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ORIGINAL ARTICLE

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Could local foods achieve recommended calcium intakes for nutritionally vulnerable populations in Uganda, Guatemala, and Bangladesh?

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Abstract

Globally, dietary intake of calcium is often insufficient, and it is unclear if adequacy could be achieved by promoting calcium-rich local foods. This study used linear programming and household consumption data from Uganda, Bangladesh, and Guatemala to assess whether local foods could meet calcium population reference intakes (Ca PRIs). The most promising food-based approaches to promote dietary calcium adequacy were identified for 12- to 23-month-old breastfed children, 4- to 6-year-old children, 10- to 14-year-old girls, and nonpregnant and nonbreastfeeding (NPNB) women of reproductive age living in two regions of each country. Calcium-optimized diets achieved 75–253% of the Ca PRI, depending on the population, and were <100% for 4- to 6-year-olds in one region of each country and 10- to 14-year-old girls in Sylhet, Bangladesh. The best food sources of calcium were green leafy vegetables and milk, across geographic locations, and species of small fish, nixtamalized (lime-treated) maize products, sesame seeds, and bean varieties, where consumed. Food-based recommendations (FBRs) achieving the minimum calcium threshold were identified for 12- to 23-month-olds and NPNB women across geographic locations, and for 4- to 6-year-olds and 10-to 14-year-old girls in Uganda. However, for 4- to 6-year-olds and 10- to 14-year-old girls in Bangladesh and Guatemala, calcium-adequate FBRs could not be identified, indicating a need for alternative calcium sources or increased access to and consumption of local calcium-rich foods.

KEYWORDS
calcium, diet modeling, dietary adequacy, food-based recommendations, linear programming, optifood

PURPOSE

In March and April 2021, the Nutrition Science Program of the New York Academy of Sciences, in partnership with the Children's Investment Fund Foundation, convened a Calcium Task Force and hosted two virtual meetings. This task force is composed of experts in micronutrients, malnutrition, pediatrics, gynecology and obstetrics, biochemistry, public health, supplementation, and food fortification. During these two virtual meetings, the task force assessed the evidence on global calcium deficiency and its health consequences, and useful indicators of calcium status. It also considered potential interventions such as calcium supplementation for pregnant women to improve pregnancy outcomes, and associated implementation challenges, as well as food-based interventions to improve the intake of this micronutrient, especially in populations with low calcium intake. The group was also asked to identify the research gaps and provide guidance for interventions and policies based on the most current available evidence. In this research article, the task force discusses the analysis on and concludes how food-based approaches could contribute to meeting calcium intake recommendations across different geographic regions on three continents for key target groups.

INTRODUCTION

Adequate dietary calcium intake is essential for bone health, metabolism, cell signaling, and the prevention of preeclampsia and its complications during pregnancy.[1] Despite its importance in health, an estimated 3.5 billion people globally are at risk of inadequate dietary intakes of calcium, underscoring the public health importance of interventions to promote dietary calcium adequacy.[2,3] Among populations in low- and middle-income countries (LMICs), especially in Asia, Africa, and Latin America, dietary calcium consumption is often low (400 mg/day), largely due to a high percentage of dietary energy provided by staple foods, such as unrefined cereals, which are low in calcium, and good food sources of calcium, such as dairy products, are consumed in small amounts.[4–6] Women of reproductive age and young children are particularly vulnerable because of their high calcium relative to energy requirements compared with adolescent boys and men.[3,6]

In settings where women have low dietary calcium intakes, high-dose calcium supplementation during pregnancy can reduce preeclampsia risk by half.[7,8] Further positive effects of maternal calcium supplementation during pregnancy may extend to children beyond the postnatal period;[9] however, the impact of calcium supplementation on bone health for both mothers and their children is unknown.[10,11] Regardless, calcium supplementation is unlikely to be a feasible or effective method of addressing insufficient calcium intakes for the broader population, due to high costs and requirements for large doses and burdensome dosing schedules.[7] Therefore, for the broader population, in areas where calcium intakes are low, other strategies, such as food-based approaches, are necessary and may prove effective.[12] Food-based approaches are also less likely than supplementation to exceed tolerable upper intake levels for calcium, making it a safe intervention strategy.

Another advantage of promoting the consumption of locally available, affordable, and habitually consumed calcium-containing foods is that the intervention can reach all household members who consume the promoted food(s).[12] Local animal- and plant-source foods that are naturally high in calcium could be promoted either through education, behavior change communication, subsidies, vouchers, transfers, or other initiatives.

