received as a gift or handout from programs running in the area, with no household purchasing seeds [62]. In contrast, 49% declared having knowledge of PVA maize and its benefits but did not grow it, primarily due to limited availability of seed. Strengthening the seed value chain for PVA maize is thus crucial to increasing its adoption. However, the cost and effort of doing so should be weighed against alternative interventions – e.g., promotion of home gardening and small stock keeping, small-scale food fortification – as recently suggested [21].

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### Authors contributions

The authors' responsibilities were as follows – FB: designed the research, conducted the research, and analyzed the data; FB, JEC: wrote the first draft of the paper; FB, SMH, EJMJ: had primary responsibility for the final content; all authors: read and approved the final manuscript.

### Conflict of interest

The authors report no conflicts of interest.

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### Declaration of generative AI in scientific writing

During the preparation of this work, the authors declare that they have not used generative AI.

## Data Sharing

Data described in the manuscript and analytic code are publicly and freely available without restriction at https://github.com/FBaudron/Baudron-et-al.-2024-The-Journal-of-Nutrition.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tjnut.2024.04.009.

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