Other relatively cost-effective strategies can be used to either increase the calcium content or the calcium bioavailability of staple foods. Wheat flour, and, to a lesser extent, maize flour and rice, are fortified with calcium to increase overall content in a number of countries, mostly through voluntary fortification standards.[12] Food processing methods, such as maize nixtamalization (soaking maize in a lime solution of calcium hydroxide to make it malleable enough for tortilla preparation) and parboiling of rice, also result in increased calcium content.[12] Finally, different fermentation processes can reduce phytate levels, resulting in increased calcium bioavailability.[12] These mechanisms, depending on the local context, could be used alone or in combination with behavior change interventions promoting calcium-rich local foods, to improve dietary calcium adequacy of all household members.[12–15]

However, the question remains as to whether it is possible to ensure adequate calcium intakes through strategies promoting only local foods in amounts habitually consumed by people living in LMICs, especially for nutritionally vulnerable groups, such as young children, adolescent girls, and women of reproductive age. Thus, the Calcium Task Force, assembled by the Nutrition Science Program of the New York Academy of Sciences, has undertaken a linear programming analysis (LPA) using secondary data from Household Consumption and Expenditure Surveys (HCES) to determine the extent to which food-based approaches could meet recommended calcium intakes for key target groups of interest across different geographic locations in three continents. The objectives of these analyses were to (1) determine whether calcium nutrient reference values could be met, using local foods, for different nutritionally vulnerable groups in Uganda, Bangladesh, and Guatemala; (2) identify local foods in each setting that would be good dietary sources of calcium given observed dietary patterns; and (3) identify food-based recommendations (FBRs) that could be promoted to improve dietary calcium intakes for nutritionally vulnerable groups in each geographic area.

METHODS

A secondary data analysis was undertaken using publicly available HCES data and LPA. The target populations of interest were 12- to 23-month-old breastfed (BF) children, 4- to 6-year-old children, 10- to 14-year-old girls, and nonpregnant and nonbreastfeeding (NPNB) women of reproductive age living in Uganda, Guatemala, and Bangladesh. These groups were selected because of their high calcium relative to energy requirements and as they were of the highest

TABLE 1 Description of the linear programming models used to answer each study objective, including the model's objective function,[a] model constraints, and the outcomes of interest.

Purpose (module)	Model's objective[a]	Model constraints	Outcomes of interest
Study objective 1: To determine if the Ca content of any diet would achieve the EFSA PRI for Ca[b] (Module 3 analyses, maximization)	Select the diet with highest Ca content (objective function maximizes the diet's Ca content)	• Diet's energy content = the average energy requirement[c] • Grams of each food ≥ 0 g • Grams of each food ≤ a maximum amount • # Servings from each food subgroup ≥ minimum # of servings • # Servings from each food subgroup ≤ maximum # of servings • # Servings from each food group ≥ minimum # of servings • # Servings from each food group ≤ maximum # of servings	The calcium content of the model diet expressed as a % of the EFSA PRI
Study objective 2: To identify good food sources of calcium for the target population (Module 2 analyses)	Select diet that comes as close as possible to meeting the EFSA PRIs for 12 nutrients (objective function minimizes the sum of deviations below the PRIs)	• Same constraints as above	List of foods and food subgroups providing ≥5% of the model diet's calcium content
Study objective 3: Test and compare alternative sets of FBRs to identify FBRs for improving dietary Ca intakes (Module 3 analyses, minimization)	Select diet with the lowest Ca content (objective function minimizes the diet's Ca content)	• Same constraints as above • Additional constraints to ensure the FBRs being tested are met: FBRs are expressed as # servings/week of either food subgroups or food groups; thus, the constraints are the diet must include a # of servings/week of foods from the food group or food subgroup ≥ the # servings specified in the FBR or set of FBRs being tested	The calcium contents, which are expressed as a % of the EFSA Ca PRI, of the modeled diets for all FBRs tested are compared

Abbreviation: FBRs, food-based recommendations.
[a]Criteria for selecting the optimized diet in each linear programming analysis.
[b]EFSA PRI = European Food Safety Authority Population Reference Intake for calcium, iron, zinc, vitamins A, C, B6, and B12, folate, thiamine, riboflavin, and niacin, adjusting the iron and zinc reference intake values for low bioavailability and the niacin PRIs for the energy content of each modeled diet (see Table S7 for the nutrient PRIs, i.e., the goals used in the Module 2 analyses).
[c]The equations used to estimate average energy requirements for each target group are listed in Table S7.

priority to the Calcium Task Force (see Table S1). Countries were chosen from a list of those with available and appropriate household-level food consumption data to provide examples from three global regions with low dietary calcium intake: Asia, Latin America, and Africa.[3,16] Within each country, two regions were analyzed to characterize regional differences in food consumption patterns. In Uganda and Guatemala, both urban and rural populations were analyzed, but the survey design restricted the analyses to only rural populations in Bangladesh. Overall, 40 individual target groups (characterized by geographic location and population group) were analyzed across a total of 10 geographic areas in three continents. A description of the HCES datasets with a justification for their selection is provided in Table S2.

The LPA was done in Modules 2 and 3 of the Optifood software, as described in detail elsewhere[17–19] and summarized in Table 1. The input model parameters for the LPA included a list of foods consumed by each target group, the average daily serving size of each food (g/day), upper and lower constraint values for the number of servings per week for each food, food subgroup, and food group. The values for these model parameters are detailed in Tables S3–S5. These parameter values were derived from country-, region-, and urban-rural-specific HCES data. The list of foods modeled for each target group included all foods reported as consumed by ≥5% of households, in which someone from the target group of interest was a resident. Items were excluded if they had no nutritional value (e.g., water and tea). A constant amount of breastmilk was included in the food lists for all 12- to 23-month-old children (503 g/day, providing 39% of energy requirements[20,21]). Target group–specific food consumption used to generate these model parameters was estimated by redistributing the HCES household-level food consumption data using the adult male equivalent (AME) method.[19,22,23] Each individual in the HCES dataset was assigned an AME based on their energy requirements in relation to those of an adult male, as listed in Table S6. During the AME assignment, it was assumed that all children under 2 years of age were BF, and that infants aged under 6 months were exclusively BF (i.e., did not consume household foods) because the median duration of breastfeeding is 28.8, 22, and 19.8 months in Bangladesh, Guatemala, and Uganda, respectively.[24–26] The AMEs of all members of each household in the dataset were then summed to provide household AME quotients.[19,22,23] Next, to estimate daily food consumption (g/day) for each target group, the total household supply of every food consumed was multiplied by the target group's AME quotient and divided by the HCES recall period (i.e., 14 in Guatemala and 7 in Uganda and Bangladesh). The resulting apparent individual food intake data were matched with food composition data to estimate the apparent calcium intake of individuals in each target population for comparison with the Optifood results, as per the methods described by Bermudez et al.[27]

The average daily serving size for each food modeled in Optifood was the median of estimated daily consumption calculated for consumers in each target group. For the calcium-rich foods (identified in objective 2 below), the proposed quantities were critically examined. In three cases, proposed quantities appeared unrealistic when compared with literature values (i.e., expressed as g/day or percentage of energy), and adjustments were made.[28–30] For example, one daily portion of small fish for each target group in Uganda was adjusted to provide a maximum of 10% of daily energy when it originally exceeded this value.[28] To estimate the lower and upper model constraint limits on the number of servings per week for each food and from each food subgroup and food group, the 10th and 90th percentiles of estimated weekly consumption (g/week for consumers and nonconsumers; adjusted to a 7-day intake for Guatemala) were divided by the estimated average daily serving sizes (for consumers). In addition, all models included an energy constraint to ensure the energy contents of modeled diets were equal to the target population's estimated average energy requirement. These values were calculated using the WHO/FAO algorithms based on the average body weight, from secondary data,[24–26,31,32] for each target population in each geographic area and, in the case of the adult women, assuming a physical activity level of 1.85 (i.e., a moderate activity level).[33] These constraints ensured that all modeled diets resembled the apparent diets of each target population of interest.

The Food Composition Tables (FCTs) used to estimate the energy and nutrient content of each food and the consequent simulated diets were the 2012 Harvest Plus FCT for Central and Eastern Uganda and published data for individual foods[34,35] for Uganda; the Nutrition Institute of Latin America and the Caribbean's (INCAP) FCT[36] for Guatemala; and the Indian National FCT and the USDA FCT[37,38] for Bangladesh. The nutrient composition for breastmilk across all analysis areas was based on references for breastmilk in developing countries.[20]

Data analyses

All analyses were done in Modules 2 and 3 of the Optifood software program.[17] In Module 2, the simulated diet of interest was the diet that came as close as possible to achieving the nutrient reference values for 12 nutrients (Table 1 and Table S7). The Module 3 diets of interest were the two diets selected to have the highest and lowest calcium contents possible (maximized and minimized calcium diets, respectively). For all simulated diets, model constraints on the diet's energy content (equality constraint) and the number of servings/week (upper and lower bounds) from individual foods, food subgroups, and foods ensured they resembled those derived from the HCES data.

To answer study objective 1, the calcium content of the maximized calcium diet from Module 3 was examined to determine for each target group whether it achieved or exceeded 100% of the calcium population reference intake (Ca PRI). If it did not achieve 100%, this indicated that recommended calcium intakes for this target population could not be met using acceptable quantities of local foods. Additionally, if 100% of the Ca PRI was met in these Module 3 maximized calcium diets but was not met in the optimized diet from Module 2 (for 12 nutrients, including calcium), this suggested that Ca PRIs could be met using local foods, but only at the expense of not meeting the PRIs of other nutrients.

To answer study objective 2, the best food sources of calcium selected for each target population were those providing at least 5% of the calcium in the target group's Module 2 diet (i.e., nutritionally best diet). The best food sources of calcium were identified from this diet instead of the maximized calcium diet because these foods were also consistent with an overall nutritious diet in which the intake of multiple nutrients was optimized. The feasibility of recommending the consumption of these foods in each geographic area was assessed by examining the percentage of households in which each food was consumed.

To answer study objective 3, up to eight FBRs were evaluated individually and in combination with other individual FBRs to select promising sets of FBRs for each of the 10 geographic areas. These FBRs were generally expressed as the number of servings per week from specific food subgroups, rather than individual calcium-rich foods, to avoid selecting an overly prescriptive set of FBRs that limited consumer choice. The food subgroups selected for these simulations were those providing at least 5% of the calcium content of the Module 2 nutritionally best diet. In these simulations, up to 247 alternative sets of FBRs (i.e., all combinations of eight, seven, six, etc. FBRs) were evaluated in Module 3 by comparing the calcium contents (expressed as % PRI) of the minimized calcium diets (i.e., the diet with the lowest calcium content possible given model constraints). When testing a set of FBRs, additional model constraints were used to ensure the simulated diet achieved the complete set of FBRs being tested. For example, if the set of FBRs being tested included 7 servings/week of milk and 3 servings/week of small fish, then the new constraints ensured the simulated lowest calcium diet included ≥7 servings of milk and ≥3 servings of small fish per week, in addition to other local foods within model constraints that met the energy target while providing the lowest possible quantity of calcium. The criteria for selecting sets of FBRs for each geographic area and target group were the sets of FBRs that met at least 65% of the Ca PRI in minimized Module 3 calcium diets using the lowest number of individual FBRs. For most target groups, multiple promising sets of FBRs were selected. If 65% of the Ca PRI could not be met, then the sets with the highest % Ca PRI using the lowest number of individual FBRs were selected. Finally, in each of the 10 geographic areas, one harmonized set of FBRs was selected for all four target groups. This was the set most often selected across all four target groups in each geographic area, and, when there was a

TABLE 2 Percentage of EFSA calcium PRI[a] met in the Module 2 nutritionally best[b] diet and the Module 3 maximized calcium diet.[c]

			Breastfed 12- to 23-month-olds		4- to 6-year-olds		10- to 14-year-old girls		NPNB[c] women	
Country	Geographic area	Location	Diet B[a]	Max Ca[b]	Diet B	Max Ca	Diet B	Max Ca	Diet B	Max Ca
Uganda	Central	Urban	102%	116%	96%	98%	100%	124%	141%	211%
		Rural	100%	126%	100%	113%	100%	185%	158%	217%
	North	Urban	119%	128%	100%	121%	100%	129%	180%	239%
		Rural	103%	131%	100%	128%	100%	150%	182%	253%
Bangladesh	Barisal	Rural	96%	110%	86%	95%	65%	73%	100%	174%
	Sylhet	Rural	89%	100%	100%	127%	96%	103%	100%	173%
Guatemala	Western Highlands	Urban	80%	112%	100%	101%	100%	122%	100%	201%
		Rural	83%	105%	100%	102%	93%	107%	133%	200%
	Dry Corridor	Urban	98%	110%	94%	95%	100%	143%	103%	224%
		Rural	91%	105%	100%	115%	100%	143%	100%	211%

Abbreviation: EFSA calcium PRI, European Food Safety Authority's Population Reference Intake for calcium.
[a]Diet modeled with the goal of minimizing deviation from the PRI for all 11 modeled micronutrients.
[b]Diet with the highest calcium content possible given the model parameters.
[c]Nonpregnant and nonbreastfeeding.

choice, priority was given to the set providing the highest % Ca PRI in the minimized calcium diets of adolescent girls or 4- to 6-year-old children.

RESULTS

Ca PRIs were achieved, in the maximized calcium diets, for 36 of the 40 target groups modeled (Table 2), indicating that calcium nutrient reference values can be met using local foods for most of these populations (objective 1). However, for 4- to 6-year-old children in urban Central Uganda; rural Barisal, Bangladesh; and urban Dry Corridor, Guatemala; and adolescent girls in rural Barisal, Bangladesh, the calcium contents of the maximized calcium diets were less than 100% of the Ca PRI and were less than 110% of Ca PRIs in a further seven target groups. The calcium contents of the Module 2 nutritionally best diets were also less than 100% of the Ca PRIs for 12- to 23-month-old BF children in Bangladesh and Guatemala (range 80–98%) and adolescent girls in Sylhet, Bangladesh (96%) and the rural Western Highlands of Guatemala (93%) even though their Module 3 maximized calcium diets exceeded 100% (Table 2). These results indicate the adequacy of other nutrients was compromised in their maximized calcium diets. The results for these maximized calcium diets also showed that young children and adolescent girls had lower % Ca PRIs than adult women, and they were the lowest for 4- to 6-year-old children in Uganda and Guatemala and for adolescent girls in Bangladesh. Comparisons across countries showed that overall, Bangladesh had the lowest % Ca PRIs in the maximized calcium diets (Table 2).

Sixteen food subgroups provided ≥5% of dietary calcium across all the different geographic locations, including vitamin A–rich dark green leafy vegetables (all geographic locations), liquid or powdered milk and small whole fish with bones (Uganda and Bangladesh), other vegetables (Bangladesh and Guatemala), refined grain bread (Uganda), whole grains and grain products (including maize tortillas) (Guatemala), cooked beans, nuts and seeds, and starchy plant foods other than bread (Uganda), and vitamin C–rich fruit (selected geographic locations in Uganda and Guatemala) (Table 3). Breastmilk provided 30–45% of the calcium in the simulated diets of 12- to 23-month-old BF children. In addition to calcium, these food subgroups also provided ≥5% of one to nine other nutrients (vitamins A, C, B6, and B12, folate, thiamine, riboflavin, niacin, iron, or zinc) in the Module 2 nutritionally best diets of adolescent girls (Table S8), making them promising FBRs to also improve overall nutrient adequacy. Of these 16 food subgroups, all were consumed by more than 20% of households in most geographic locations where they were selected, except refined grain bread, which was consumed by 5–19% of households (Table S9). Thus, except for refined grain bread, these were identified as FBRs worth testing in Module 3, as detailed in Table S10.

The final sets of harmonized FBRs selected for each geographic location are displayed in Table 4. Each set included either three or four individual recommendations, depending on the region. All sets included dark green leafy vegetables, and apart from Northern Uganda, all sets included milk or cheese. Other food subgroups included in these sets were small fish eaten with bones (Uganda and Bangladesh), lime-treated maize products (Guatemala), sesame seeds (Northern Uganda), beans or sweet potato (Central Uganda), and refined or enriched grain products (fortified blended flour–Incaparina in urban Guatemala).

The calcium content of the Module 3 minimized calcium diets for these final sets of harmonized FBRs selected for each of the 10 geographic areas met or exceeded 65% of the Ca PRI for all target populations in Uganda, and for all 12- to 23-month-old target and most groups of NPNB women in Guatemala and Bangladesh (Table 4). These results indicate that, if followed, the selected sets of FBRs would reduce the percentage of individuals at risk of inadequate calcium

TABLE 3 Percentage of the calcium content of the Module 2 nutritionally best diet provided by “good food sources of calcium”[a] by geographic area and age group.

	Breastfed 12- to 23-month-olds				4- to 6-year-olds				10- to 14-year-old girls				NPNB[b] women			
	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca	% Ca
Food	R[c]	U[d]	R	U	R	U	R	U	R	U	R	U	R	U	R	U
Uganda	Central		Northern		Central		Northern		Central		Northern		Central		Northern	
Mukene, fish	17	22	29	28	31	27	34	34	43	43	26	43	41	39	36	36
Dodo (amaranth)	12	16	13	12	19	17	21	17	21	20	34	19	24	26	23	24
Milk, fresh	12	12		8	16	23		13		8		7				
Sesame seeds			12	11	11		25	15	12		20	6	12		19	21
Peas or beans, dry	8					9				8		5		6	6	
Starchy roots[e]						7					5					
Loaf or bun					6	11			6	11		8	6	9	5	9
Breastmilk	36	35	35	30												
Guatemala	Western Highlands		Dry Corridor		Western Highlands		Dry Corridor		Western Highlands		Dry Corridor		Western Highlands		Dry Corridor	
Maize tortilla	29	9	24	30	38	41	70	50	54	61	38	60	60		9	
Flour tortilla									12					38		48
Maize flour or atol					9	18						8		5	6	9
Incaparina				9										6	10	11
Green leaves	6	7	8	7	11	6	10	8	7	5	9	8	7	9	16	16
Milk, fresh	10	18		10	5			10								
Cheese, curd or hard					5	7	5				18				7	
Beans, black														7	7	
Bread										8				11	17	
Broccoli								8							15	
Breastmilk	42	45	39	36												
Bangladesh	Barisal		Sylhet		Barisal		Sylhet		Barisal		Sylhet		Barisal		Sylhet	
Milk, liquid, or powder			23		10		15		21		16		7		6	
Small fish, varieties[f]	35		15		46		38		39		39		63		63	
Baim fish											7					
Green leaf, varieties[g]			10		9		7		11		11					
Water gourd									6							
Starchy roots[h]					9		15									
Breastmilk	37		40													

[a]Providing ≥5% of the calcium content in the Module 2 “nutritionally best” diet.
[b]Nonpregnant and nonbreastfeeding.
[c]Rural areas, and for Bangladesh, all areas are rural.
[d]Urban areas.
[e]White flesh sweet potato or cassava flour.
[f]Small fish varieties were mrigal fish, bele fish, chapila fish, jatka fish, moa fish, dhela fish, or bata fish.
[g]Green leafy vegetables were jute leaves, helencha leaves, bathua leaves, and danta shak.
[h]Starchy roots were green banana and potato.

intakes to low levels. However, this criterion was mostly not met for 4- to 6-year-old children and 10- to 14-year-old girls in Guatemala and Bangladesh (Table 4), indicating that other intervention strategies are needed for these populations. The full set of results for the FBRs tested (i.e., over 9000 sets of FBRs) are available on request.

DISCUSSION

Results from these analyses indicate that the calcium content of diets based only on local foods could potentially meet Ca PRIs for 12- to 23-month-old children and NPNB women in Uganda, Guatemala, and

TABLE 4 Final sets of FBRs[a] selected by geographic area and % calcium PRI in the Module 3 minimized calcium diets by target group.

Country	Area	R/U	Selected FBR options	% Ca PRI in minimized diets by age group: 12- to 23-month-old BF[b] children	4- to 6-year-old children	10- to 14-year-old girls	NPNB women[c]
Uganda	Central	Rural	GLV6 - Milk4 - SmallFish7 - Beans7	77.3	76.5	93.3	128.2
		Urban	GLV7 - Milk4 - SmallFish7 - SwPotato7	74.6	66.1	84.5	142.9
	Northern	Rural	GLV7 - SmallFish7 - Sesame6	96	72.7	92	143.5
		Urban	GLV7 - SmallFish7 - Sesame6	72.2	67.1	78.2	136
Bangladesh	Sylhet	Rural	GLV7 - Milk6 - SmallFish5	65.5	66.2	48.1	65.2
	Barisal	Rural	GLV7 - Milk6 - SmallFish5	73.6	49.5	51.2	65.2
Guatemala	Western Highlands	Rural	GLV4 - Milk4 - Maize_tortilla7	73.9	41.3	30.7	70.8
		Urban	GLV4 - Refine_grt7 - Milk4 - Maize_tortilla7	69.6	36.9	37.7	47.7
	Dry Corridor	Rural	GLV7 - Cheese4 - Maize_tortilla7	99.5	54.2	45.9	73
		Urban	GLV7 - Milk4 - Enrich_grt5 - Maize_tortilla7	90.9	46.1	65	96.2

Abbreviation: FBRs, food-based recommendations.

[a]The acronyms used for the FBRs are: GLV6 (GLV7, GLV9) = 6 (7, 9) servings/week of green leafy vegetables; Milk4 (Milk7, Milk8) = 4 (7, 8) servings/week of milk; Beans7 = 7 servings/week beans; Smallfish7 (Smallfish5) = 7 (5) servings/week of small fish eaten whole with bones; SwPotato7 = 7 servings/week of sweet potato; Sesame6 = 6 servings/week of sesame seeds; Maize_tortilla7 = 7 servings/week of maize tortilla; Refine_grt7 = 7 servings per week of refined grains and products (unenriched, unfortified); Cheese4 = 4 servings/week of cheese; Enrich_grt5 = 5 servings/week of a fortified grain product (e.g., Incaparina).

[b]Breastfed; the set of FBRs for this target group includes a recommendation to feed the child breastmilk every day.

[c]Nonpregnant and nonbreastfeeding women of reproductive age.

Bangladesh, whereas it was not possible to simulate diets that met them for 4- to 6-year-old children in 3 of the 10 geographic areas and for 10- to 14-year-old girls in one geographic area. Furthermore, for 12- to 23-month-old BF children and 10- to 14-year-old girls in Bangladesh and Guatemala, selecting a high calcium diet could compromise the adequacy of other nutrients because the calcium content of the Module 2 nutritionally best diet was <100%. These results underscore the challenge of providing young children and 10- to 14-year-old girls diets that will meet calcium reference nutrient values given local food consumption patterns and locally available food sources of calcium. These findings are also in line with the high proportion of apparent calcium intakes for each geographic area below the calcium average requirement, in particular, the estimated apparent calcium intakes for 4- to 6-year-old children and adolescent girls (Table S11). They also concur with dietary surveys showing a high percentage of children in LMICs are at risk of inadequate calcium intakes.[3,39,40] Nevertheless, the current analyses showing that Ca PRIs could be achieved in simulated diets based on local foods in quantities habitually consumed, for 36 of the 40 target groups analyzed, are encouraging, as they show that there is scope to improve dietary calcium adequacy for nutritionally vulnerable populations in these settings.

Important food sources of calcium in these diets were green leafy vegetables, liquid or powdered milk, lime-treated maize products, small fish eaten with bones, and legumes or seeds, especially sesame seeds. Breastmilk was also an important source of calcium for BF 12- to 23-month-old children. Not only were green leafy vegetables, lime-treated maize products, and small fish eaten with bones excellent food sources of calcium, but they were also good sources of other nutrients examined and were consumed in relatively high percentages of households in these settings (i.e., >25%, >40%, and >55% in Uganda, Guatemala, and Bangladesh, respectively). In settings where liquid or powdered milk was regularly consumed, these products are good sources of calcium, although small serving sizes meant their contribution to dietary calcium in the simulated diets was often lower than small fish or lime-treated maize products. These findings are consistent with other published studies identifying affordable sources of calcium for complementary feeding in South Asia (including Bangladesh) and East Africa (including Uganda).[41,42]

The amount of absorbed calcium from some animal-source foods, especially dairy, is superior to that of calcium-rich plant-based products, unless fortified.[12] However, high costs, limited shelf life (fresh products), and, for dairy products, lactose intolerance or malabsorption can be barriers to the promotion of these foods.[12] Nonetheless, the HCES food consumption data suggest that some animal-source foods could be successfully promoted in multiple study settings; for example, 50–60% of households reported milk consumption in Central Uganda and 55–60% of households in Sylhet and Barisal, Bangladesh were consuming small fish (Table S9). Furthermore, in all simulations for all target groups, the average daily servings sizes modeled for these food items were considered to be realistic, ranging from 4 to 45 g/day for small dry fish, from 28 to 186 g/day for fresh milk, and from 4 to 18 g/day for powdered milk. For small dry fish, the amounts used in the simulations are similar to the estimated average daily quantity of raw fish consumed per person in Bangladesh and Cambodia of 128 g/day, and in these two countries, the low market value of small fish suggests they may feasibly be consumed by the poor.[43]

Across all 10 geographic locations, the final sets of harmonized FBRs selected included green leafy vegetables (4–7 servings per week) and at least one calcium-rich animal-source food (4–11 servings per week, depending on the area), including dairy products (8 of 10 areas) and/or small fish eaten with bones (6 of 10 areas). Other food subgroups in the harmonized FBRs, depending on the setting, were lime-treated maize products and calcium-fortified grain products in Guatemala, and legumes/seeds (especially sesame) or sweet potatoes in Uganda. These FBRs were expressed as the number of servings per week of foods from specific food subgroups instead of individual calcium-rich foods to increase flexibility in consumer choice, although in reality, choice in some settings was limited to only one or two foods within the subgroup, given seasonal availability. For example, in the Ugandan analyses, dodo (amaranth) was the only food choice modeled in the green leafy vegetable subgroup. The number of individual recommendations within each final set of harmonized FBRs (i.e., three or four individual FBRs) was also low, which is more likely to be manageable, given that there are limits to how much information people can absorb, the number of changes that are feasible, and the challenges to the capacity of programs promoting dietary change.[44] This number was also similar to or lower than those in sets of FBRs developed for 12- to 23-month-old Ugandan children to improve overall dietary adequacy of 11 nutrients,[45] as additional food subgroups may be required to provide other nutrients. Nevertheless, there was a high degree of overlap in FBRs selected for 12- to 23-month-old children in the current and previous studies,[19,46] underscoring the importance of milk, green leafy vegetables, small fish, beans, whole grains, and sweet potatoes as food sources of not only calcium but other multiple nutrients. The final FBRs also align with the broader national food-based dietary guidelines for Bangladesh[47] and Guatemala[48] and the guidelines on maternal, infant, young child, and adolescent nutrition in Uganda;[49] however, similar to previous Optifood studies, additional food groups are recommended in the national guidelines to promote the adequacy of multiple micronutrients, rather than calcium alone.

The final sets of harmonized FBRs selected for each geographic area were selected from among over 9000 alternative sets of FBRs, and for some target groups, there were sets of FBRs that were slightly superior for improving dietary calcium adequacy. Thus, for programmers involved in designing food-based interventions to improve dietary calcium adequacy for a specific age group, these alternative, non-harmonized sets of FBRs might be of interest. Either way, before implementation, it is important to assess the feasibility and acceptability for the target population of following the selected set of FBRs, using tools, such as ProPAN or Trials of Improved Practices.[17,50] Through such trials, individuals provide feedback on the acceptability and feasibility of following a set of FBRs over the long term after implementing them for 1 or 2 weeks. Using these trials in rural Western and Eastern Uganda, Bekele and Turyashemererwa found that while seasonality and cost were barriers, the Optifood-developed complementary feeding recommendations were largely feasible and acceptable as the foods promoted were familiar to caregivers.[46] Fahmida et al. applied similar methods to test complementary feeding recommendations in rural Indonesia and found that caregivers were more likely to put FBRs for lower-cost foods (e.g., green leafy vegetables and legume products) into practice than FBRs for more expensive animal-source foods.[51] For this reason, additional strategies may be needed to improve the affordability of nutritious foods if FBR use is found to be constrained by economic access.

Adoption of these final sets of FBRs, if followed, would be expected to reduce the percentage of women, girls, and children at risk of inadequate dietary calcium intakes to low levels for all populations in Uganda and for most populations of 12- to 23-month-old BF children and NPNB women in Guatemala and Bangladesh. However, achievement of this outcome for 4- to 6-year-old children and 10- to 14-year-old girls in Guatemala and Bangladesh might require additional food-based strategies, including the promotion of increased consumption of local calcium-rich foods, such as milk or small fish, or the development, provision, and promotion of calcium-fortified products.

Despite using data on current dietary patterns and food availability to develop these sets of FBRs, their ability to impact nutrient intake could be constrained by poverty and other barriers faced in accessing the recommended foods in adequate amounts. This analysis did not consider food prices and household purchasing power. However, complementary LPAs have found that, for a high proportion of households in Guatemala, Bangladesh, and Uganda, nutritious diets would be unaffordable and that nutrient needs would be most expensive to meet for adolescent girls and women.[52–54] Therefore, interventions such as improved production, market access, subsidies, free distribution of calcium supplements, biofortification, livelihoods, and/or social safety nets may be needed to enable people to put these FBRs into practice.[12]

A strength of this study was the use of 40 regionally representative target groups from 10 geographic regions in three continents to define the LPA model parameters. HCES data are routinely collected in over 115 countries around the world,[55,56] which facilitates these or similar analyses for other countries or for one country over time to monitor changes in food-based opportunities.[19] Another strength is that these analyses only take seconds to run in Optifood once the model parameters have been established. As such, similar analyses could be conducted to explore the potential of meeting recommended intakes of other or multiple micronutrients for a variety of target groups in different subnational settings globally.

Through this study, a process was also developed to use LPA to determine whether a diet based on local foods could meet the nutrient reference values for a single nutrient without compromising the dietary adequacy of other nutrients. Specifically, the nutrient contents (expressed as % PRI) of the diet with the highest content of the nutrient of interest (Module 3 maximized diet), and the most nutritious diet (Module 2, nutritious diet) are compared. A content >100% PRI for the nutrient of interest in both diets indicates a diet can be selected to achieve its PRI without compromising the intake of other nutrients, whereas a content <100% PRI for the nutrient of interest in both diets or one diet indicates that it will be difficult to select a diet that meets its PRI (both diets <100%) or if met, that the intake of other nutrients might be compromised if foods high in the nutrient of interest are promoted (one diet <100%).

The disadvantages of using HCES data to define the model parameters must be recognized. Several assumptions are required to generate the LPA model parameters, which might not be correct, including assumptions of equal intrahousehold food distribution based on the estimated average energy requirements of individual household members.[19,57] In some HCES datasets, respondents are asked to estimate quantities of groups of foods instead of individual foods over 1 or 2 weeks, which is prone to recall bias, and the foods often are not grouped on the basis of nutrition criteria.[19,57] Despite these weaknesses, a previous study comparing the use of HCES and individual 24-hour recall–derived model parameters showed high levels of agreement in LPA outcomes for 12- to 23-month-old children in Uganda, Guatemala, Bangladesh, and Kenya.[19]

Another limitation is that this analysis considered only the total calcium content of modeled foods, rather than bioavailable calcium. While estimates of absorbable calcium exist in the literature, they are for some foods only,[12,58] and were not available for all 354 locally specific foods modeled across the 10 geographic locations. Furthermore, given the variance of calcium bioavailability across similar foods, such as different green leafy vegetables,[58,59] it would not be possible to apply food-subgroup-specific bioavailability estimates to analyzed foods.

CONCLUSIONS

Overall, these analyses indicate that FBRs based on reasonable amounts of local foods can be used to promote dietary calcium adequacy for 12- to 23-month-old BF children and NPNB adult women across all geographic locations, and for 4- to 6-year-old children and 10- to 14-year-old girls in Uganda. However, for 4- to 6-year-old children and 10- to 14-year-old girls in Bangladesh and Guatemala, sets of FBRs could not be identified that met the criteria of ≥65% of the Ca PRI in the minimized calcium diets, indicating a need to promote an increase in the consumption of locally available calcium-rich foods from current levels or the development, provision, and promotion of alternative food sources of calcium, such as calcium-fortified products, to ensure population-level dietary calcium adequacy.

AUTHOR CONTRIBUTIONS

F.K., M.W.B., and E.L.F. conceptualized the project. F.K. and E.L.F. conceptualized the analyses. F.K. and E.L.F. did the analyses. F.K., Z.H.R., and E.L.F. wrote the first draft of the manuscript. All authors edited the manuscript and approved the final version.

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COMPETING INTERESTS

The authors declare no competing interests.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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